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Searches for new physics in dijet and multijets final states

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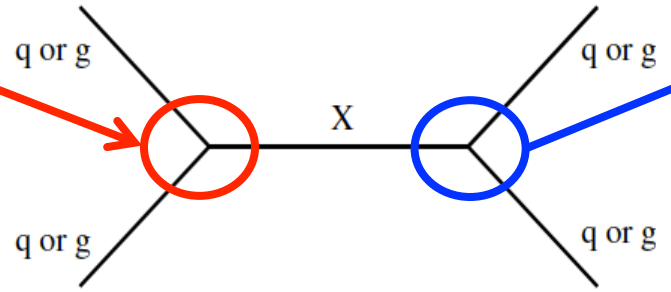
Physics Motivation

- **Standard Model** of particle physics **incomplete theory**
  - Extensions of the SM predict the existence of **new particles at the TeV scale**

- Resonance searches:
  - Most solid way to discover New Physics
    - Resonances are fully reconstructed
    - Small systematics
    - Difficult to imitate for a background

- **The searches for new resonances decaying into jets are among the most important ones at LHC**

If a resonance is produced by a proton-proton collision



it must couple to quarks and gluons

Summary of searches

- Data collected by CMS in Run2 @ 13 TeV:
  - **2015** Integrated luminosity = 2.7 fb^{-1}
  - **2016** Integrated luminosity = 35.9 fb^{-1}

- Searches with jets in the final state discussed in this talk:

Method	Analysis	Lumi	Reference
Bump search	Dijet	35.9 fb^{-1}	CMS-PAS-EXO-16-056
	Boosted dijet	35.9 fb^{-1}	CMS-PAS-EXO-17-001
	Pairs of dijet (boosted regime)	2.7 fb^{-1}	CMS-PAS-EXO-16-029
Angular analysis	χ_{dijet} analysis	35.9 fb^{-1}	CMS-PAS-EXO-16-046

NEW

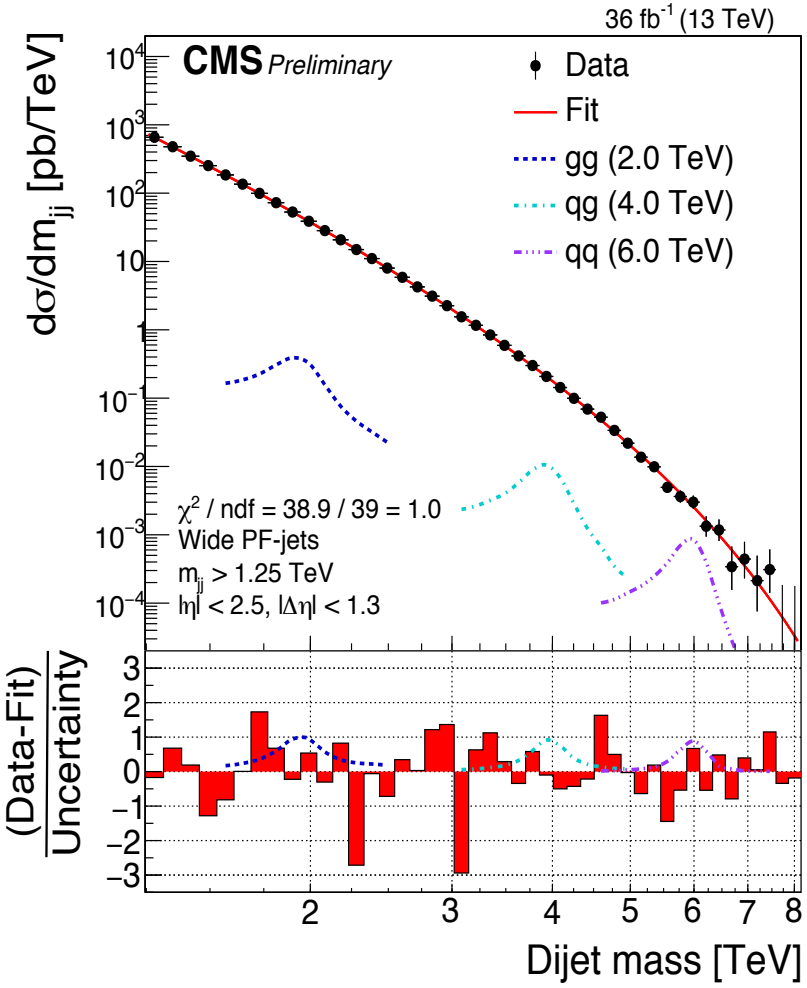
- New results for Dark Matter interpretation

Bump search: Dijet analysis strategy

- Trigger requires HT = $\sum_{jets} p_T^{jet}$ > 900 GeV
  - Trigger fully efficient at m_{jj} > 1.2 TeV
- One fit function for the whole high-mass range:

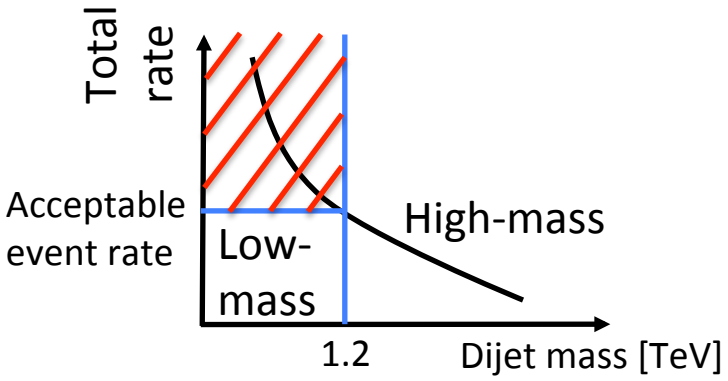
$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3\log(x)}} \qquad x = \frac{m_{jj}}{\sqrt{s}}$$

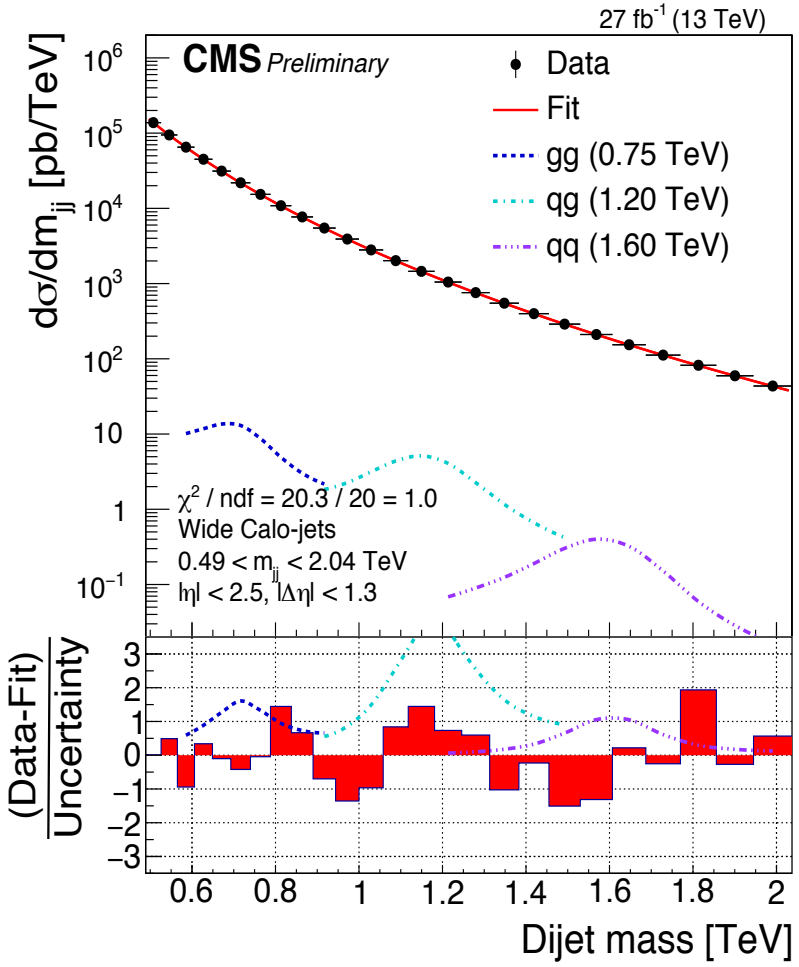
- No excess of events observed



Bump search: Low-mass Dijet analysis strategy

Data transfer rate [kB/sec] = **event rate [evt/sec] X event size [kB/evt]**





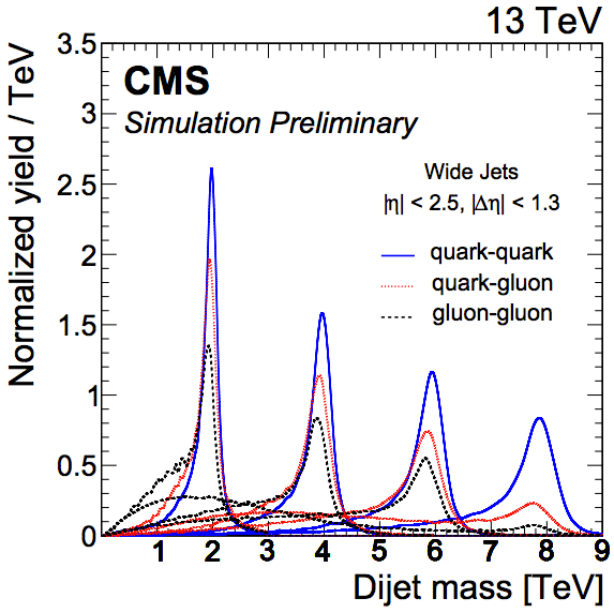
- Trigger HT > 250 GeV
  - Trigger fully efficient at m_{jj} > 500 GeV
- **Data Scouting:** Reduced data format
  - Jets reconstructed at trigger level
  - Specific jet energy correction to take into account the different reconstruction
- One fit function for the whole low-mass range:

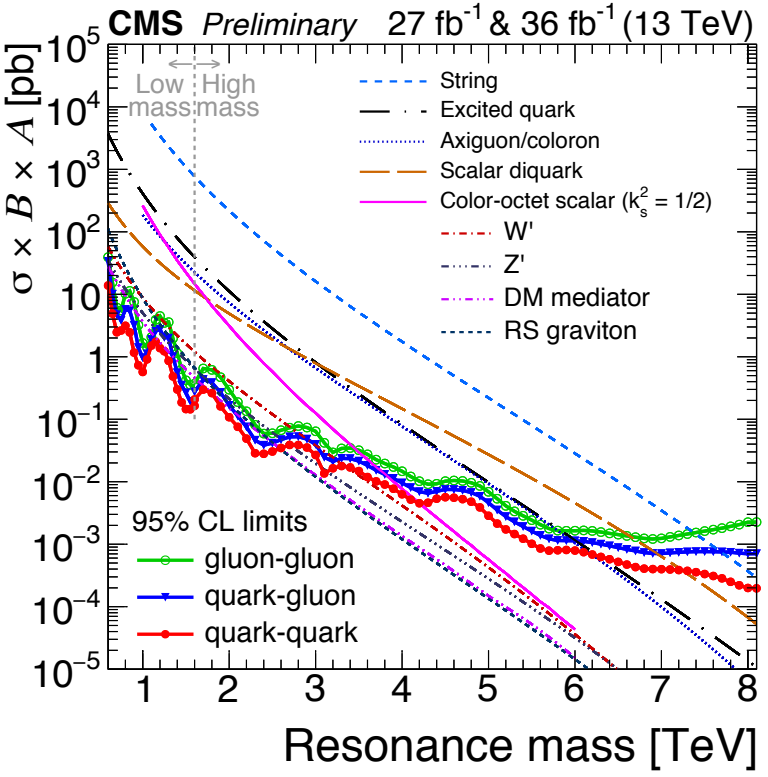
$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3\log(x)+p_4\log(x)^2}}$$

- No excess of events observed

Bump search: Dijet search results

- Different signal shape as a function of the final state: qq, qg, gg



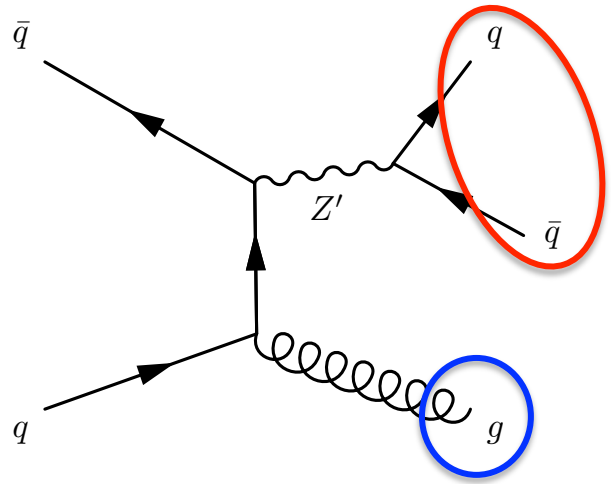


- Upper limits on nine benchmark models slightly improved since ICHEP because of the higher statistics (3 times larger)

- Dijet results to constrain the Dark Matter search (next slides)

Model	Final State	Observed (expected) mass limit [TeV] 36 fb^{-1} 13 TeV	12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.7 (7.7)	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	7.2 (7.4)	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$q\bar{q}$	6.1 (6.0)	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	6.0 (5.8)	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4 (3.6)	3.0 (3.3)	—	—
W′	$q\bar{q}$	3.3 (3.6)	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
Z′	$q\bar{q}$	2.7 (2.9)	2.1 (2.3)	—	1.7 (1.8)
RS Graviton	$q\bar{q}$, gg	1.7 (2.1)	1.9 (1.8)	—	1.6 (1.3)
DM Mediator ($m_{DM} = 1$ GeV)	$q\bar{q}$	2.6 (2.5)	2.0 (2.0)	—	—

Bump search: Dijet Boosted



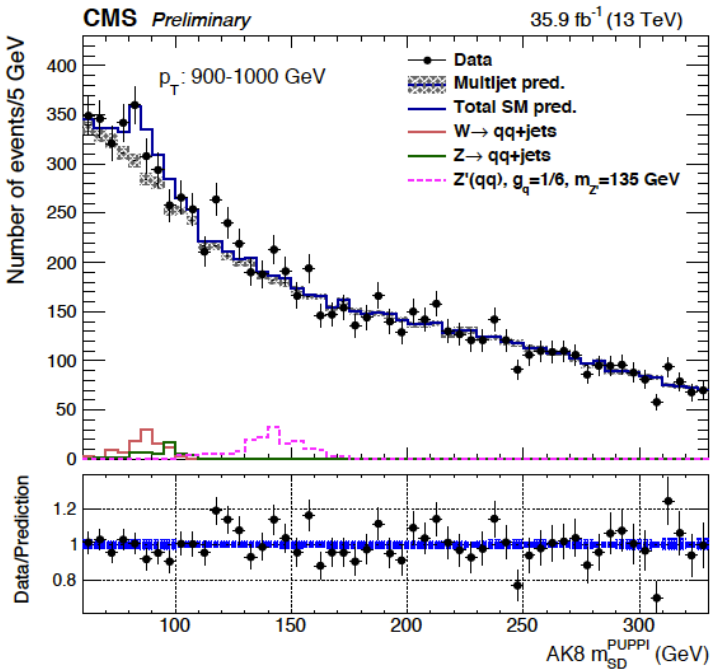
- Search for **light narrow vector resonances** decaying to quarks (Z' production)

- **Boosted** regime: New particles not produced at rest
  - Its product partons will be boosted and fragmentation will be collimated forming one single large jet
  - Compared to regular QCD jets, this jet will contain internal structure
  - Discriminator variable based on jet substructure
- **ISR jet** produced in association with the resonance

- Dijet Topology: 1 jet with a substructure + 1 jet

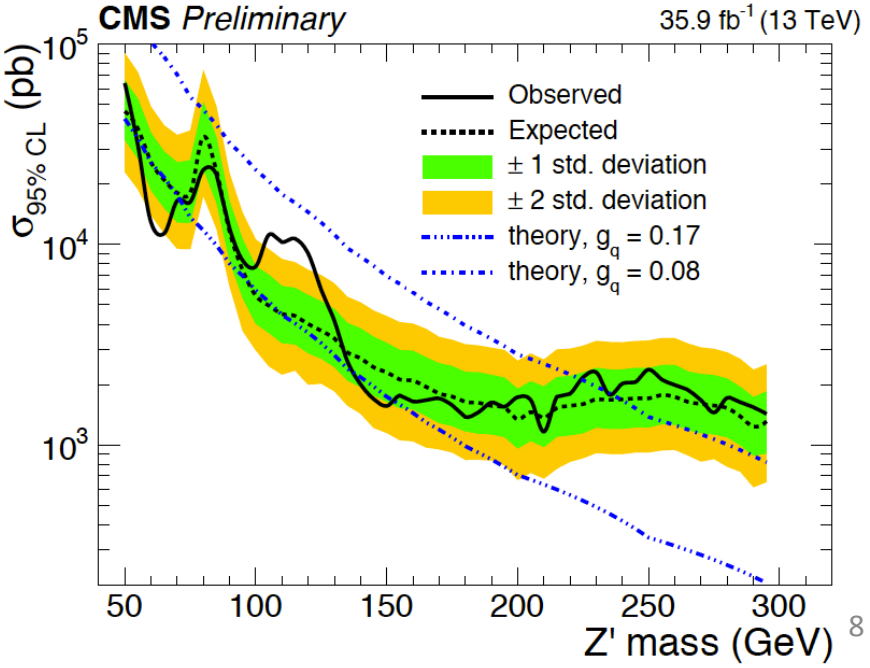
- Complementary approach to the Data Scouting
  - Allows to probe mass region below 300 GeV

Bump search: Dijet Boosted results



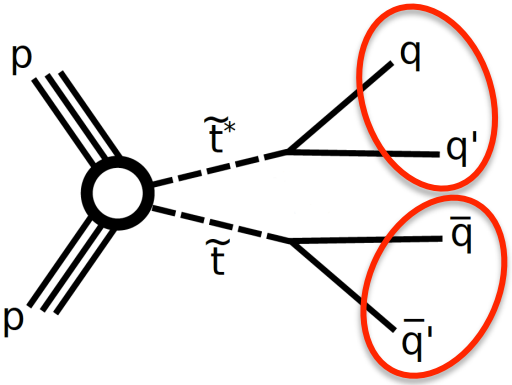
- First search for dijet resonances @ mass < 100 GeV at CMS
- Upper limits on cross section for a Z' production
- Z' model can decay also in Dark Matter particles
  - Dijet Boosted results constrains Dark Matter search (next slides)

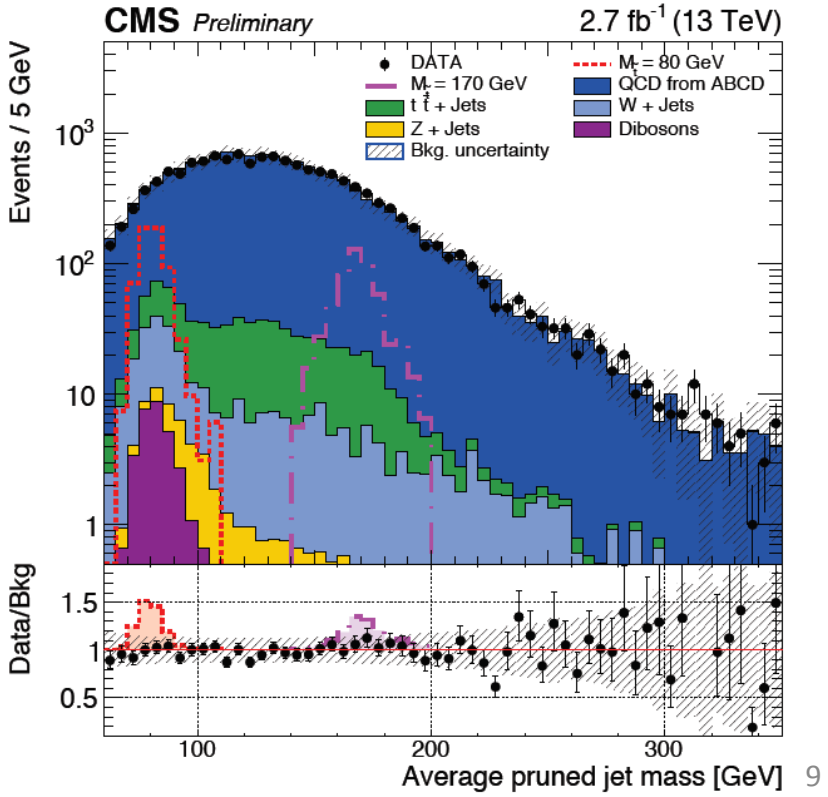
- Search performed in bin of jet p_T
- Highest bin shown: $900 < p_T < 1000$ GeV
- Data-driven background estimation using control regions
- No significant excess observed (@ 115 GeV local significance 2.9σ, global 2.2σ deviation)



Bump search: Pair-produced dijet

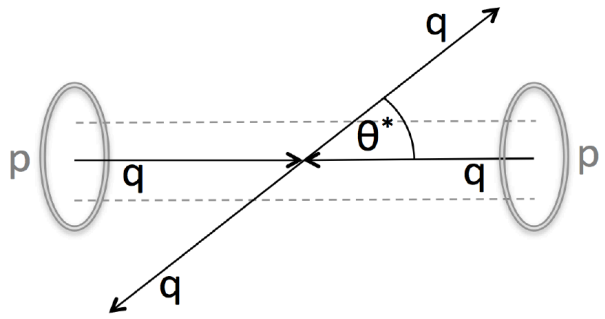
- Stop pair production predicted by SUSY
- **Boosted regime:**
  - Topology: two jets with large cone size and an internal structure
  - Discriminator variable based on jet substructure
- Analysis performed with **~3fb^{-1} of 2015 data**
- No excess of events observed
- Set limits for stop pair production assuming a 100% branching ratio into two light quarks from 80 to 240 GeV





Angular search: χ_{dijet} analysis

- Probe parton-parton scattering angle:

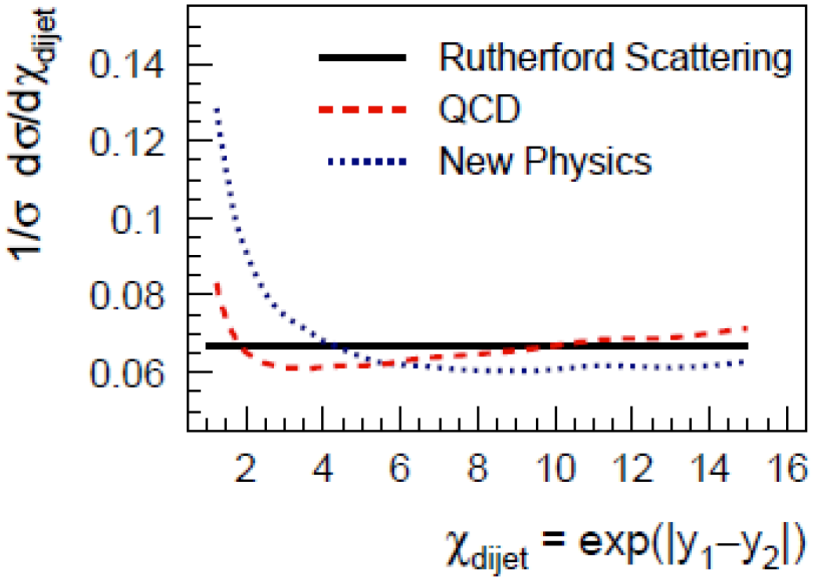


- Angular variable:

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

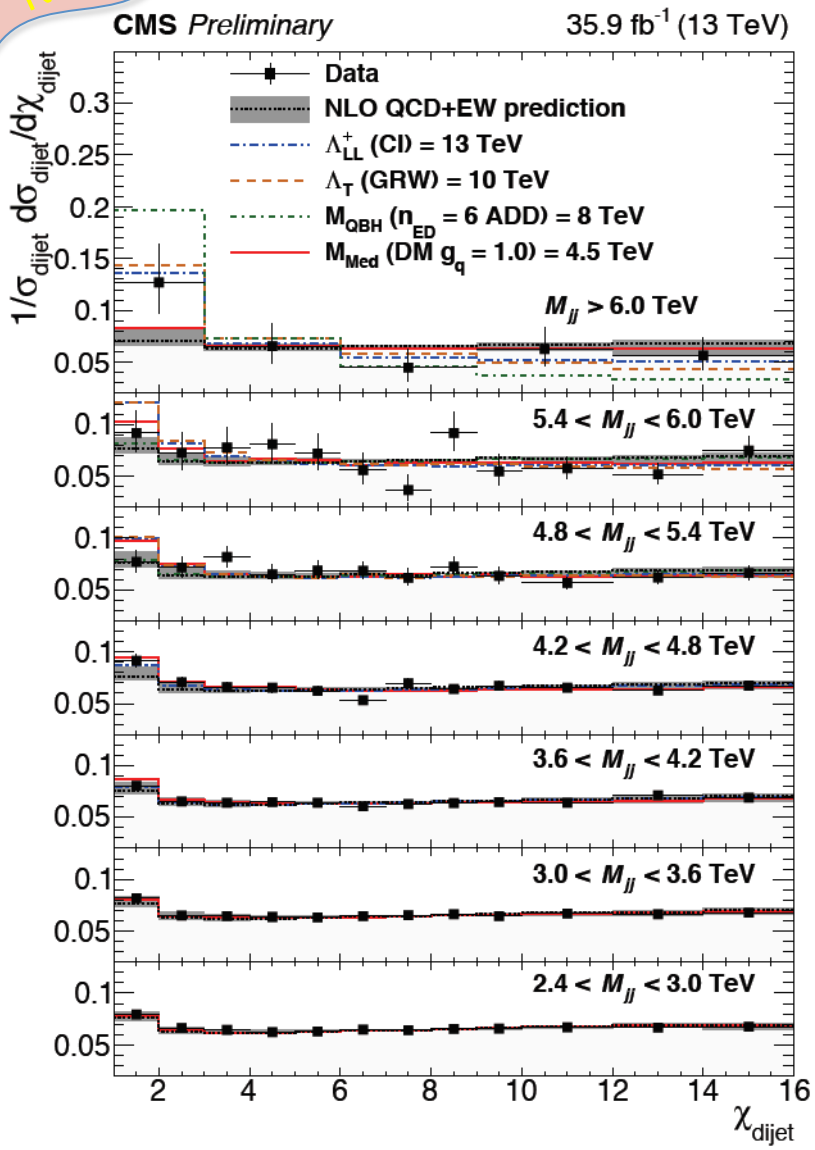
- χ_{dijet} relatively flat for leading QCD process

- New Physics will change the χ_{dijet} distribution at low χ_{dijet}
  - Extra Spatial Dimension
  - Quantum Black Holes production
  - Quark Contact Interaction
  - **Dark Matter Search**



Angular search: χ_{dijet} analysis results

NEW

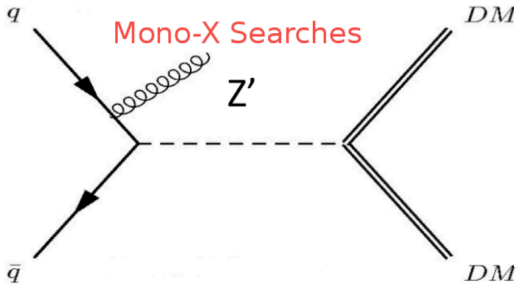


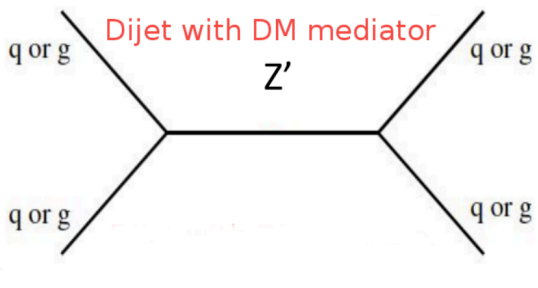
- Analysis performed in dijet mass bins
- Data unfolding
  - Data brought to the particle level
- No excess observed
- Improved lower limits on theoretical models with respect the previous results
- Observed (Expected) limits on Quantum Black Holes:
  - M_{QBH} (ADD) = 8.3 (8.7) TeV
  - M_{QBH} (RS) = 6.0 (6.5) TeV

Dark Matter interpretation

- Results from
  - Dijet bump search
  - Dijet angular search
  - Dijet Boosted search

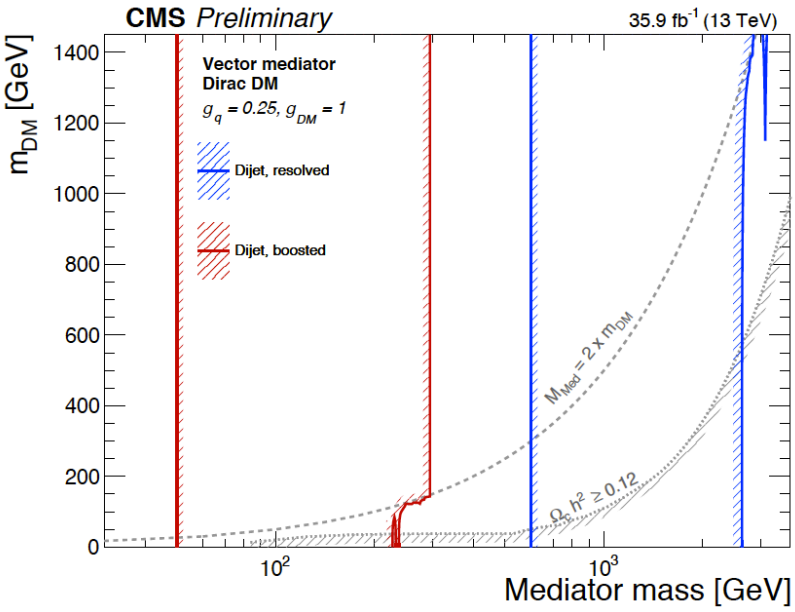
can be interpreted for Dark Matter search

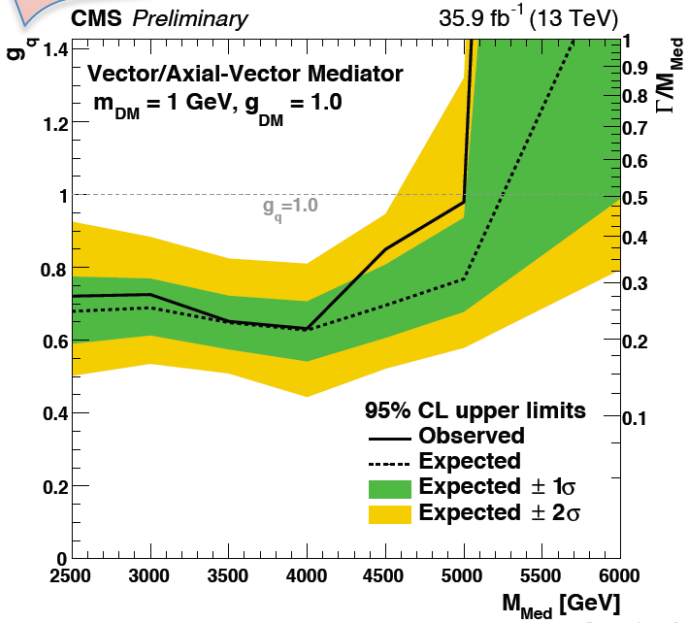




- DM mediator can decay to dijets or dark matter pairs
- Set limits on the DM mediator in the plane (Mediator mass, DM mass or quark coupling)

NEW





Dijet search valid for narrow resonances:

Up to Γ/M_{med}~0.1

→ g_q ~ 0.4

→ No sensitivity to higher g_q

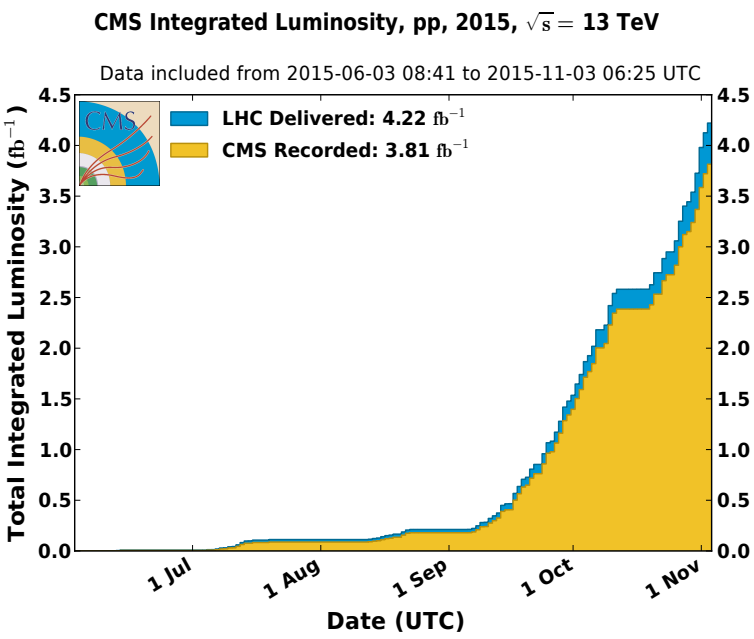
More details in yesterday talks by Shin-Shan Yu and Deborah Pinna

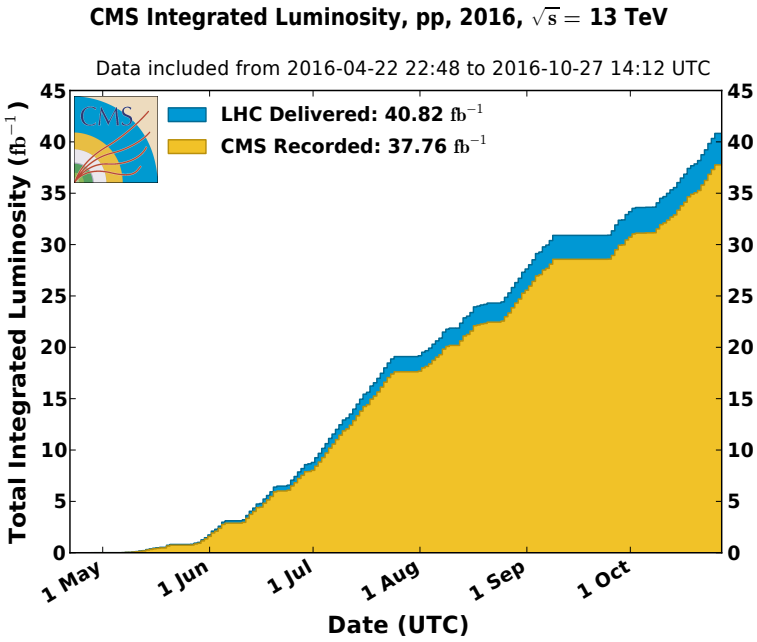
Conclusions

- Searches with jets in the final state with 2015 and 2016 data collected by the CMS experiment were presented
- No evidence for new physics observed so far
- Many analyses have to be performed with the full dataset
- Interpretation for the Dark Matter search
  - Searches with jets in final state complementary
  - Covering as much as possible the phase-space (mass and width)
- Looking forward for the next years of data

BACKUP

CMS Luminosity

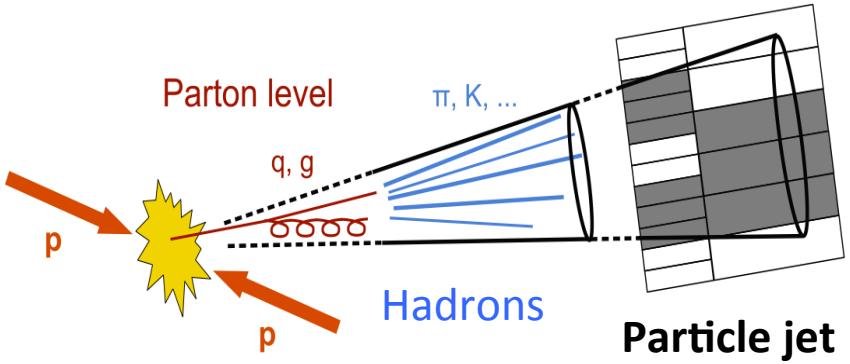




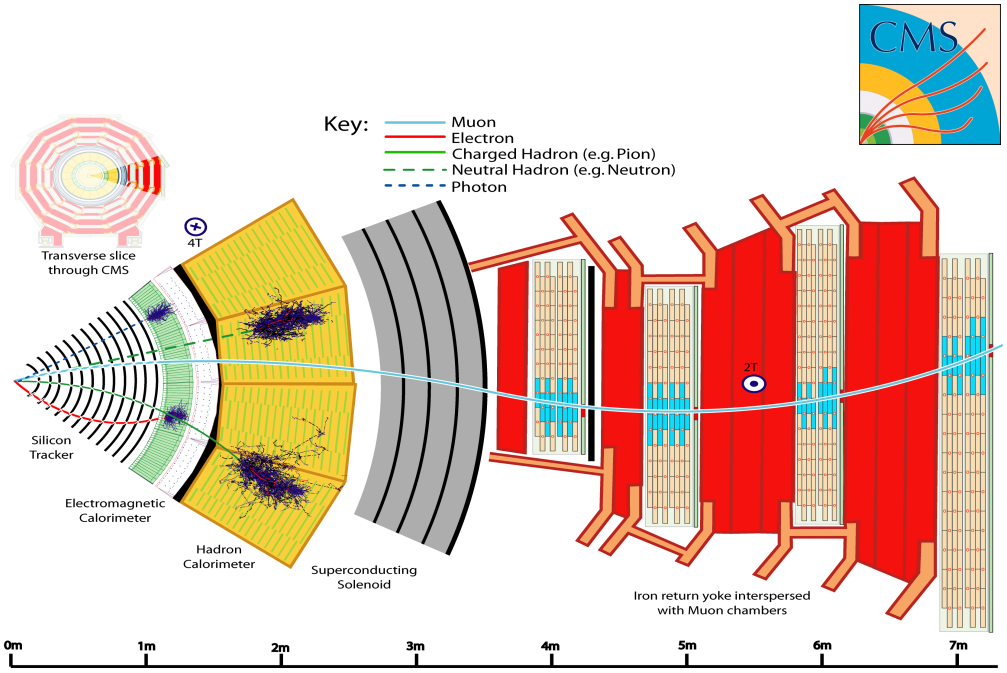
Final **2015** luminosity = 2.7 fb^{-1}
Final **2016** luminosity = 35.9 fb^{-1}

Experimental point-of-view

- **Quarks/Gluons hadronization**
  - Collimated bunches of high-energy hadrons
  - Partons into jets by clustering algorithm

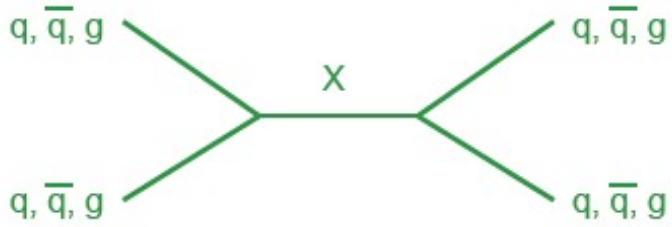


- Sub-detectors mainly involved in jet reconstruction:
  - **Tracker**
  - **Electromagnetic calorimeter**
  - **Hadronic calorimeter**

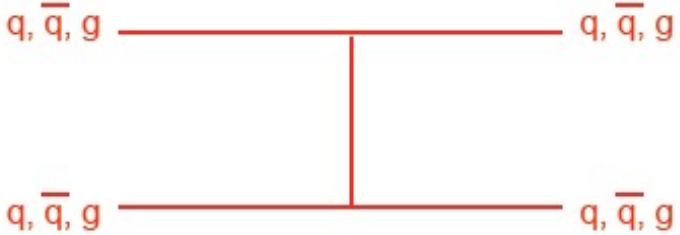


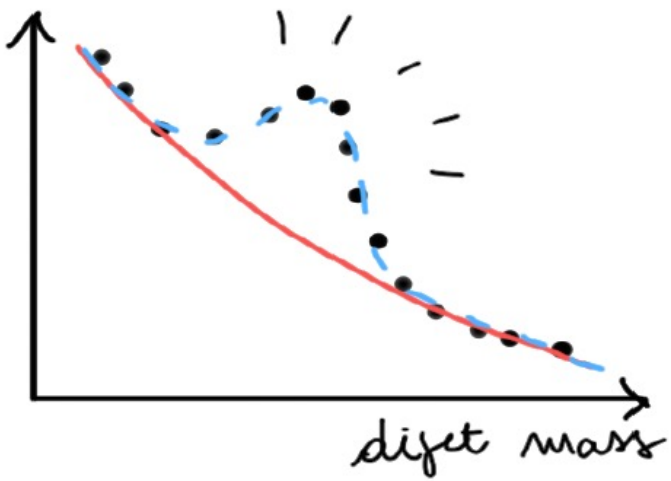
Dijets final state

Resonant Signal



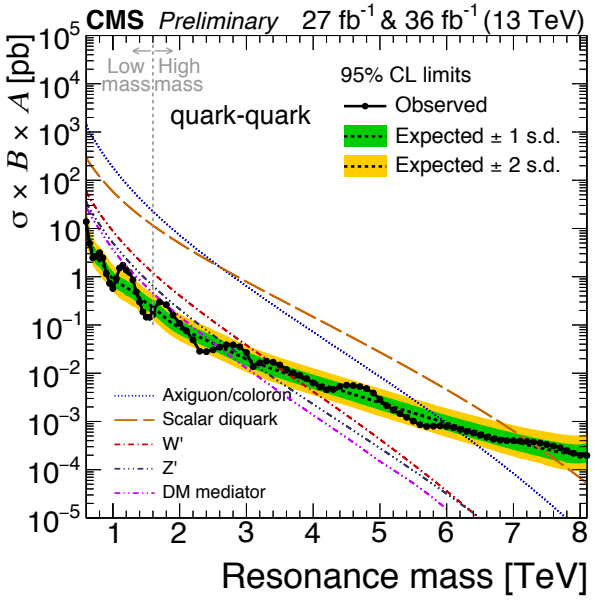
QCD Background

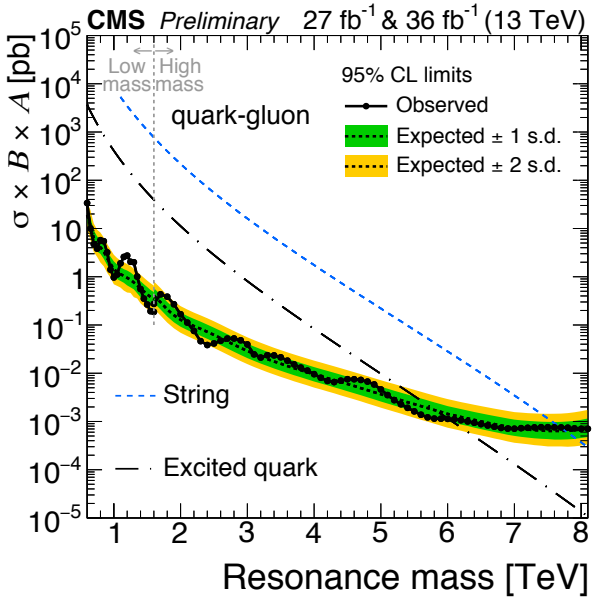


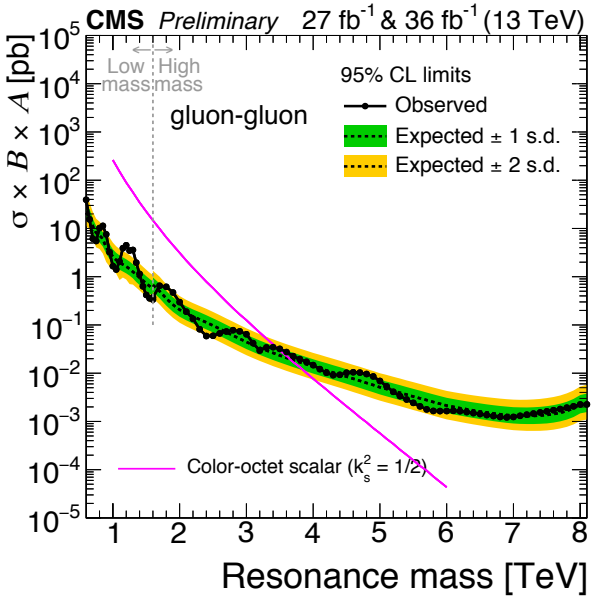


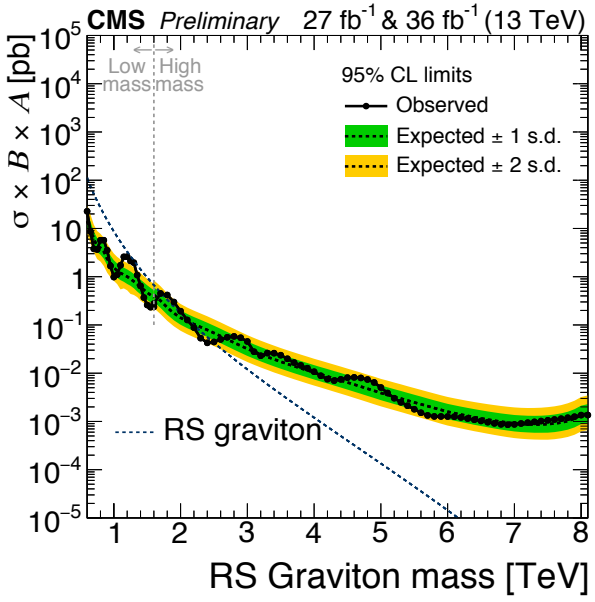
- Search for a bump over a falling spectrum
- Background t-channel, signal s-channel
  - Different angular distribution that can be exploited to search new particles

Dijet bump search: Cross section limits









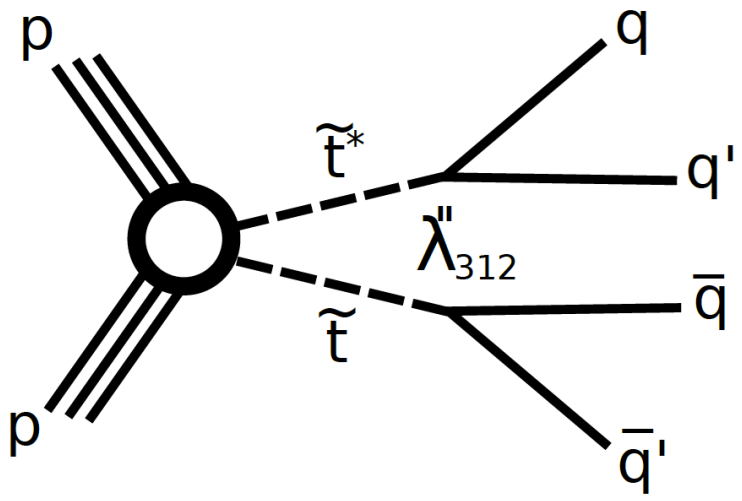
- Cross section upper limits on qq, qg, gg resonances
- Cross section upper limits on RS Gravitons (σ limit is sum of qq and gg limits weighted by the RSG branching fractions)

Multijets: Pair-produced dijet

- One of the possible models BSM that predicts dijet resonances pairs in the final state is **R**-**P**arity **V**iolation-**SU**per**SY**mmetry (RPV-SUSY), described by the superpotential:

$$W = \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{\mathbf{ijk}} \mathbf{U_i^c D_j^c D_k^c} + \mu'_i L_i H_u$$

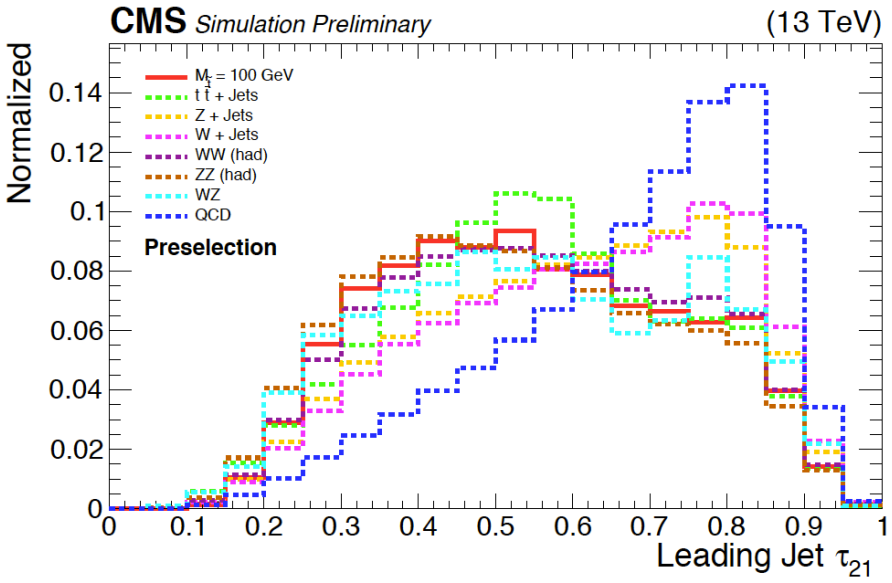
- Under RPV, it is possible that one of the couplings (λ) have a non-zero value.
- For hadronic RPV, each RPV stop decays into a pair of quarks via the UDD coupling.
- **Benchmark model:**
  Pair production of hadronic RPV stops decaying into two light-quarks via the coupling λ''_{312}



Jet substructure

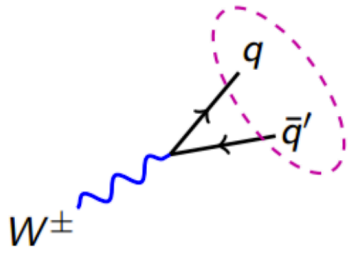
Variable used for Pair-produced dijet search

$$\tau_{21} = \frac{\sum_k p_{T,k} \cdot min(\Delta R_{1,k}, \Delta R_{2,k})}{\sum_k p_{T,k} \cdot \Delta R_{1,k}}$$



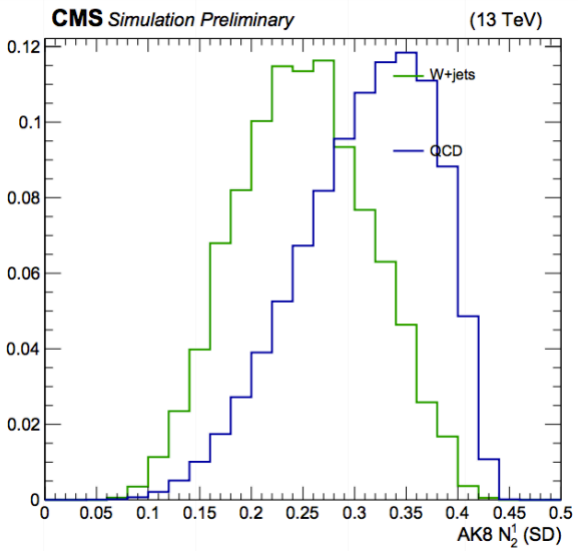
Variable used for Z'+jet search

$$N_2^1 = \frac{{}_2e_3^1}{\left({}_1e_2^1\right)^2}$$



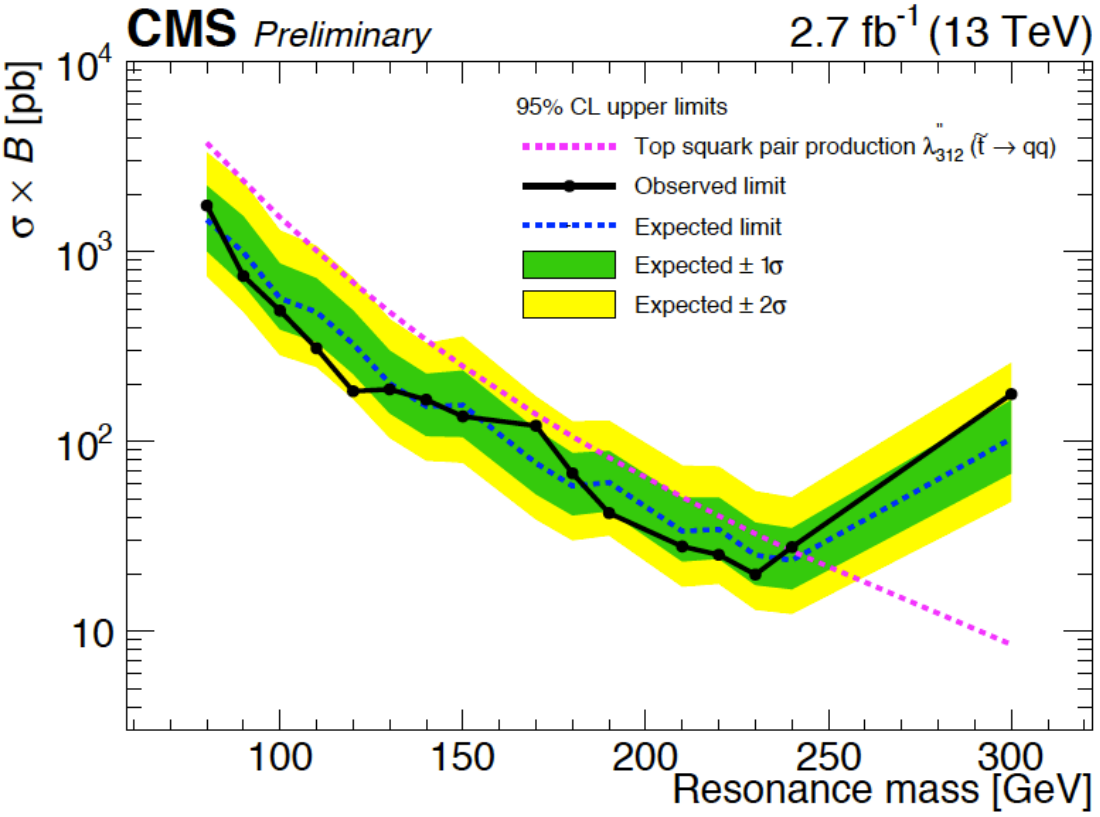
$${}_1e_2^1 = \sum_{1 \le i < j \le n_J} z_i z_j \Delta R_{ij} \qquad \text{with} \quad z_i \equiv \frac{p_{Ti}}{\sum_{j \in \text{jet}} p_{Tj}}$$

$${}_2e_3^1 = \sum_{1 \le i < j < k \le n_J} z_i z_j z_k \min\{\Delta R_{ij}\Delta R_{ik}, \Delta R_{ij}\Delta R_{jk}, \Delta R_{ik}\Delta R_{jk}\}$$



Bump search: Pair-produced dijet results

- Set upper limits on the pair production cross section of stops assuming a 100% branching ratio into two light quarks
- Set limits for stop pair production from 80 to 240 GeV



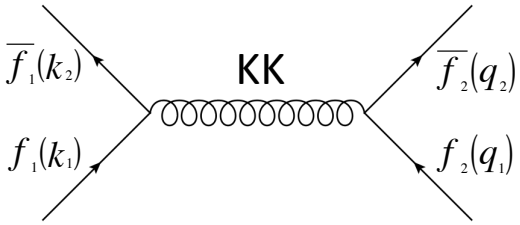
Dijet angular search theory

- **Quark Contact Interaction:**
  - Quark compositeness interaction represented as CI terms:

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

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

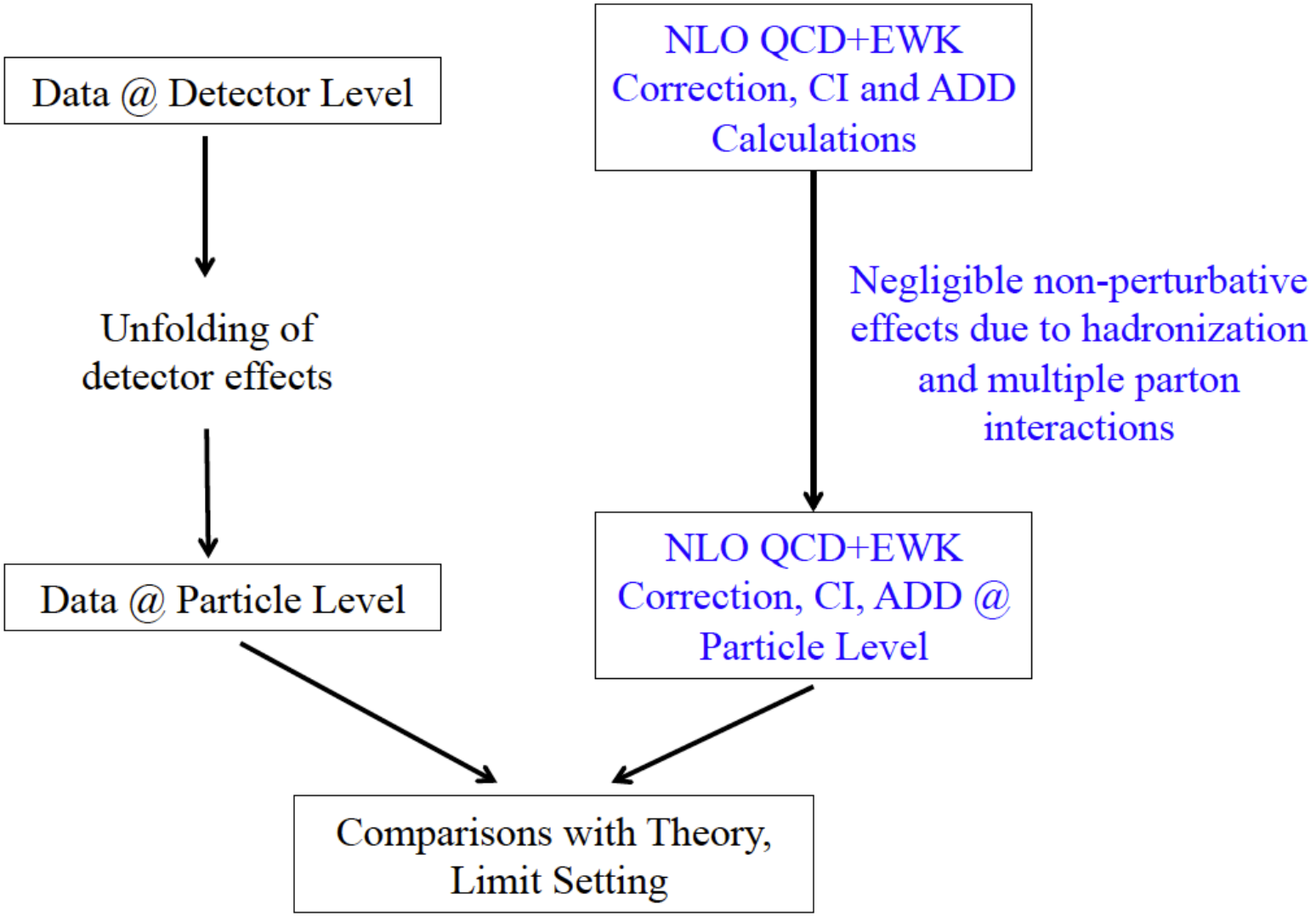
- **Large Extra Spatial Dimensions (ADD model):**
  - Virtual Kaluza-Klein graviton exchange processes modify χ_{dijet} distribution
  - Two parameterizations: GRW (Giudice, Rattazzi, Wells) and HLZ (Han, Lykken, Zhang)



- **Quantum Black Holes:**
  - Two benchmark scenarios: ADD with 6 extra dimensions (ADD6), RS with 1 extra dimension (RS1)
  - Parameters: black hole mass, number of extra dimensions

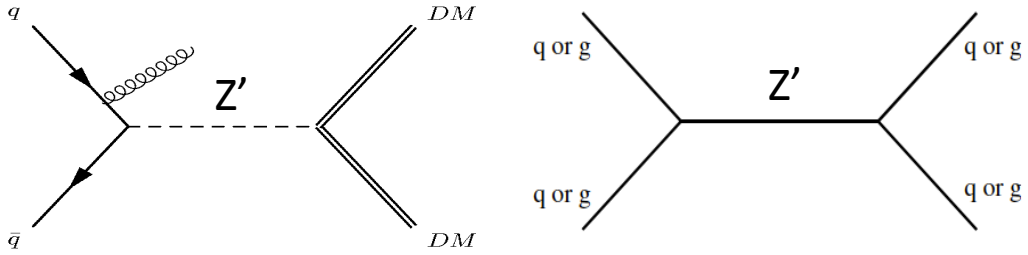
- **Dark Matter Intepretation:**
  - Z' mediator with $g_{DM} = 1$ and $m_{DM} = 1\text{GeV}$

Angular dijet search: Analysis strategy



Dark Matter Theory

Assumed a particular theoretical model:
Dark matter mediator (Z') can decay into DM particles or into dijet final state



Total width:

$$\Gamma^{\text{tot}}_{\text{AV}} = \Gamma^{\chi\bar{\chi}}_{\text{AV}} + 3 \times \sum_{q=u,d,s,c,b,t} \Gamma^{q\bar{q}}_{\text{AV}}$$

Partial widths:

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

$$\Gamma^{q\bar{q}}_{\text{AV}} = \frac{g^2_q M_{\text{med}}}{4\pi}\left(1 - 4\frac{m^2_q}{M^2_{\text{med}}}\right)^{3/2}$$

- Sensitivity at m_{DM} and m_{med} with dijet final state
- The exclusions computed for an universal coupling $g_q = 0.25$ and $g_{DM} = 1.0$
- DM-nucleon scattering cross section:

vector:

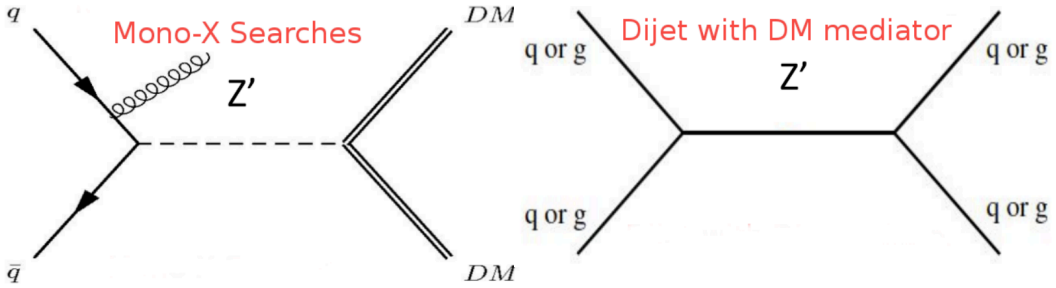
$$\sigma_{\text{SI}} \simeq 6.9 \times 10^{-41}\ \text{cm}^2 \cdot \left(\frac{g_q g_{\text{DM}}}{0.25}\right)^2 \left(\frac{1\,\text{TeV}}{M_{\text{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\text{GeV}}\right)^2$$

axial-vector:

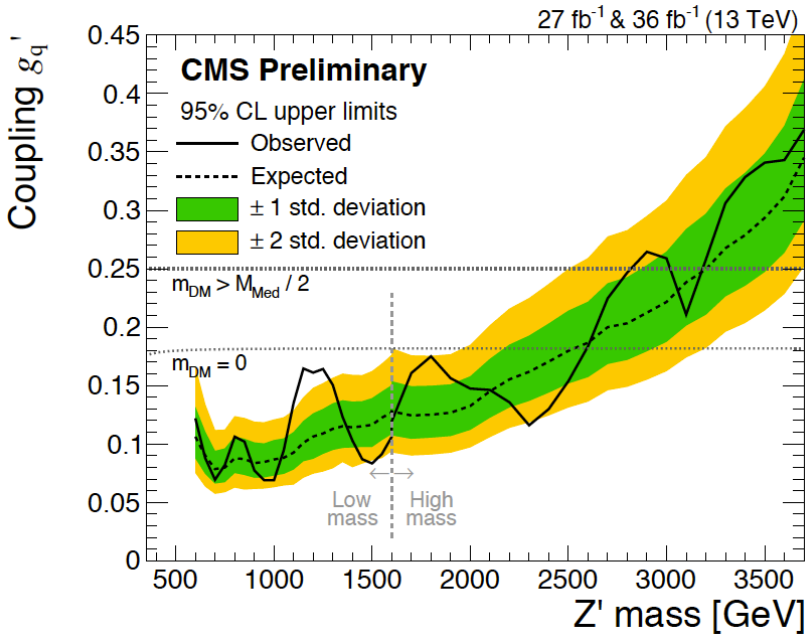
$$\sigma^{\text{SD}} \simeq 2.4 \times 10^{-42}\ \text{cm}^2 \cdot \left(\frac{g_q g_{\text{DM}}}{0.25}\right)^2 \left(\frac{1\,\text{TeV}}{M_{\text{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\text{GeV}}\right)^2$$

Dark Matter interpretation

- DM mediator can decay to dijets or dark matter pairs
- Set limits on the DM mediator in the plane (Mediator mass, DM mass or quark coupling)

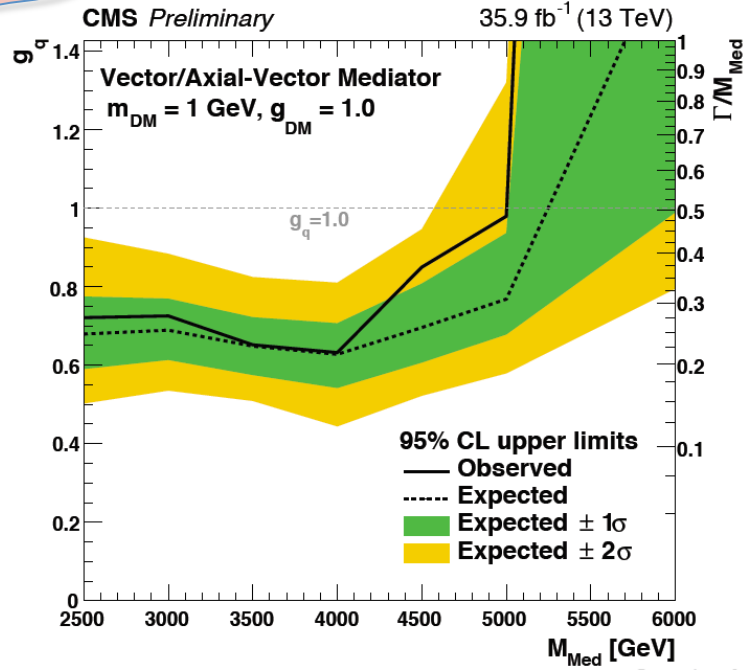


Dijet search



NEW

Angular analysis

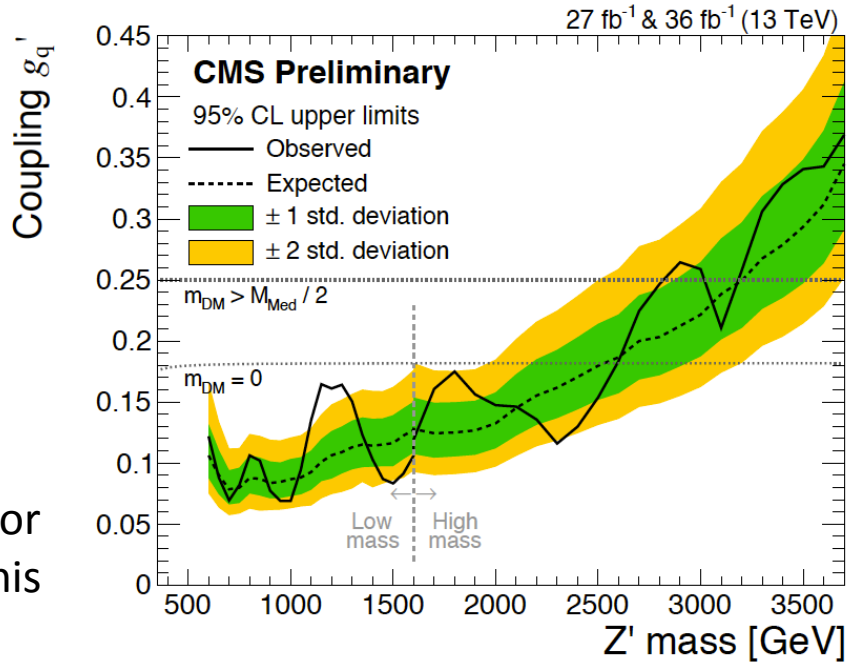


Quark coupling

g_q' quark coupling without DM
g_q quark coupling with DM decay

Z' only couples to quarks

Dotted horizontal lines = the coupling strength for which the cross section for dijet production in this model is the same as for a DM mediator



If $m_{DM} > M_{med}/2 \rightarrow g_q' = g_q = 0.25$

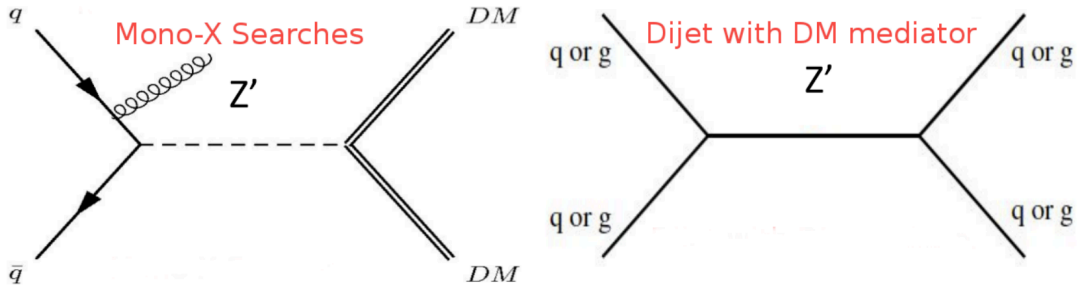
If m_{DM} = 1 GeV (indistinguishable from 0) $\quad g'_q = \dfrac{g_q}{\sqrt{1+16/(3N_f)}}$

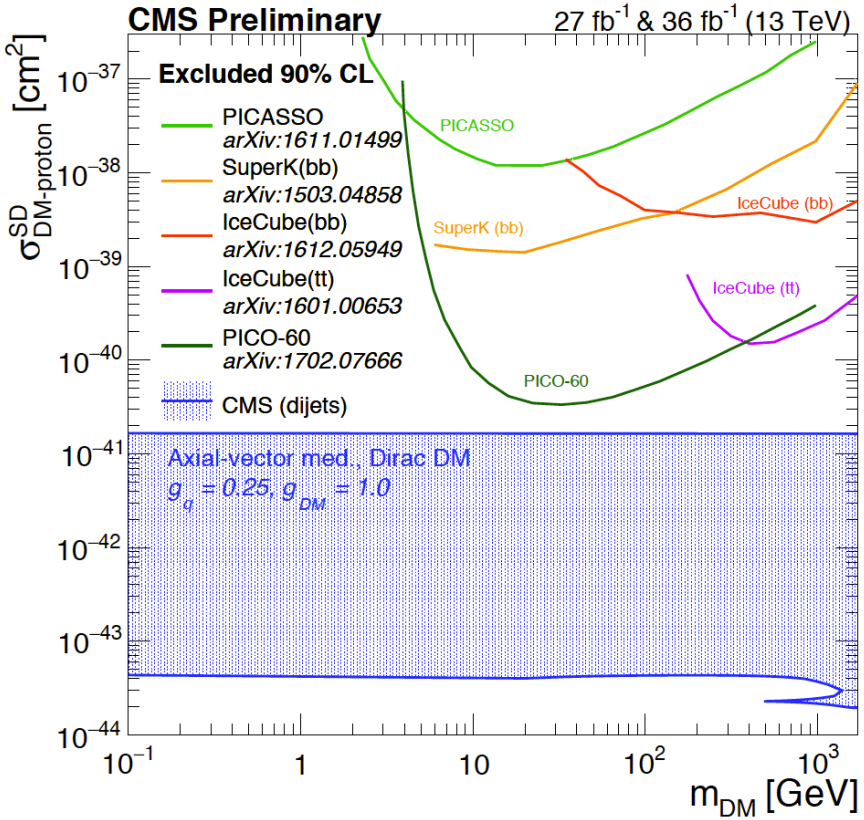
Where N_f is the number of flavour contributing to the width of the resonance $\quad N_f = 5 + \sqrt{1-4m_t^2/M_{Med}^2}$

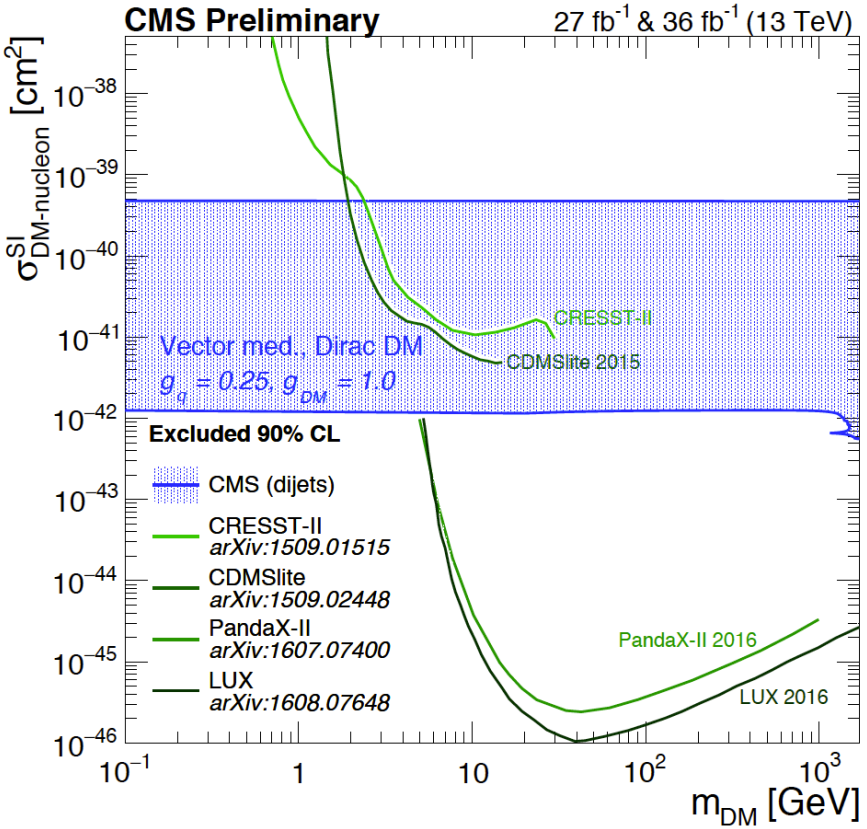
$g_q = 0.25 \rightarrow g_q' \sim 0.182$

Dark Matter interpretation and Direct Search

- DM mediator can decay to dijets or dark matter pairs (leptophobic)
- Set limits on the DM mediator in the plane (DM mass, DM-Nucleon cross section)





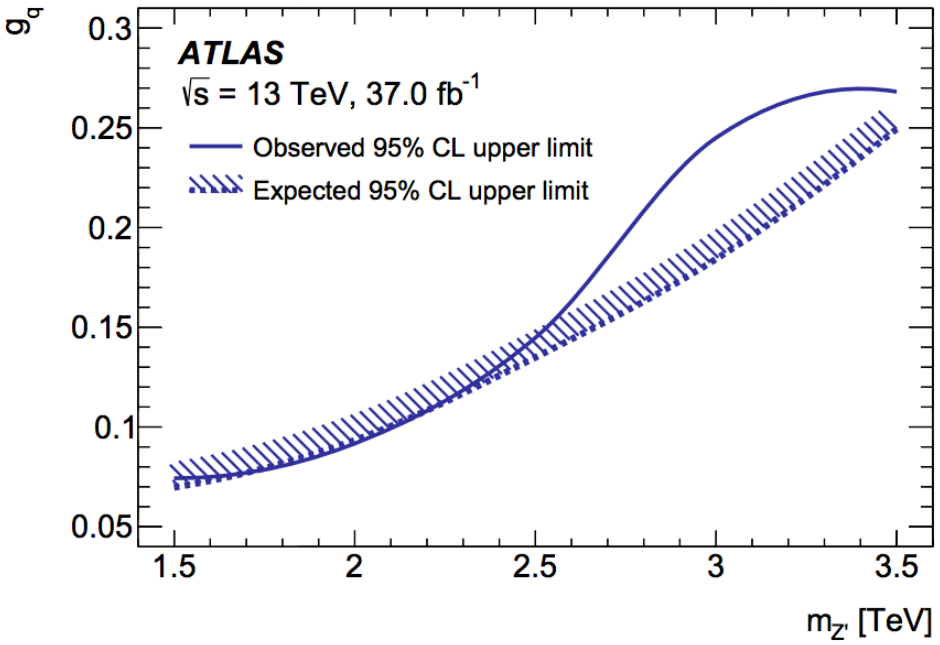


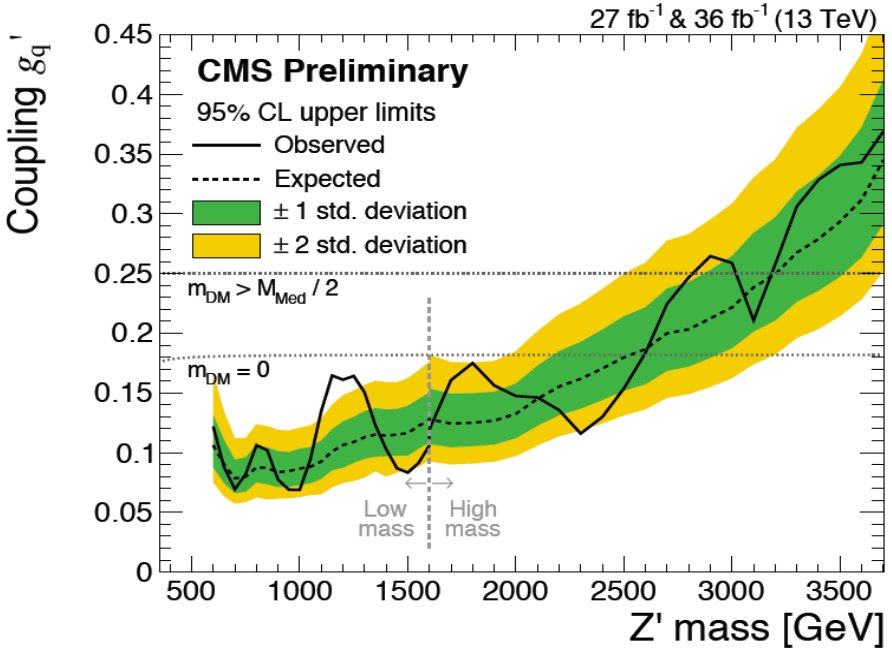
ATLAS Dijet results

Dijet bump search and Dijet angular analysis

	Model	95% CL exclusion limit	
		Observed	Expected
(ADD)	Quantum black hole	8.9 TeV	8.9 TeV
	W'	3.6 TeV	3.7 TeV
	W^*	3.4 TeV 3.77 TeV – 3.85 TeV	3.6 TeV
	Excited quark	6.0 TeV	5.8 TeV
	$Z'(g_q = 0.1)$	2.1 TeV	2.1 TeV
	$Z'(g_q = 0.2)$	2.9 TeV	3.3 TeV
	Contact interaction ($\eta_{LL} = -1$)	21.8 TeV	28.3 TeV
	Contact interaction ($\eta_{LL} = +1$)	13.1 TeV 17.4 TeV – 29.5 TeV	15.0 TeV

ATLAS/CMS Dark Matter interpretation





- Upper part excluded
  - Up to g_q = 0.5 (searches valid for narrow resonance)