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CMS Searches for Dark Matter with Heavy Quarks or Jets

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CMS Compact Muon Solenoid

Contents

- The CMS experiment

- A digression: how we exclude your pet theory

- Searches of DM in association with top quark pairs

- DM searches in jet final states
  - Narrow dijet resonances
  - Wide dijet resonances
  - Angular distributions
  - Boosted dijets

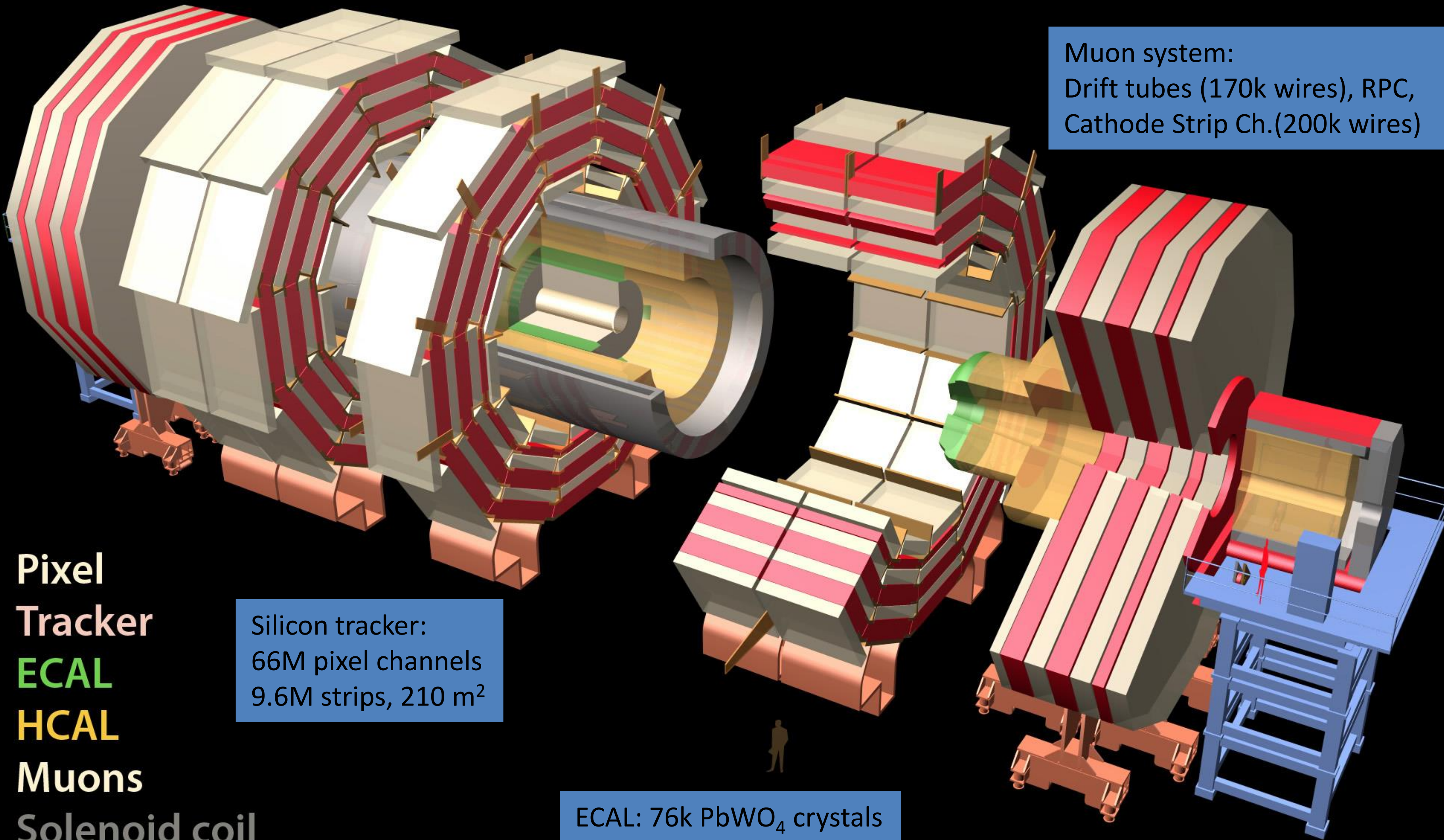
- Concluding remarks

The CMS Collaboration

1700 physicists, 700 students, 950 engineers/technicians, 180 institutions from 43 countries

The CMS Detector

10k CPU cores,
2M lines of code



Muon system:
Drift tubes (170k wires), RPC,
Cathode Strip Ch.(200k wires)

Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

Silicon tracker:
66M pixel channels
9.6M strips, 210 m^2

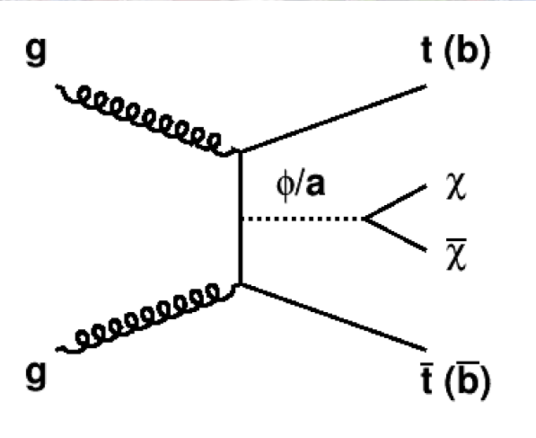
ECAL: 76k $PbWO_4$ crystals
HCAL: 15k scint/brass ch.

Total weight 12500 t, Overall diameter 15 m, Overall length 21.6 m, Magnetic field 4 Tesla

1 - Search for Dark Matter with Top Quark Pairs

In MFV scenarios, favoured by observed lack of NP in EW scale flavour physics, the NP associated with DM inherits Yukawa structure of SM → DM mediator interaction with top quarks is preferred

A new search[1] considers dilepton decays of top quarks associated with large extra missing energy in 36/fb of 13 TeV 2016 data
A simplified scenario is used to benchmark the search



Signal is generated with MadGraph5[2] + MadSpin[3] with up to one additional parton & MLM recombination scheme[4]

Assumed Yukawa couplings between mediator and quarks, and flavour-universal g_q=1; DM mediator-fermion interaction also set to g_χ=1; M_{DM}=1 GeV considered

Preliminary selection:
missing p_T>50 GeV, >=2 jets, >=1 b-tag
2 OS leptons >25,15 GeV
Z-veto and low-mass veto for SF categories

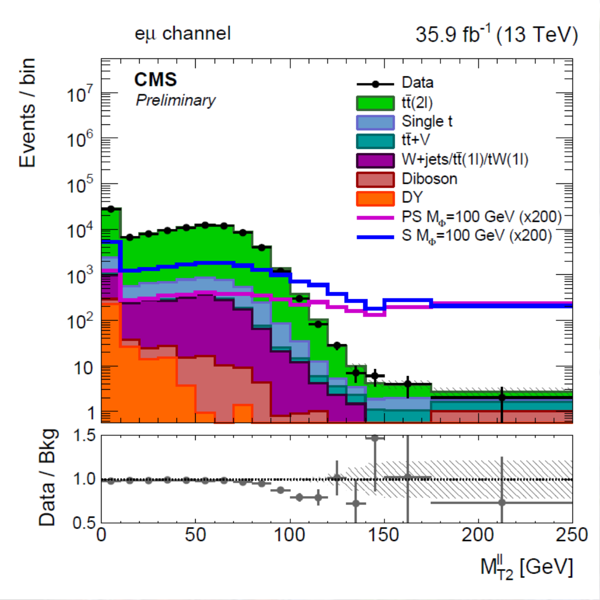
[1] CMS Collaboration, CMS PAS-EXO-17-014 (2018).
[2] J. Alwall et al., JHEP **07** (2014) 079
[3] P. Artoisenet et al., JHEP **03** (2013) 015
[4] J. Alwall et al., Eur. Phys. J. **C53** (2008) 473–500

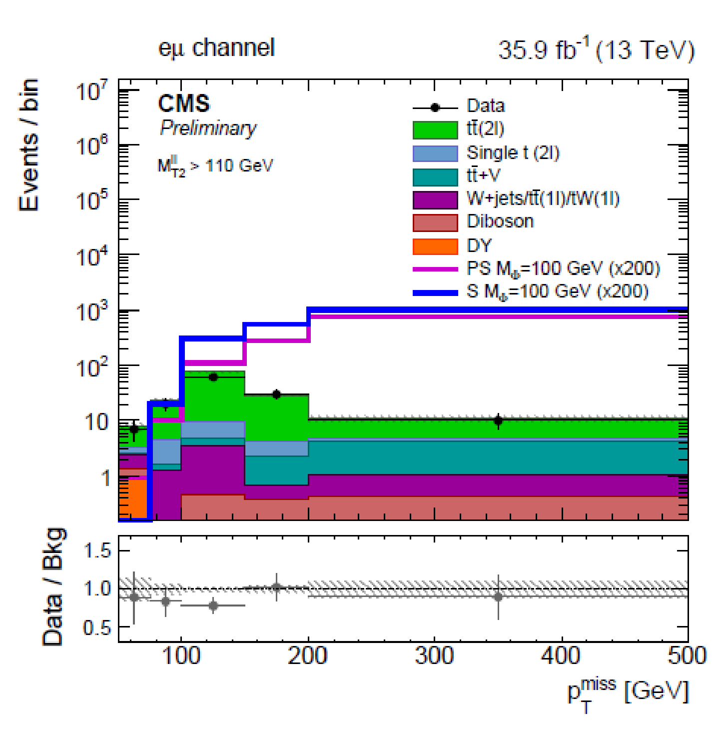
P_T^{miss} Analysis Detail

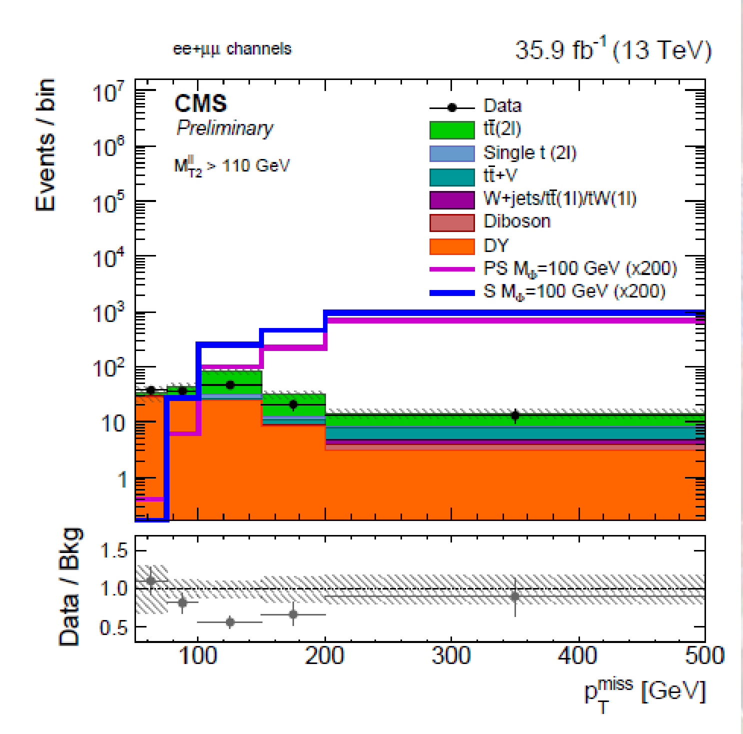
The Stransverse mass distribution

$$M_{T2}^{\ell\ell} = \min_{\vec{p}_{T1}^{miss}+\vec{p}_{T2}^{miss}=\vec{p}_T^{miss}} \left(\max\left[M_T\left(\vec{p}_T^{\ell_1}, \vec{p}_{T1}^{miss}\right), M_T\left(\vec{p}_T^{\ell_2}, \vec{p}_{T2}^{miss}\right) \right] \right)$$

is used to define low- and high-purity regions M_{T2}<>110 GeV







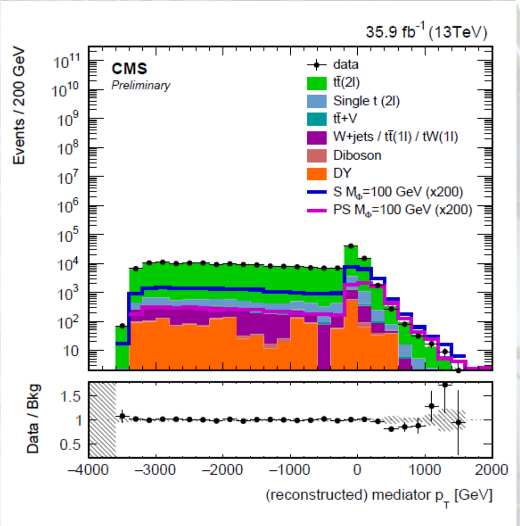
Four regions are selected: eμ or ll events with M_{T2}<>110 GeV. Missing p_T shapes are fit simultaneously (Left: the two high-purity categories)

MVA-Based Analyses

Two MVA-based analyses determine kinematics of tt decay and distinguish signal

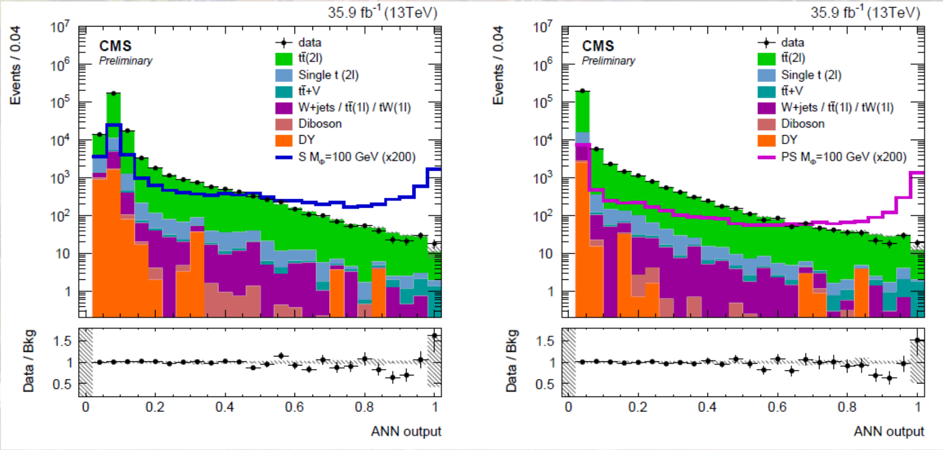
- **NN-based** kinematical discrimination based on reconstruction of mediator p_T after kinematic fit
- **BDT based** studies top spin correlations due to DM mediator radiation (PS case produces different pattern in several variables)

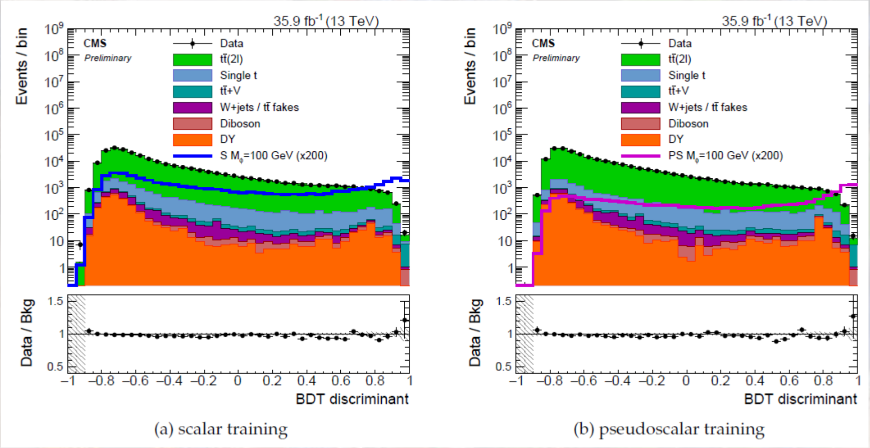
A scalar or pseudoscalar mediator is assumed in the simplified model scenarios considered in the analysis



Top: P_T^{dark} distribution (M_{med}=100 GeV assumed)

Signal distributions are scaled by x200 in all graphs



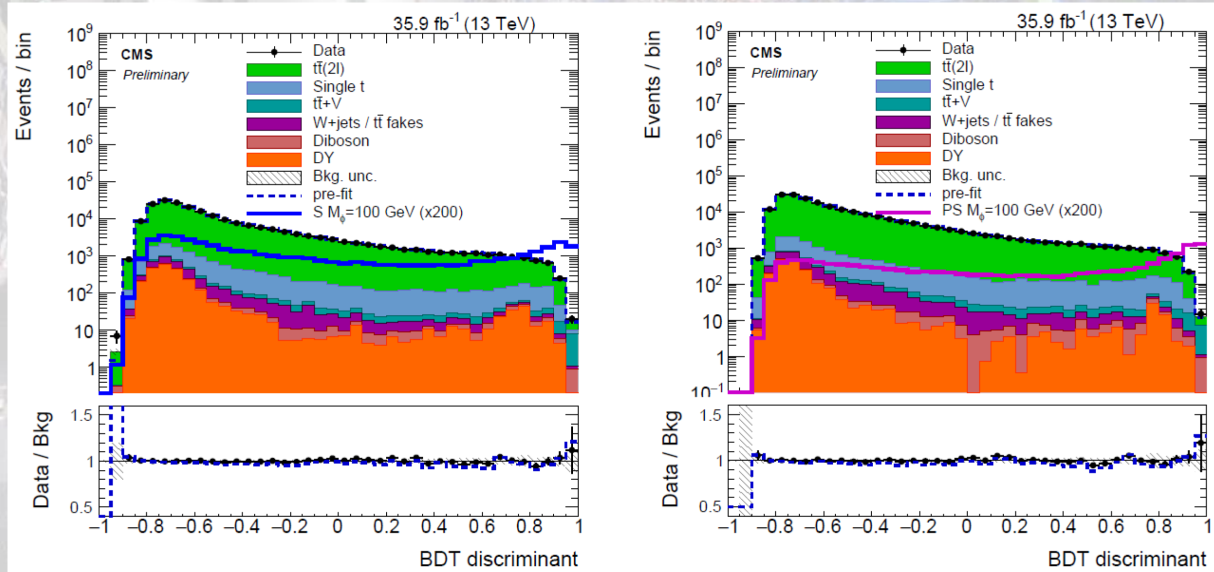


Left: ANN output distribution for scalar and pseudoscalar mediator with M_{med}=100 GeV

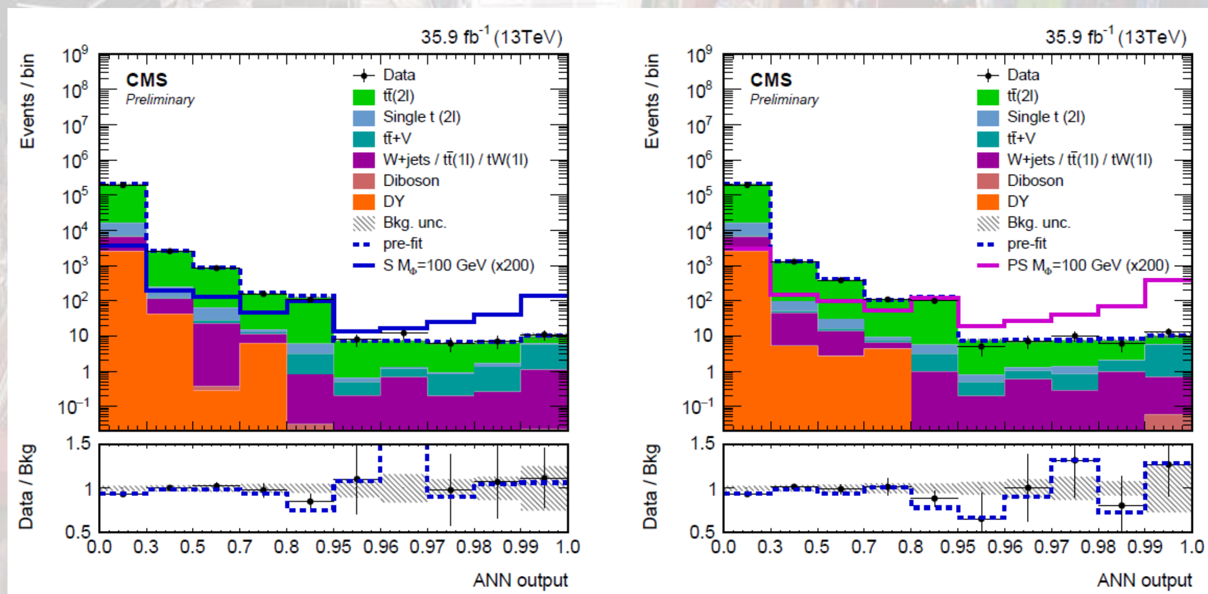
Right: pre-fit BDT distributions for scalar and pseudoscalar mediators, with M_{med}=500 GeV

Post-Fit Distributions in tt+DM Search

Top: BDT distributions for scalar (left) and pseudoscalar mediator (right)



Bottom: ANN distributions for scalar (left) and pseudoscalar mediator (right)

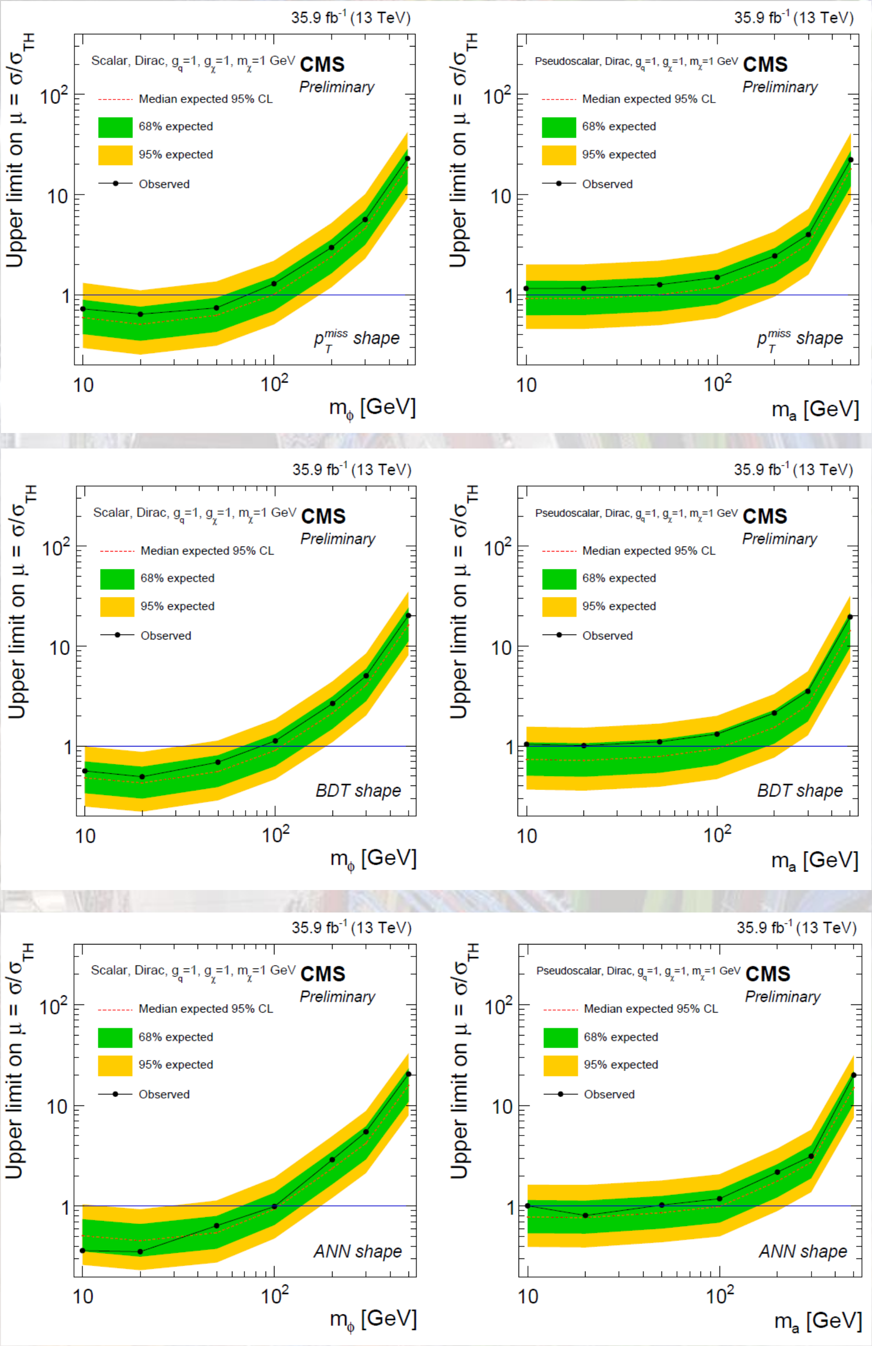


Results

The discriminant shapes are fit using the Combine tool[1] in ROOSTATS, and upper limits are extracted using the CLs criterion and the techniques of the Higgs combination[2]

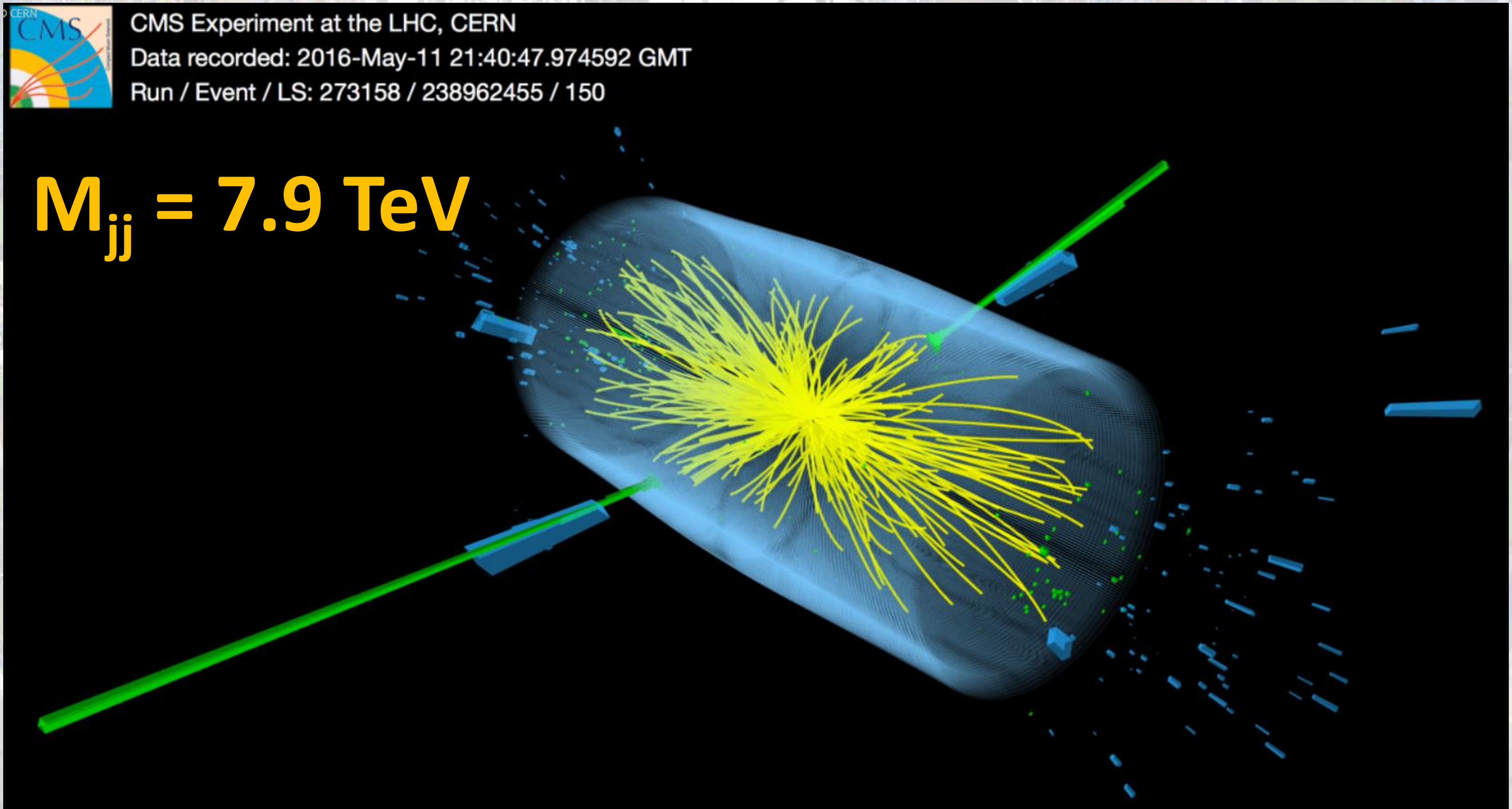
Physics backgrounds are estimated with MC simulation, lepton fakes with jet samples; most normalizations are extracted from data.

Assuming coupling values of $g_q = g_\chi = 1$ and DM mass of 1 GeV, the observed (expected) 95% CL exclusions for a scalar mediator are $m_\varphi < 74$ (99) GeV, and the expected exclusion for a pseudoscalar mediator is $m_a < 50$ GeV; no observed exclusion is set on PS mediator mass



[1] L. Moneta et al., arXiv:1009.1003 (2010); [2] ATL-PHYS-PUB-2011-011, CMS-NOTE-2011-005, CERN, 2011.

SEARCHES IN DIJET EVENTS



2 - Search for DM Resonances in Dijets

High-mass objects that couple to partons can be sought as resonances in the dijet mass spectrum; but jet pairs are the most common result of pp collisions → large QCD background, modeled with parametric functions

In a simplified model of DM[1,2], quarks and DM interact via massive s=1 mediators decaying only to qq and DM particle pairs

- Analysis targets g_q=0.25, g_{DM}=1 as benchmark
- For g_q>0.4 width becomes larger than 10% → dedicated search for non-narrow resonances (see below)

The latest CMS search from data in the 2016 run is performed in 27/fb of luminosity at low-mass collected by **scouting techniques**, and 36/fb at high-mass: arXiv:1806.00843 (CMS PAS-EXO-16-056)

- Low mass: H_T>250 GeV (search fully efficient for M_{jj}>0.49 TeV)
- High mass: H_T>800/900 GeV (search fully efficient for M_{jj}>1.25 TeV)

Wide jets (ΔR<1.1) are constructed from ΔR=0.4 anti-kT jets to include FSR effects and improve the reconstruction of event kinematics

[1] A.Boveia et al., arxiv:1603.04156
[2] J.Abdallah et al., Phys. Dark Univ. **9-10** (2015) 8

Dijet Mass Spectra

Background-only fits are shown below for low-mass scouted data (left) and high-mass data (right)

High-mass data are fit with the parametrization

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

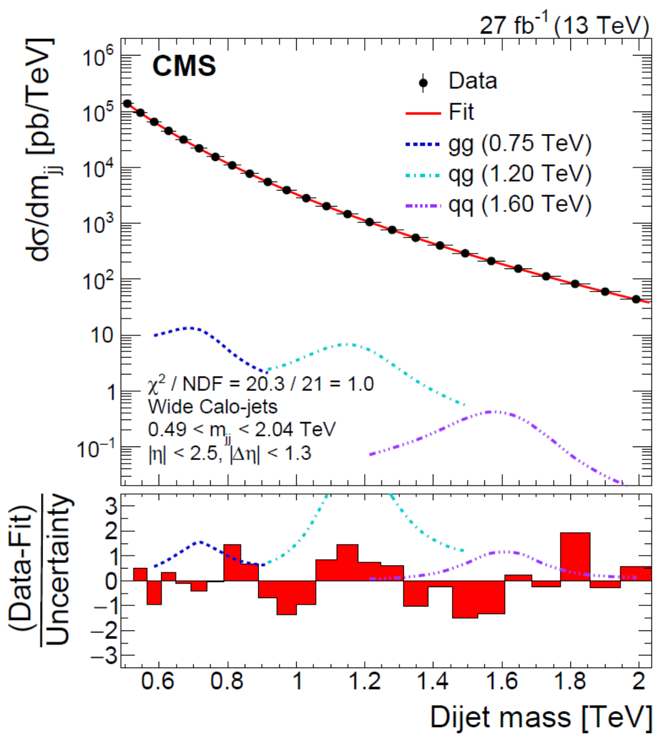
Low-mass data use one more parameter:

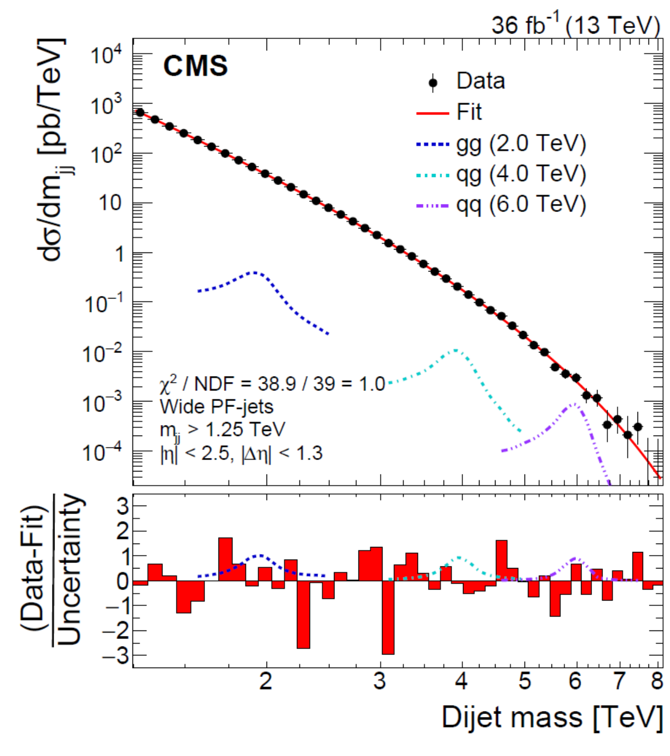
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)+P_4\ln^2(x)}}$$

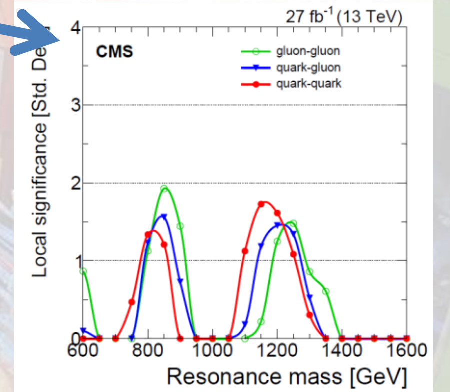
$$x = m_{jj}/\sqrt{s}$$

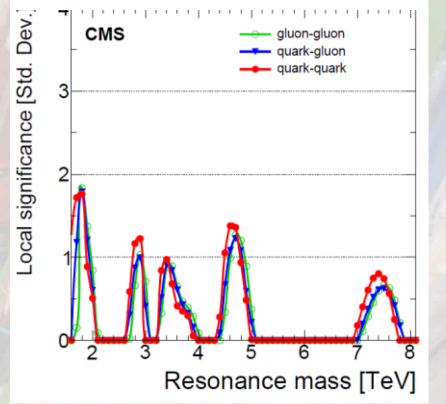
The F-test with α=0.05 is used to choose the form

No significant structure is observed (see below, right)





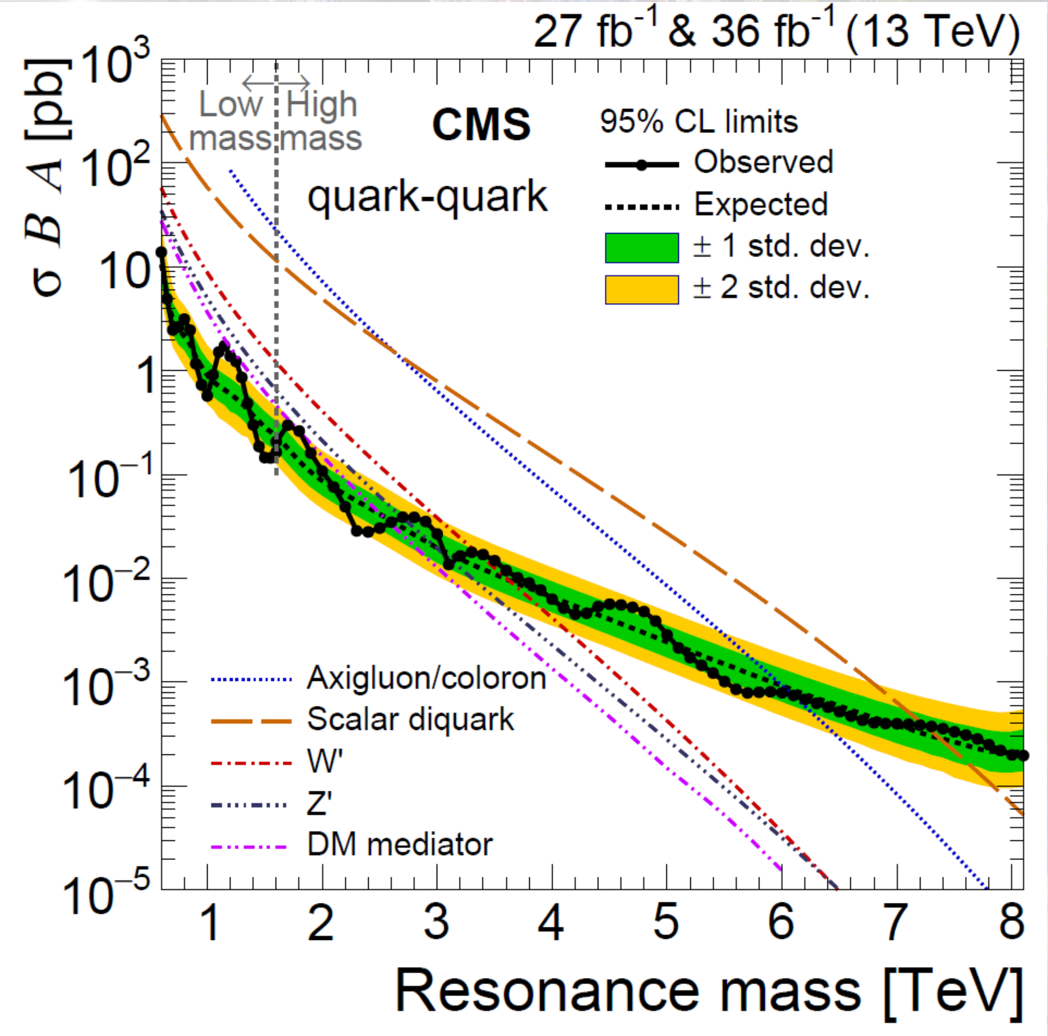




Cross Section Limits

For narrow resonances, the limit on the product of cross section, branching ratio to jet pairs, and selection acceptance is compared to theoretical predictions for a number of NP models

For the considered dark matter model, with g_q=0.25, g_{DM}=1, and M_{DM}=1 GeV the lower mass limit is set at 2.6 TeV

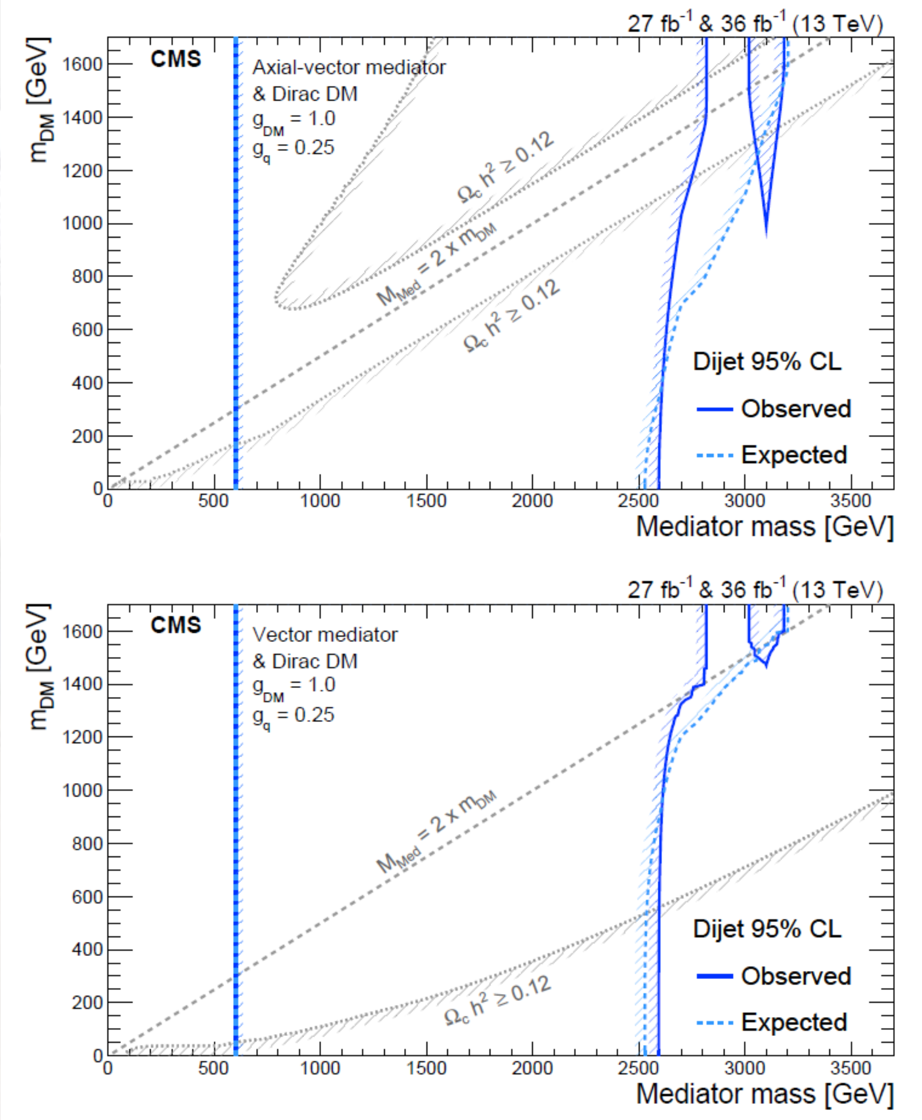


Limits in DM mass : Mediator Mass Plane

For axial-vector (top) and vector (bottom) mediators the limits extend to 2.5-3 TeV for example model chosen with g_q=0.25, g_{DM}=1, depending weakly on DM mass

Grey curves show limit where DM abundance would exceed bound from cosmological relic density (very coupling-dependent, only applies to chosen values)

For larger g_q (>0.4) the narrow-width approximation fails, and dedicated searches for wide signal shapes are required (see below)



2' - Wide Dijet Resonance Search

High-mass data and the same background model discussed above are used to extract limits on broad resonances

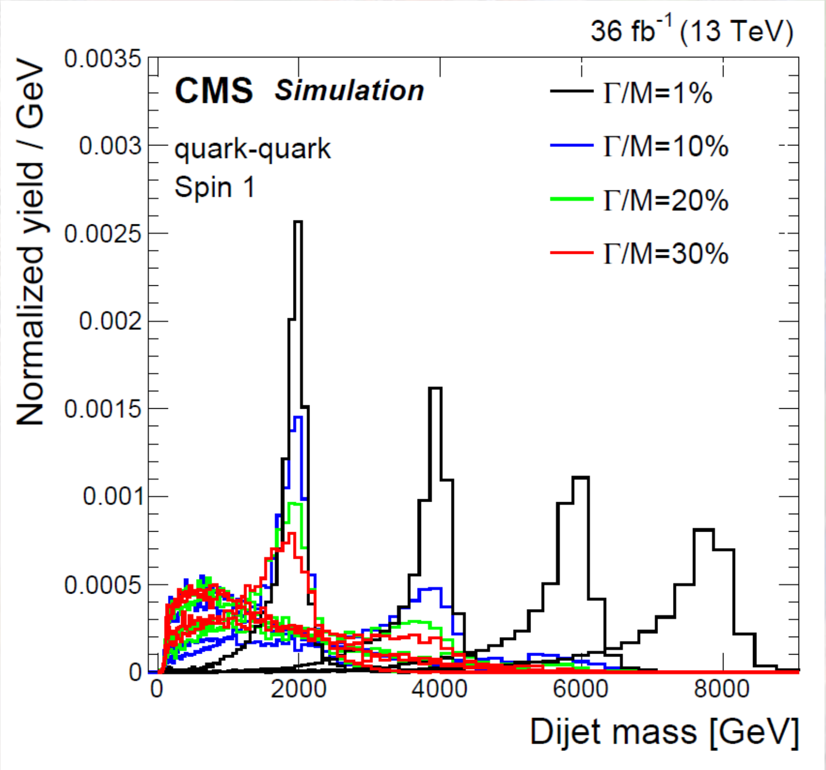
The cross section of a vector mediator is computed at LO with MADGRAPH for g_{DM}=1, m_{DM}=1 GeV and g_q in the range 0.1-1.0.

With the above parameters the width is expressed by the approximation

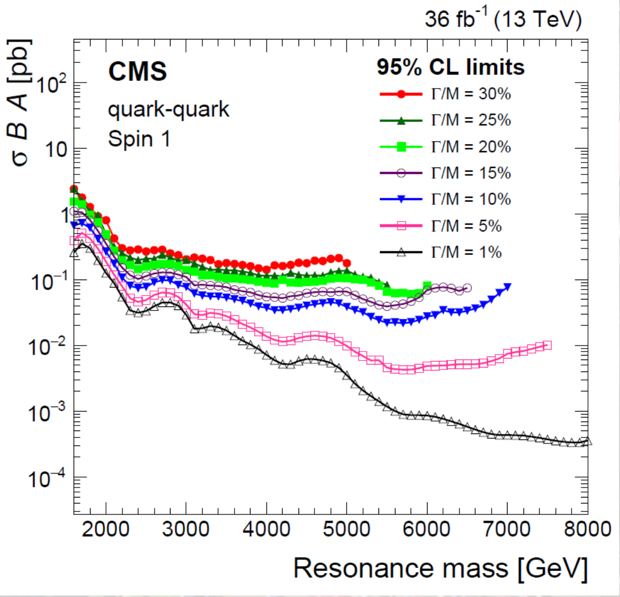
$$\Gamma_{\mathrm{Med}} \approx \frac{(18 g_{\mathrm{q}}^2 + 1) M_{\mathrm{Med}}}{12\pi}$$

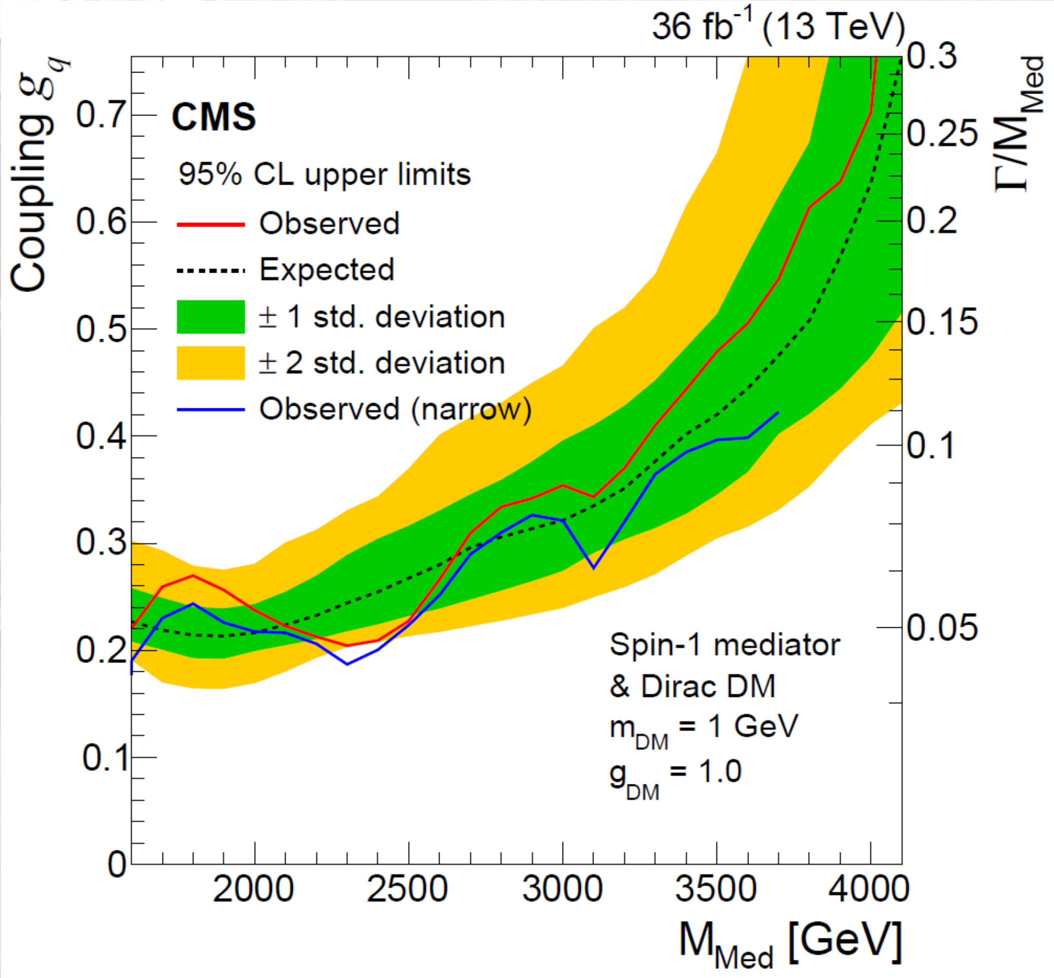
As resonances get broader, the effect of QCD radiation and PDF-driven enhancement of low-mass tails becomes more and more pronounced

Results are only reported for parameter space regions where the low-mass tails remain well understood



Wide Resonance Search: Limits in the g_q:M_{med} Plane





For each value of M_{med} the predictions for the cross section for mediator production as a function of g_q are converted to a function of the width using the above formula, and are then compared to cross section limits to find the excluded values of g_q for a spin-1 resonance

3 - Searches in Dijet Angular Distributions

QCD scattering of quarks and gluons produces flattish distribution in **$\chi = \exp(|y_1 - y_2|)$** → new physics can be sought at low values of χ

In the already mentioned simplified model[1,2] DM mediators (vector or axial-vector) decay to quark pairs or DM particle pairs, described by couplings g_q and g_{DM}.

- For large (>0.4) values of g_q, searches for resonances become insensitive due to large (>10%) width of the resonance

  → angular distributions are more sensitive in a large swath of parameter space

New CMS result submitted in March: arXiv:1803.08030 (CMS-EXO-16-046)

[1] J. Abdallah et al., Phys. Dark Univ. **9-10** (2015) 8

[2] G. Busoni et al., arXiv:1603.04156 (2016).

Analysis Detail

36/fb of 2016 13-TeV pp collisions used

- collected data with p_T>450 GeV || H_T>900 GeV trigger

- 7 M_{jj} regions from leading jets from 2.4 to >6 TeV
  - 350k events in low bin, 95 events in highest one
- M_{jj}:χ is unfolded to particle level by matrix inversion for comparison to theory predictions
  - NLO QCD with NLOJET++[1] in FASTNLO[2] framework, with EW corrections[3]. CT14[4] PDFs are used
  - DM model with MadDM[5] with g_{DM}=1 & M_{DM}=1 GeV

- Limits are extracted with asymptotic CLs using detector-level distributions
  - On DM mediators, use is made of M_{jj} bins from 0.5 to 1.2 times the sought state
  - Main systematic uncertainties: JES (3.6→9.2%), QCD NLO renormalization and factorization scales (8.5→19%)

[1] Z. Nagy, Phys. Rev. Lett. **88** (2002) 122003

[2] T. Kluge, K. Rabbertz, and M. Wobisch, hep-ph/0609285

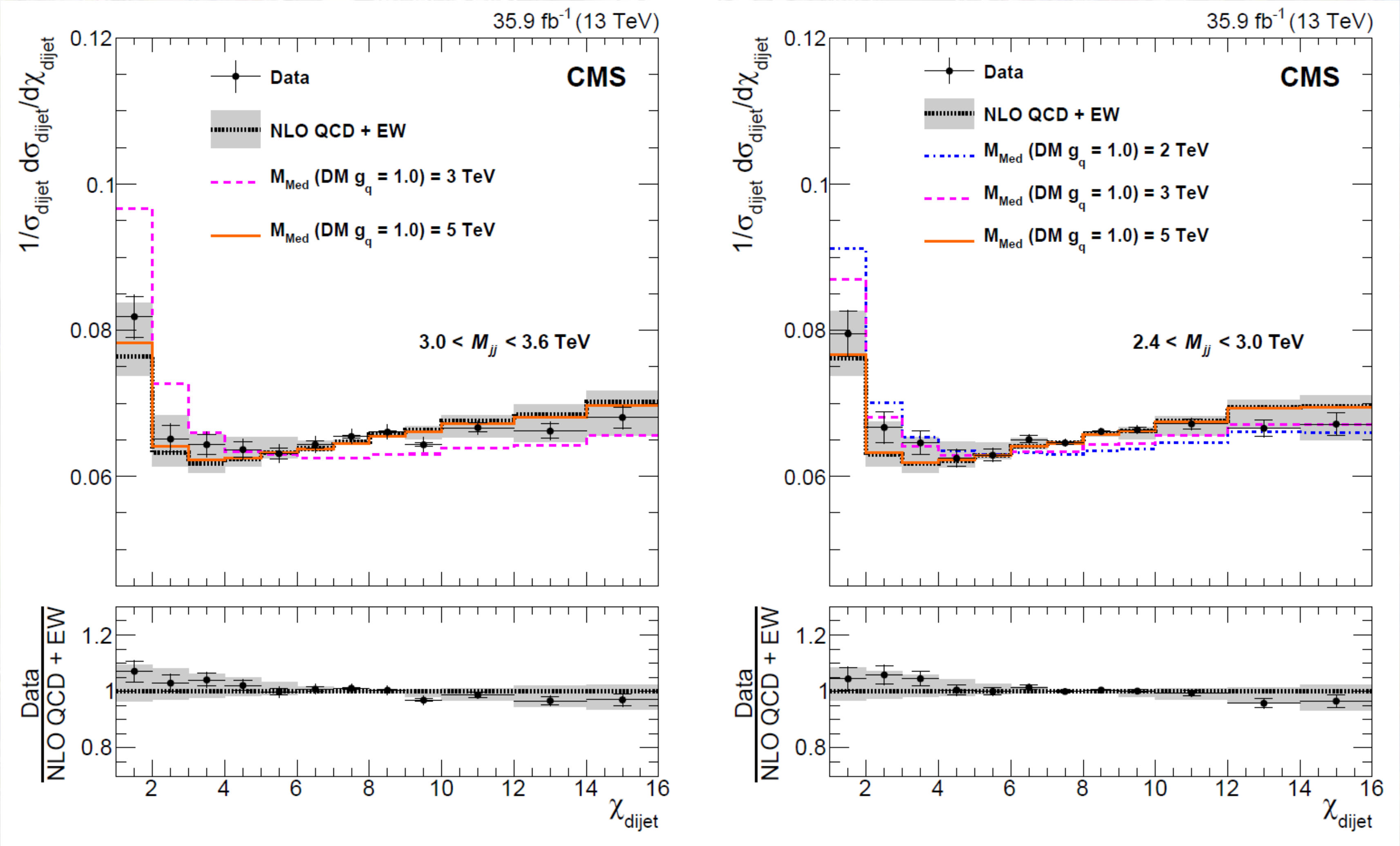
[3] S. Dittmaier, A. Huss, and C. Speckner, JHEP **11** (2012) 095

[4] S. Dulat et al., Phys. Rev. D **93** (2016) 033006

[5] M. Backovic et al., Phys. Dark Univ. **5-6** (2014) 18; M. Backovic et al., Phys. Dark Univ. **9-10** (2015) 37.

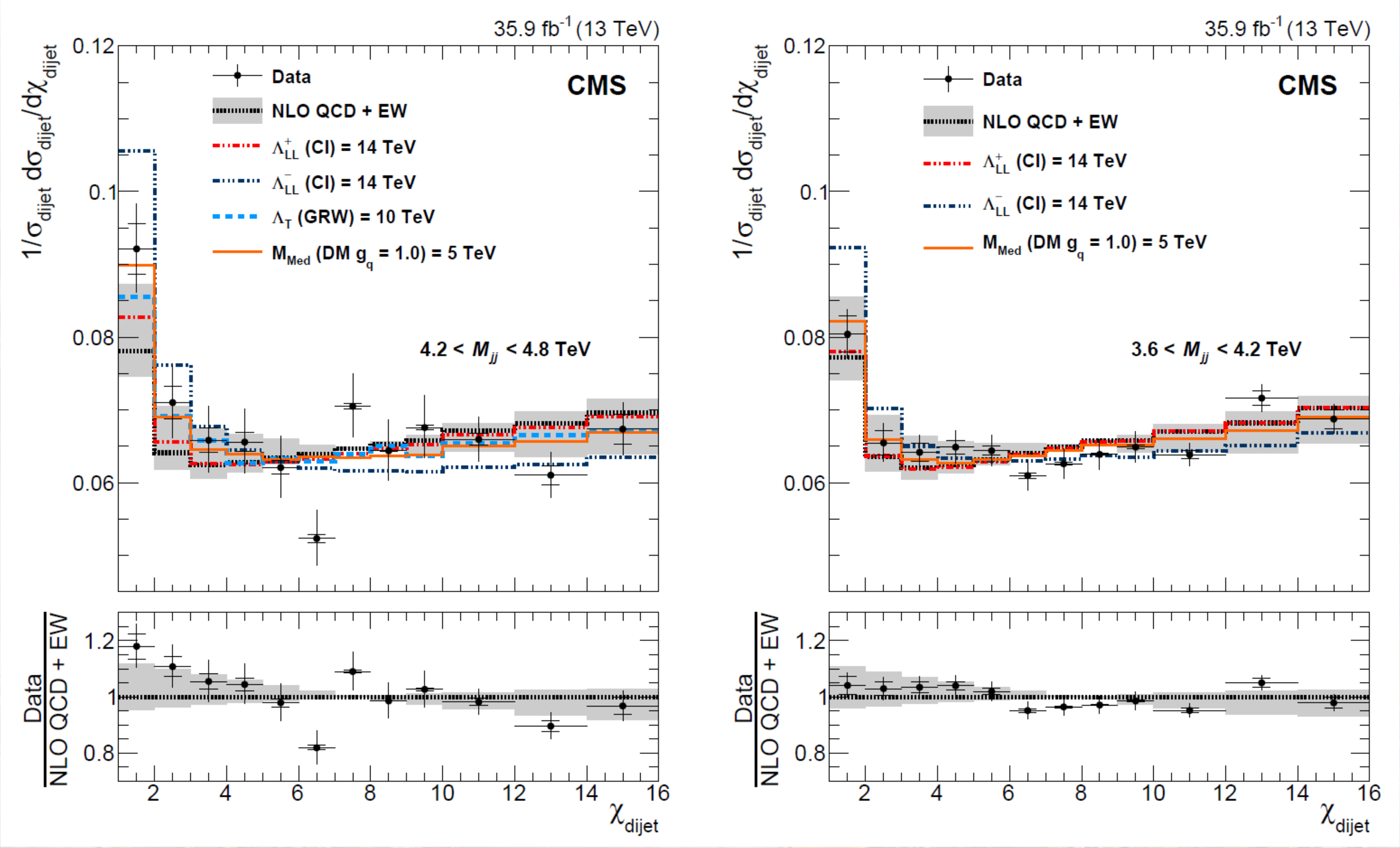
Low Dijet Mass Bins

Unfolded distributions of χ are compared to NLO QCD and to the inclusion of DM effects, in M_{jj} intervals. Below, 3.0-3.6 TeV (left) and 2.4-3.0 TeV (right)



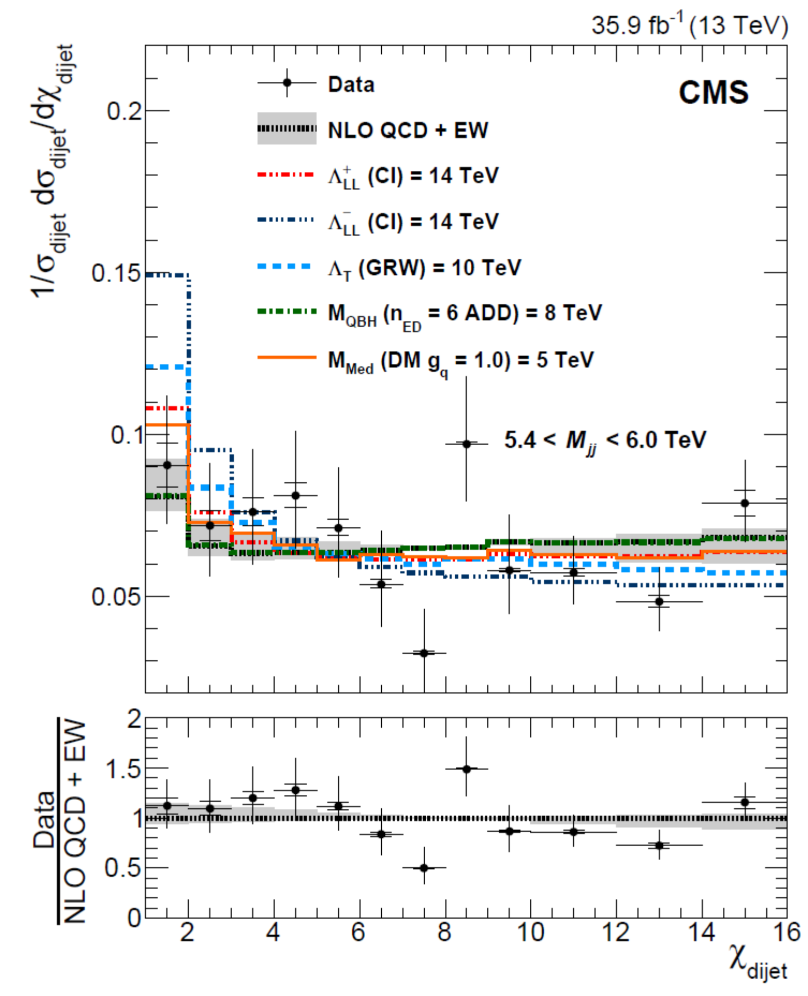
Intermediate Dijet Mass Bins

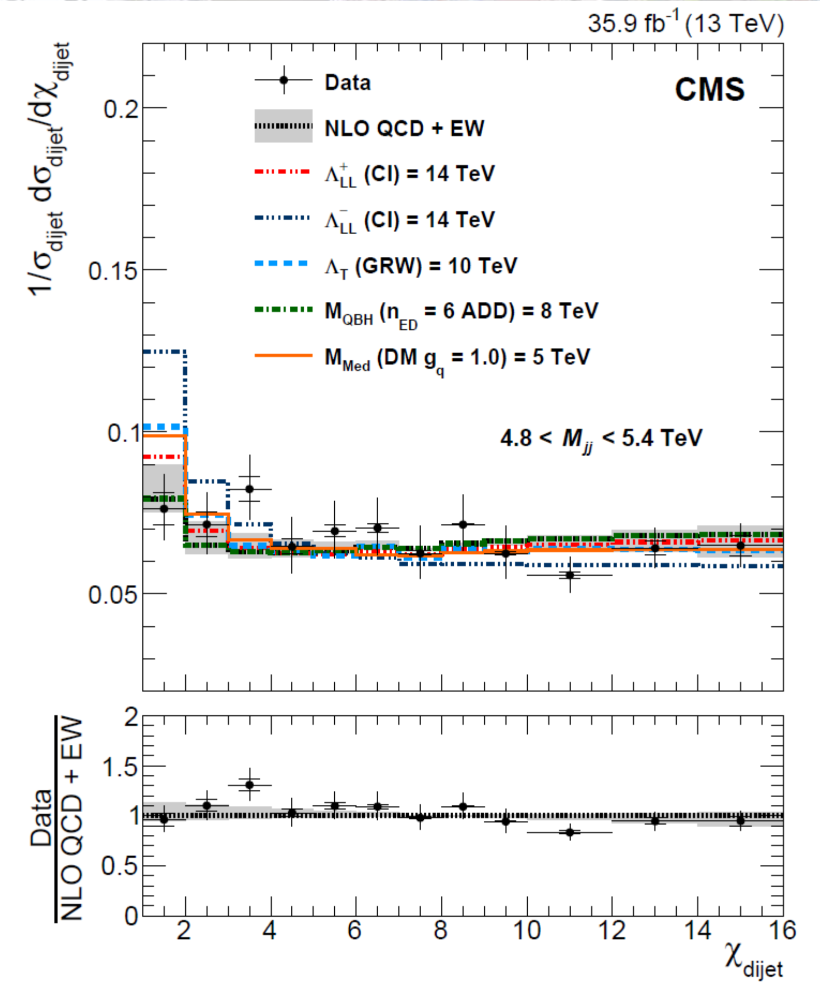
Unfolded distributions of χ are compared to NLO QCD and to the inclusion of DM effects, in M_{jj} intervals. Below, 4.2-4.8 TeV (left) and 3.6-4.2 TeV (right)



High Dijet Mass Bins

Unfolded distributions of χ are compared to NLO QCD and to the inclusion of DM effects, in M_{jj} intervals. Below, 5.4-6.0 TeV (left) and 4.8-5.4 TeV (right)



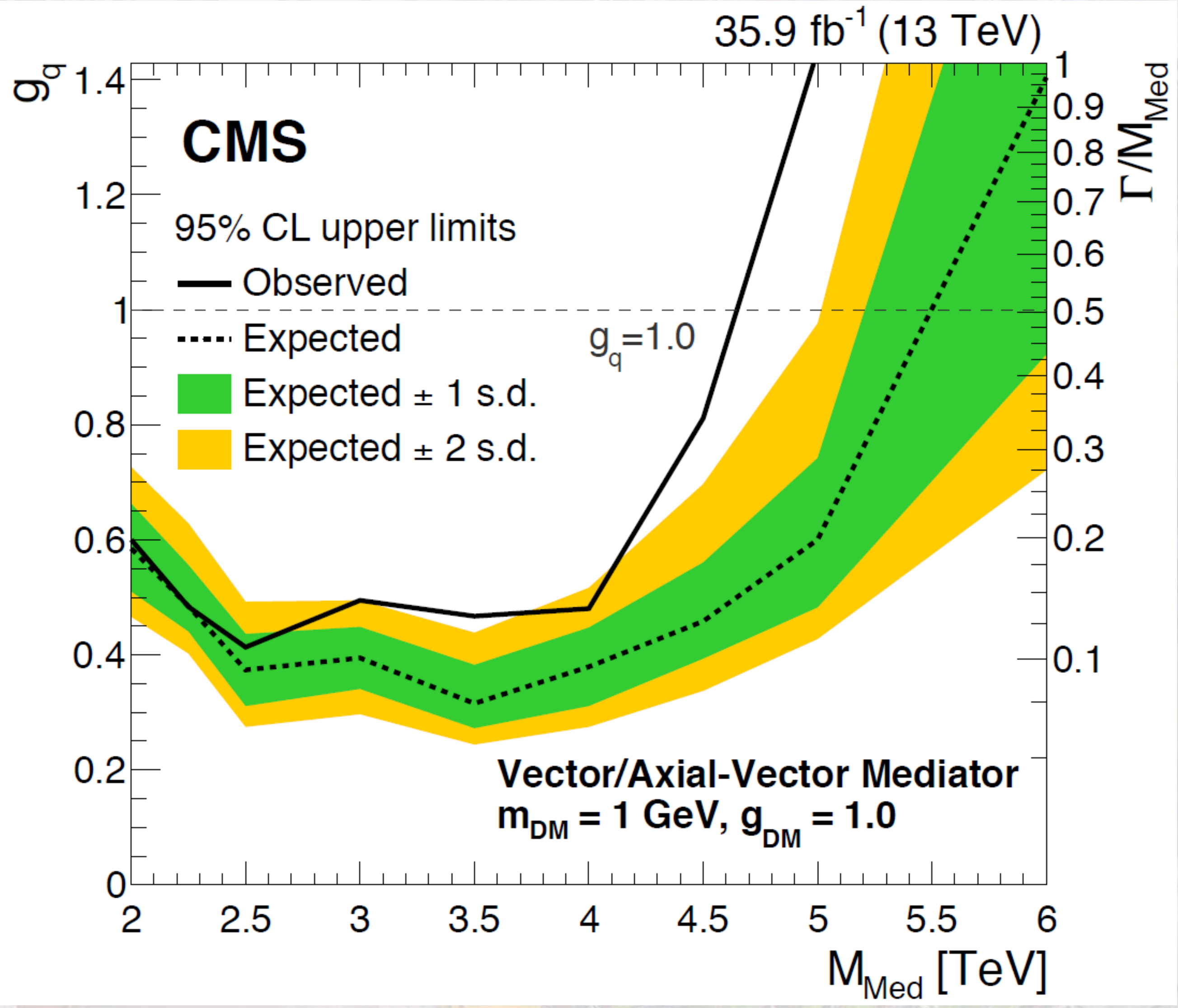


Limits in g_q:M_{med} Plane

The region above the black curve is excluded at 95% C.L. for M_{DM}=1 TeV and g_{DM}=1

Limits at high mass are weaker than expected due to concurrent fluctuations in low-mass bins

Significance of small excesses up to 2.8σ for models with 4.5<M_{med}<6 TeV

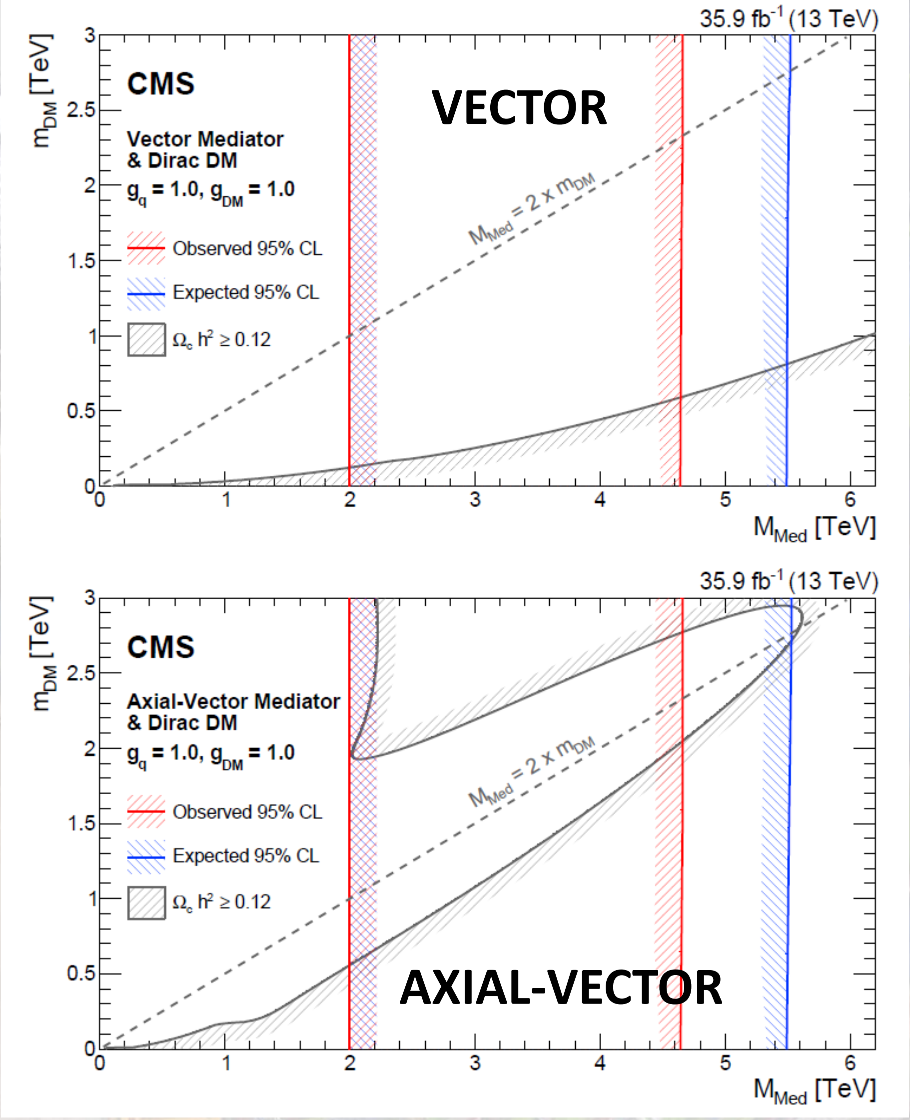


Comparison to Cosmological Bounds

Mediator mass limits are compared with limits from cosmological relic density[1], for the benchmark model $g_{DM}=g_q=1$ in the $M_{DM}:M_{med}$ plane

For considered model, vector and axial-vector cross section are almost equal → same limits on M_{med}

Very little dependence on M_{DM} in experimental limit for above choice of parameters (width dominated by quark decay channel)



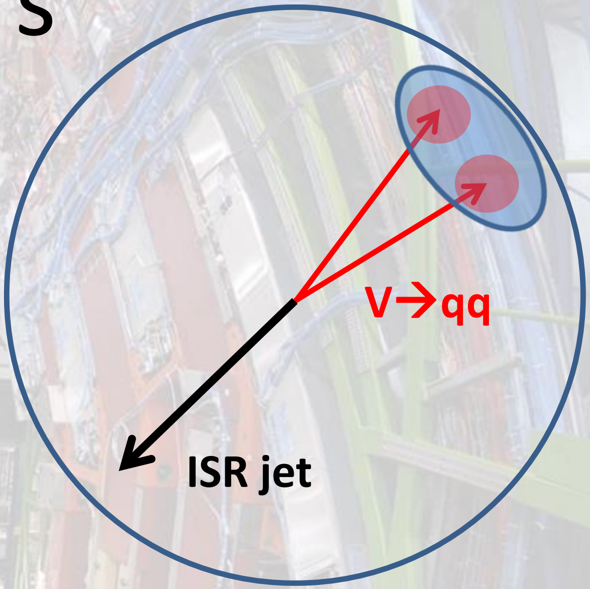
[1] Planck Collaboration, Astron. Astrophys. **594** (2016) A13

4 - Low-mass Vector Resonances Search in Boosted Jet Pairs

Jet events can now **probe low-mass mediators** decaying into quark pairs, V→qq, thanks to new jet substructure techniques

The production model calls for ISR to provide the resonance with large p_T; the dijet system can then pass trigger selection

Resulting boosted jet can be reconstructed and the mass of the decaying object measured

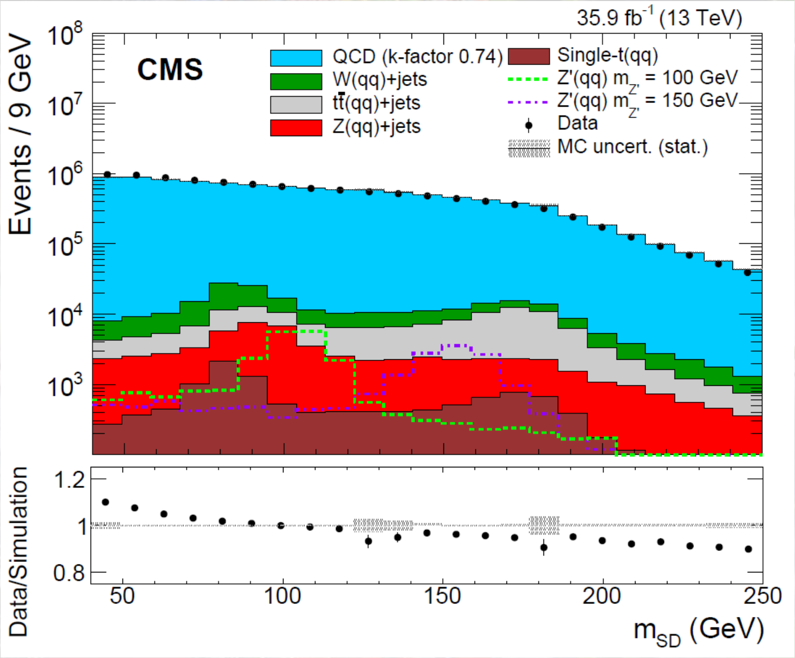


36/fb of 2016 13-TeV pp collisions used for this search. Technique is new – no previous results except a CMS analysis of smaller dataset acquired in 2015[1].

MADGRAPH used for reference Z' signal model, with up to 3 jets, and for backgrounds from QCD and V+jets, using NNPDF3.0[2] and Pythia8[3].

[1] CMS Collaboration, Phys. Rev. Lett. **119** (2017) 111802
[2] NNPDF Collaboration, JHEP **04** (2015) 040
[3] T. Sjostrand et al., Comput. Phys. Commun. **191** (2015) 159

Analysis Strategy

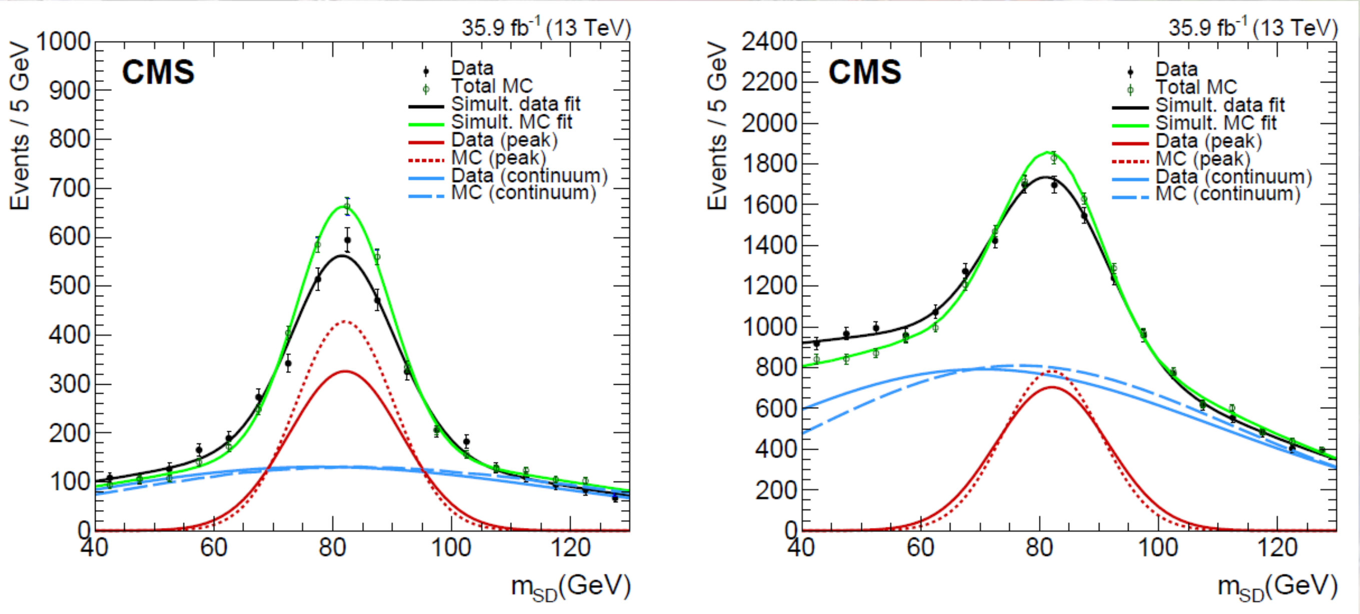


Events must have one large-radius jet with p_T>500 GeV in the central region (|η|<2.5)

Jet mass is groomed with "soft-drop" algorithm[1,2] to remove soft QCD radiation and pile-up effects

Variables sensitive to the substructure of the jet are used and calibrated to be decorrelated with jet mass

Calibration of jet mass scale, resolution, and selection dividing high- and low-purity are obtained in sample of boosted semileptonic tt events selected in data (see right)

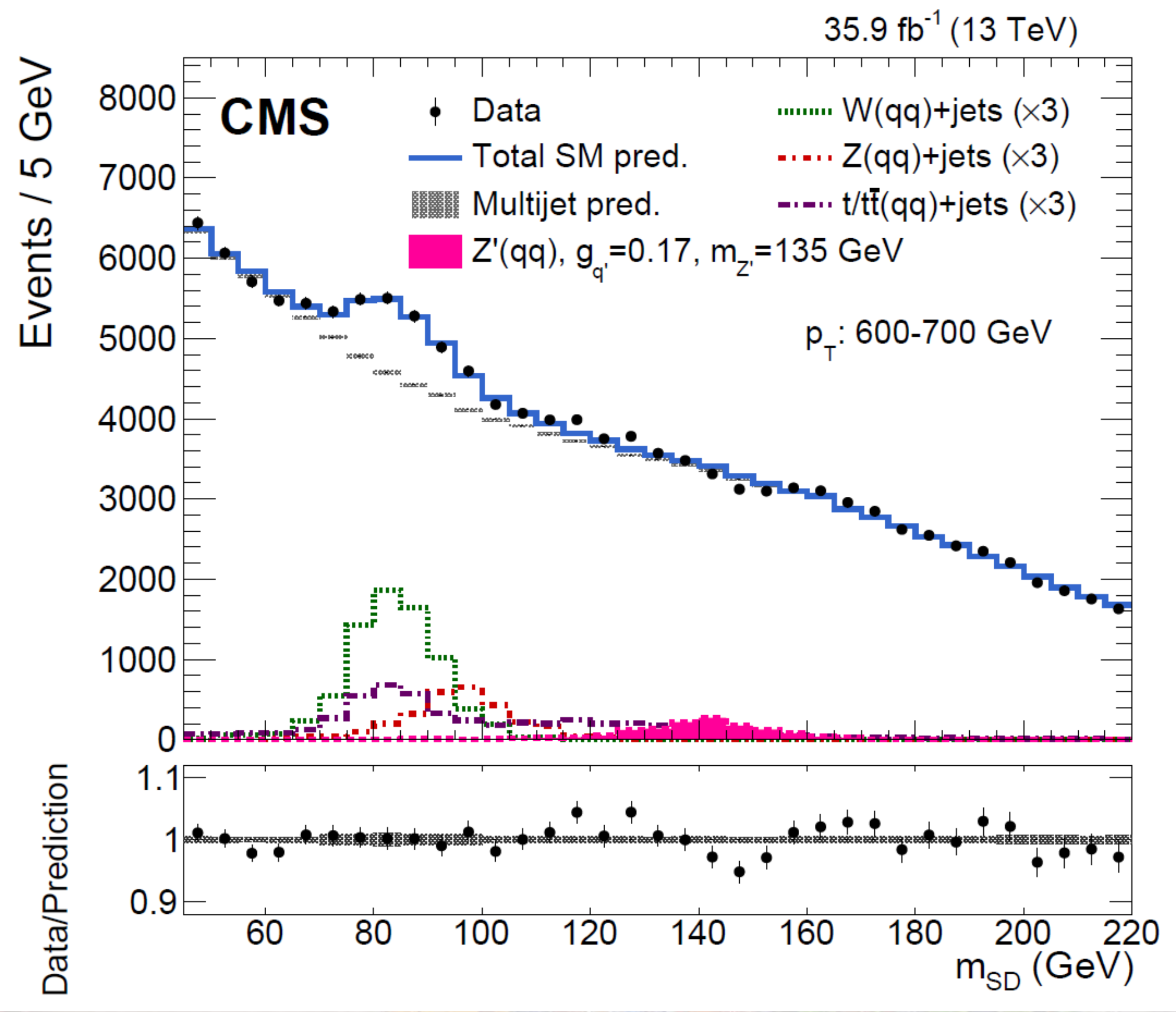


Above: W mass in boosted jet from tt decay, in data and MC
Left: high-purity selection; right: low-purity selection

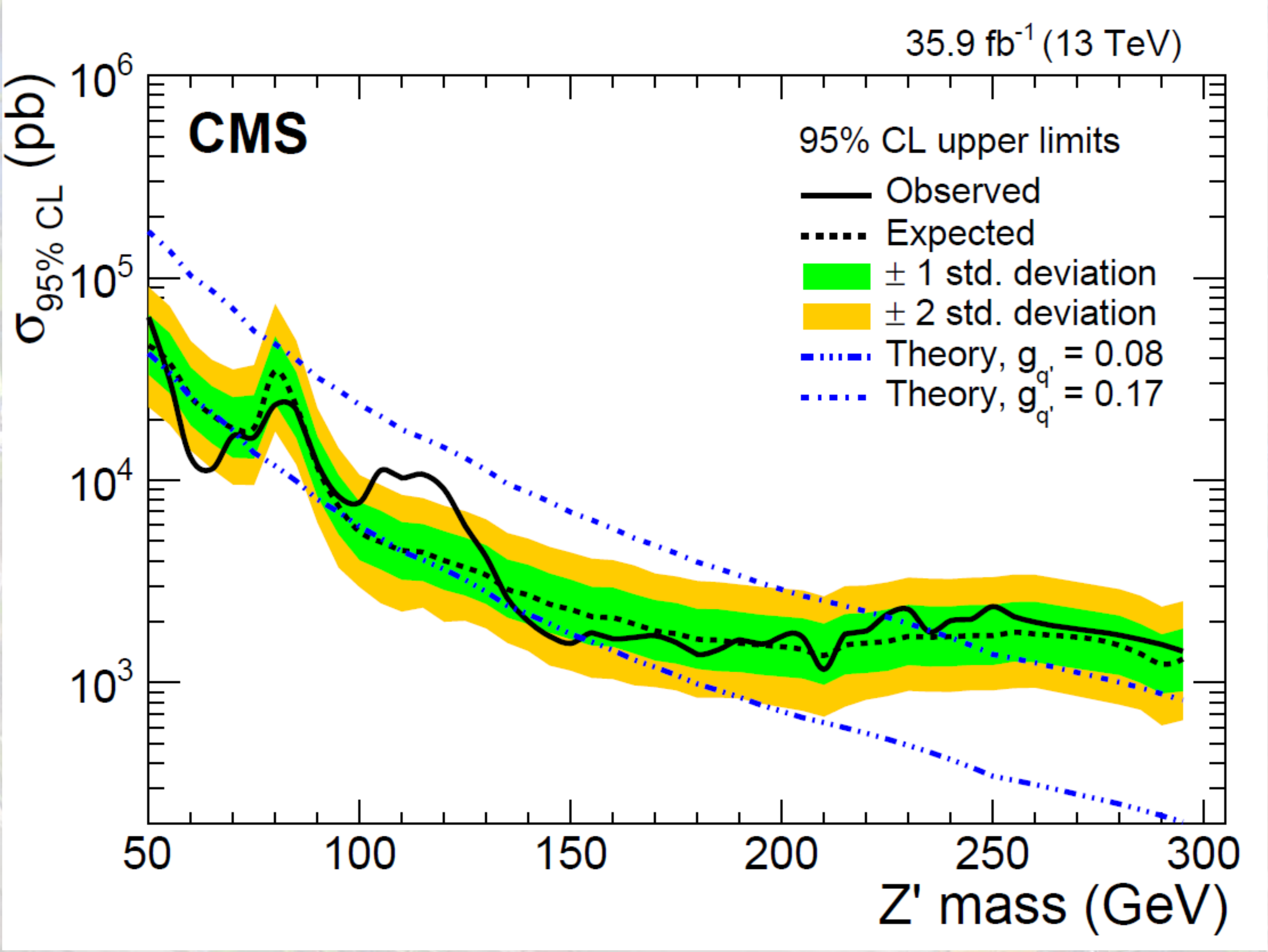
[1] M. Dasgupta et al., JHEP **09** (2013) 029
[2] A. J. Larkoski et al., JHEP **05** (2014) 146

Sample Fit – $600<p_T<700$ GeV

The "soft-drop" jet mass is fit with a binned likelihood in pass and fail regions simultaneously in five jet p_T ranges, using the Combine tool in Roostats and accounting for V+jets, tt, and QCD backgrounds



Cross Section Limit vs Z' Mass



The expected and observed limits on signal cross section are here compared with two theory predictions for different couplings $g_{q'}$

Most significant deviation from bgr-only at 115 GeV, local significance 2.9 sigma (see next slide)

p-value in Z' Search

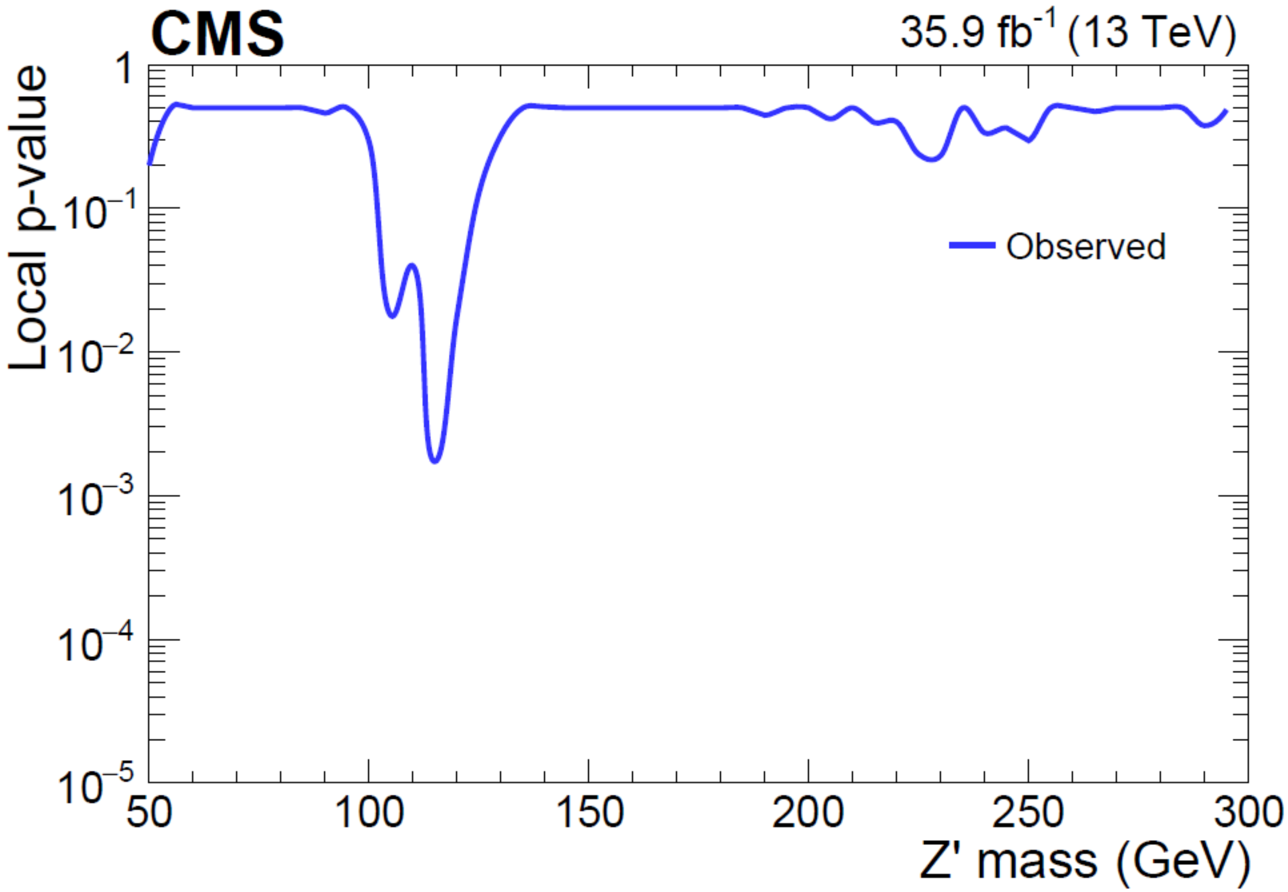
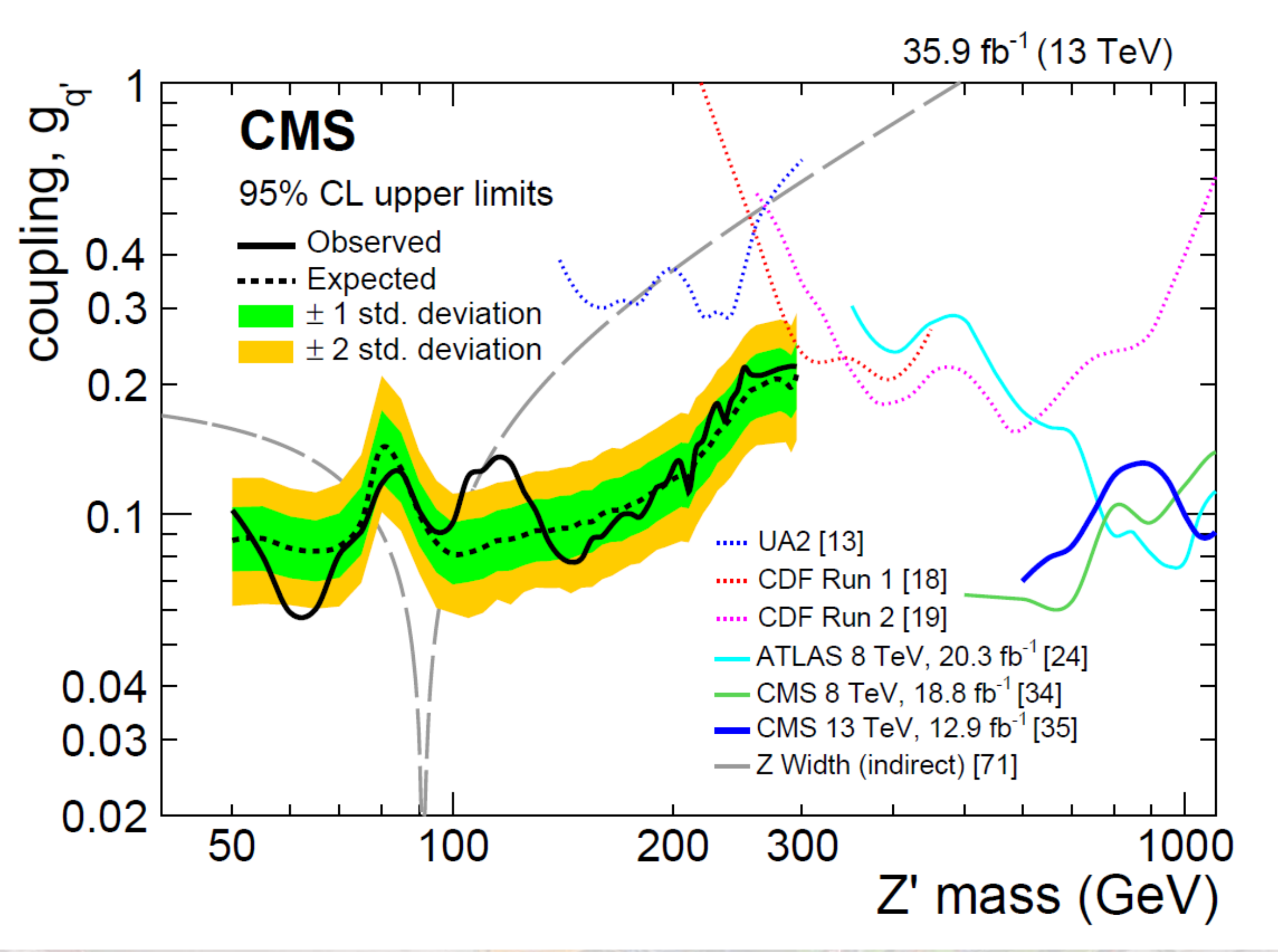


Figure 11: The observed p-value, obtained from the fit to data, as a function of the Z' boson mass. The maximum local observed p-value, at 115 GeV, is 1.72×10^{-3} and corresponds to 2.9 standard deviations from the background-only expectation, and the global p-value, calculated over the probed mass range, corresponds to 0.0138 and 2.2 standard deviations.

Result in Coupling vs Mass Plane

The search extends to untested region of Z' masses and strongly constrains the leptophobic coupling $g_{q'}$

CMS coupling limit is shown in comparison to indirect limit based on Z width measurements at LEP[1] (grey dashed curve)



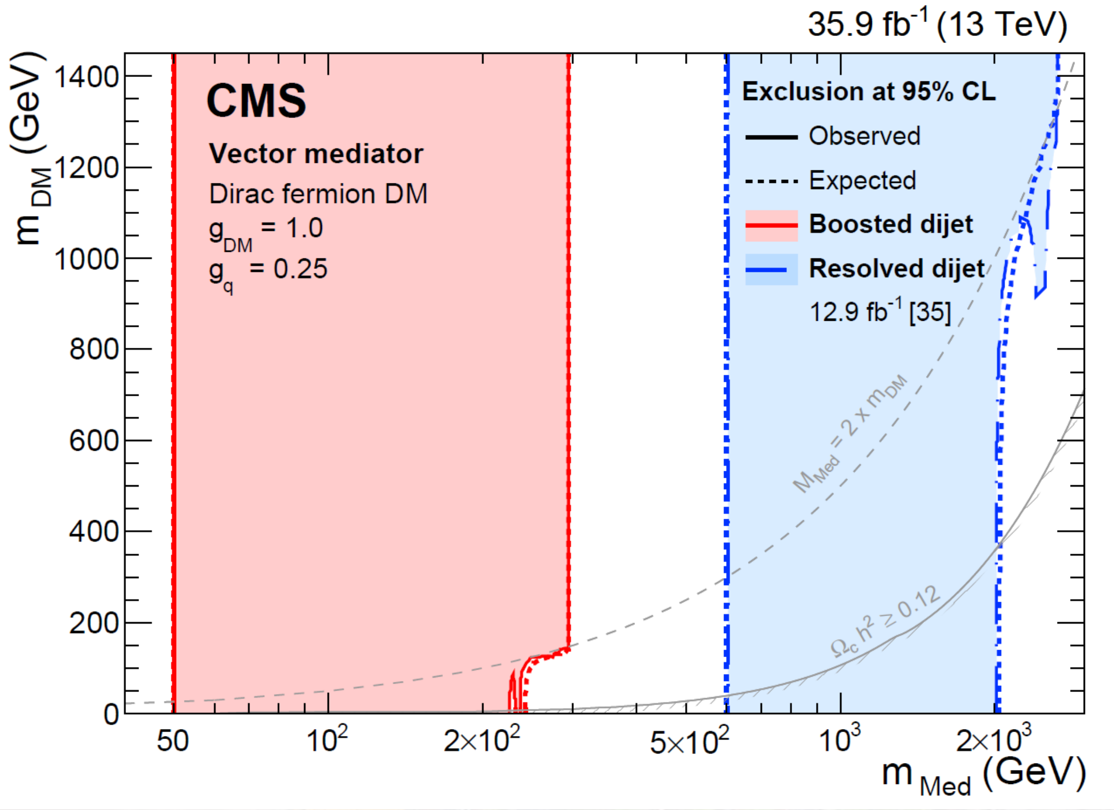
[1] B. A. Dobrescu and C. Frugiuele, Phys. Rev. Lett. **113** (2014) 061801

DM Results of Boosted Dijet Search

Results of search can be cast in context of simplified DM model.

95% CL limits are reported in M_{DM}:M_{med} plane (dashed=exp limits)
Branching fraction of 100% is assumed for a leptophobic vector mediator decaying to dijets.
The exclusion is computed for a quark coupling choice $g_q = 0.25$ and $g_{DM} = 1$.
Excluded regions also shown from the dijet resolved analysis[1]

Results are compared to constraints from cosmological relic density of DM (light gray) determined as described in[2] from astrophysical measurements [3,4] using MADDM.



[1] CMS Coll., Phys. Lett. B **769** (2017) 520
[2] T. du Pree, K. Hahn, P. Harris, and C. Roskas, arXiv:1603.08525 (2016)
[3] WMAP Coll., Astrophys. J. Suppl. **170** (2007) 377
[4] Planck Coll., Astron. Astrophys. **571** (2014) A16

Summary

- CMS is pursuing Dark Matter searches in a wide range of physics scenarios. The sensitivity of hadronic final states to DM is fairly high for models with vector and axial-vector mediators

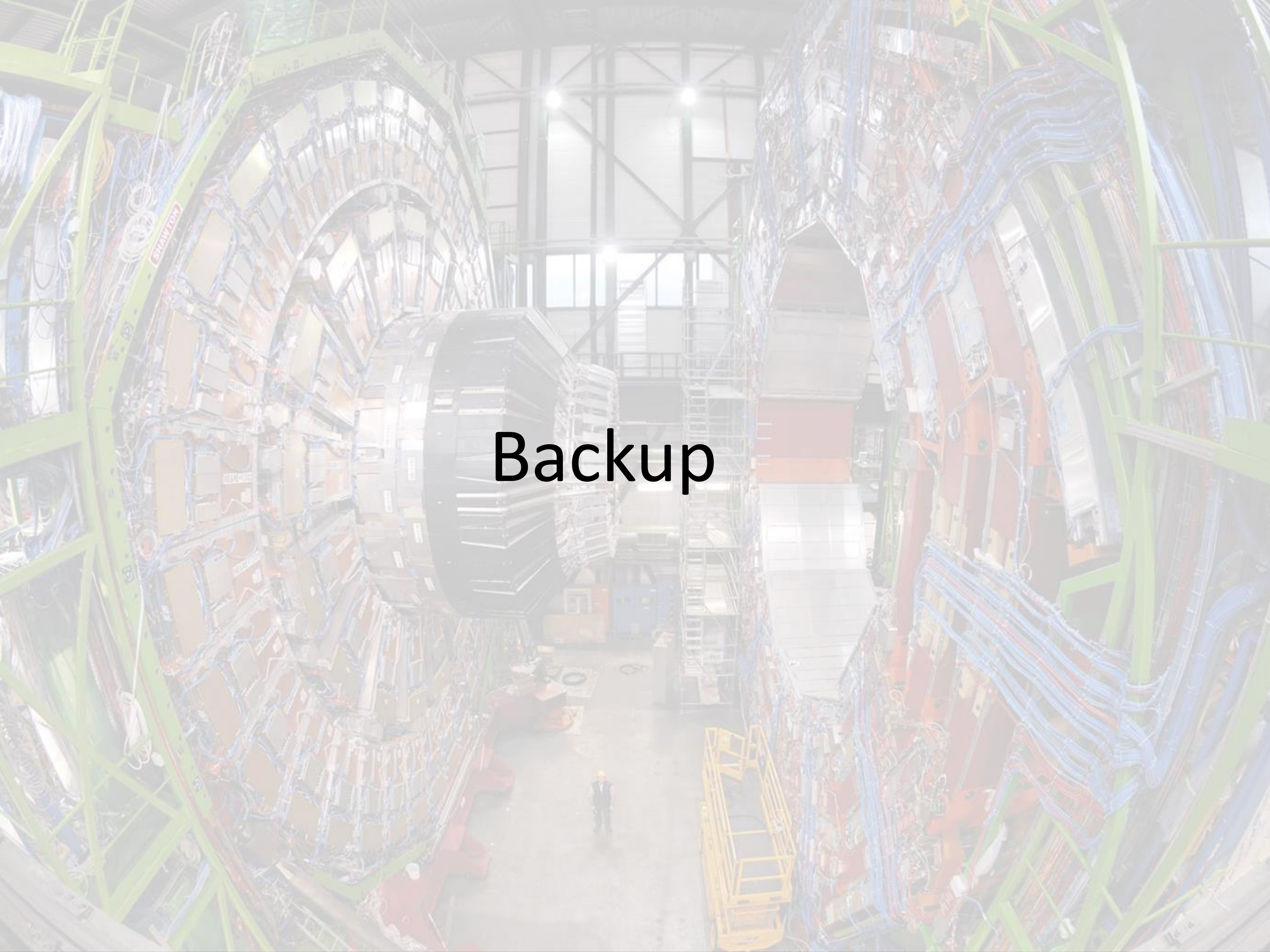
- **No >3σ hints** of signal in searches of DM associated with heavy quark pairs

- Extended limits on mediator mass derived from dijet final states
  - Small excess of events in dijet angular analysis makes limits slightly worse than expected there

- Looking forward to more results on DM searches with recent great performance of LHC and foreseen new heaps of data!
  - expect to have **x4 more data** than ones presented by end of 2018

All results presented here are available at this link:
https://cms-results.web.cern.ch/cms-results/public-results/publications/

Backup



Nuts and Bolts of Combine

Hypothesis testing to extract limit on new particle cross sections at the LHC is now mostly done using the Combine tool of RooStats.

The first step involves writing down extensively the likelihood function!

1) One writes a global likelihood function, whose parameter of interest is the signal strength modifier μ. If s and b denote signal and background, and θ is a vector of systematic uncertainties, then for a single channel:

$$\mathcal{L}(\mathrm{data}\,|\,\mu,\theta) = \mathrm{Poisson}\left(\,\mathrm{data}\,|\,\mu\cdot s(\theta)+b(\theta)\,\right)\cdot p(\tilde{\theta}|\theta)$$

Note that θ has a "prior" coming from a hypothetical auxiliary measurement.

Nuisances are treated in a frequentist way by taking for them the likelihood which would have produced as posterior, given a flat prior, the PDF one believes the nuisance is distributed from.

In L one may combine many different search channels where a counting experiment is performed as the product of their Poisson factors:

$$\prod_i \frac{(\mu s_i + b_i)^{n_i}}{n_i!}\, e^{-\mu s_i - b_i}$$

or from a unbinned likelihood over k events, factors such as:

$$k^{-1}\prod_i (\mu S f_s(x_i) + B f_b(x_i))\,\cdot\, e^{-(\mu S+B)}$$

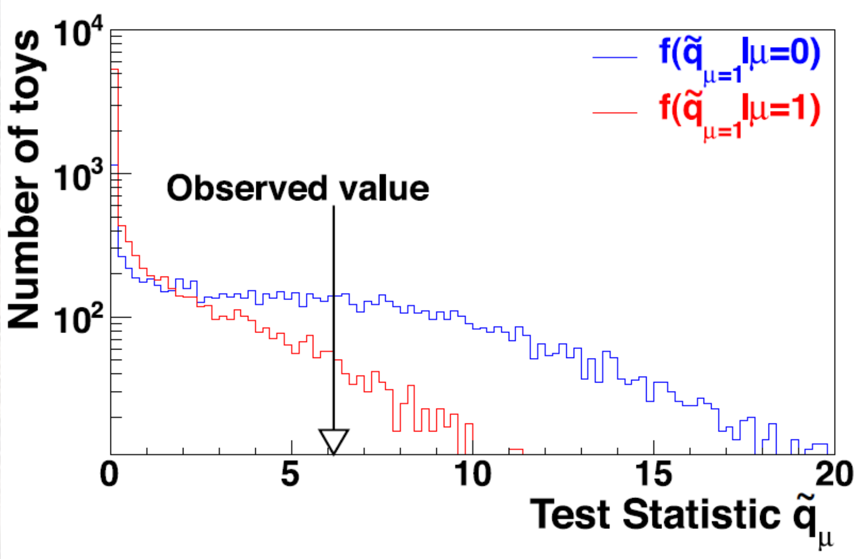
2) One then constructs a profile likelihood test statistic q_μ as

$$\tilde{q}_\mu = -2\ln \frac{\mathcal{L}(\mathrm{data}|\mu, \hat{\theta}_\mu)}{\mathcal{L}(\mathrm{data}|\hat{\mu}, \hat{\theta})}$$

Note that the denominator has L computed with the values of μ^ and θ^ that globally maximize it, while the numerator has $\theta=\theta^\wedge_\mu$ computed as the conditional maximum likelihood estimate, given μ.

3) ML values θ_μ^ for H_1 and θ_0^ for H_0 are then computed, given the data and $\mu=0$ (bgr-only) and $\mu>0$

4) Pseudo-data is then generated for the two hypotheses



With the data, one constructs the PDF of the test statistic given a signal of strength μ (H_1) and $\mu=0$ (H_0).

5) With pseudo-data one can then compute the integrals defining p-values for the two hypotheses. For the signal plus background hypothesis H_1 one has

$$p_\mu \;=\; P(\,\tilde{q}_\mu \geq \tilde{q}_\mu^{obs}\,|\,\text{signal+background}) \;=\; \int_{\tilde{q}_\mu^{\rm obs}}^{\infty} f(\tilde{q}_\mu|\mu,\hat{\theta}_\mu^{\rm obs})\,d\tilde{q}_\mu$$

and for the null, background-only H_0 one has

$$1-p_b \;=\; P(\,\tilde{q}_\mu \geq \tilde{q}_\mu^{obs}\,|\,\text{background-only}) \;=\; \int_{q_0^{\rm obs}}^{\infty} f(\tilde{q}_\mu|0,\hat{\theta}_0^{\rm obs})\,d\tilde{q}_\mu$$

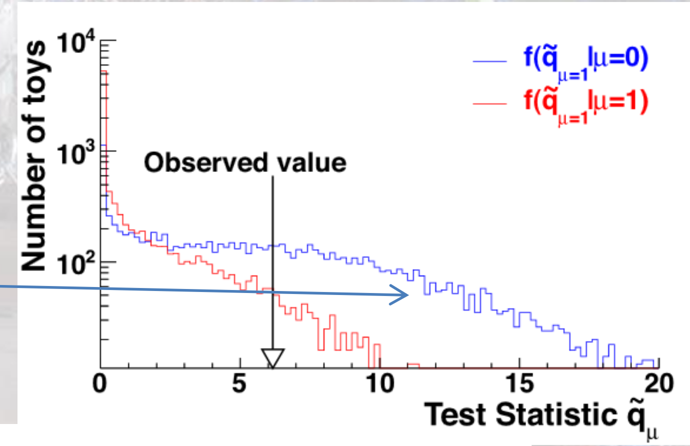
6) Finally one can compute the value called CL_s as

$$\mathbf{CL_s = p_\mu/(1-p_b)}$$

CL_s is thus a "modified" p-value, in the sense that it describes how likely it is that the value of test statistic is observed under the alternative hypothesis by also accounting for how likely the null is: the drawing incorrect inferences based on extreme values of p_μ is "damped"

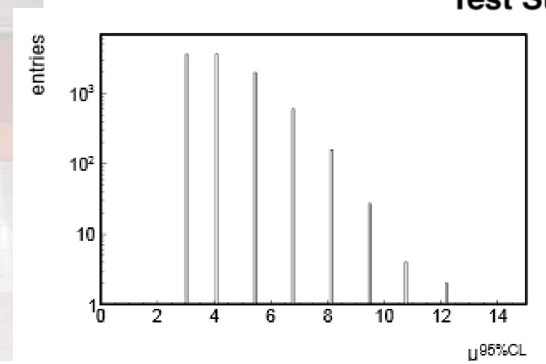
7) We can then **exclude H_1 when $CL_s < \alpha$**, the predefined *size* of the test (usually 0.05)

Derivation of Expected Limits



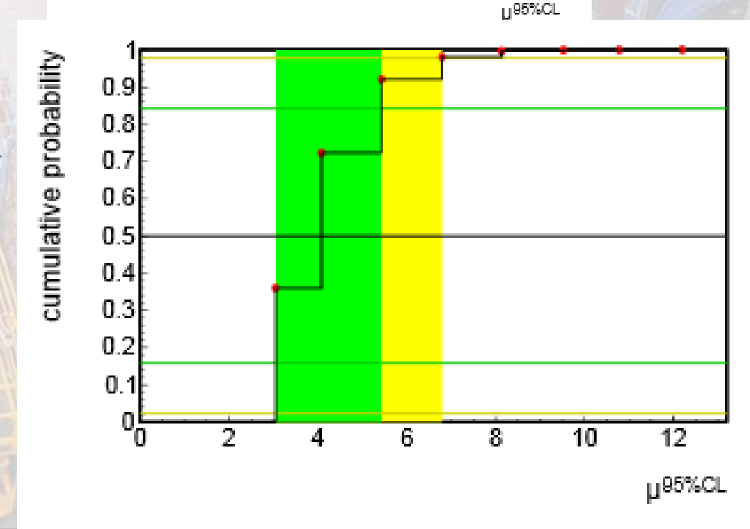
One starts with the **background-only hypothesis μ=0**, and determines a distribution of possible outcomes of the experiment with toys, obtaining the CLs test statistic distribution for each investigated Higgs mass point

From CLs one obtains the PDF of upper limits μ^{UL} on μor each M_h. [*E.g. on the right we assumed b=1 and s=0 for μ=0, whereas μ=1 would produce <s>=1*]



Then one computes the cumulative PDF of μ^{UL}

Finally, one can derive the median and the intervals for μ which correspond to 2.3%, 15.9%, 50%, 84.1%, 97.7% quantiles. These define the "expected-limit bands" and their center.

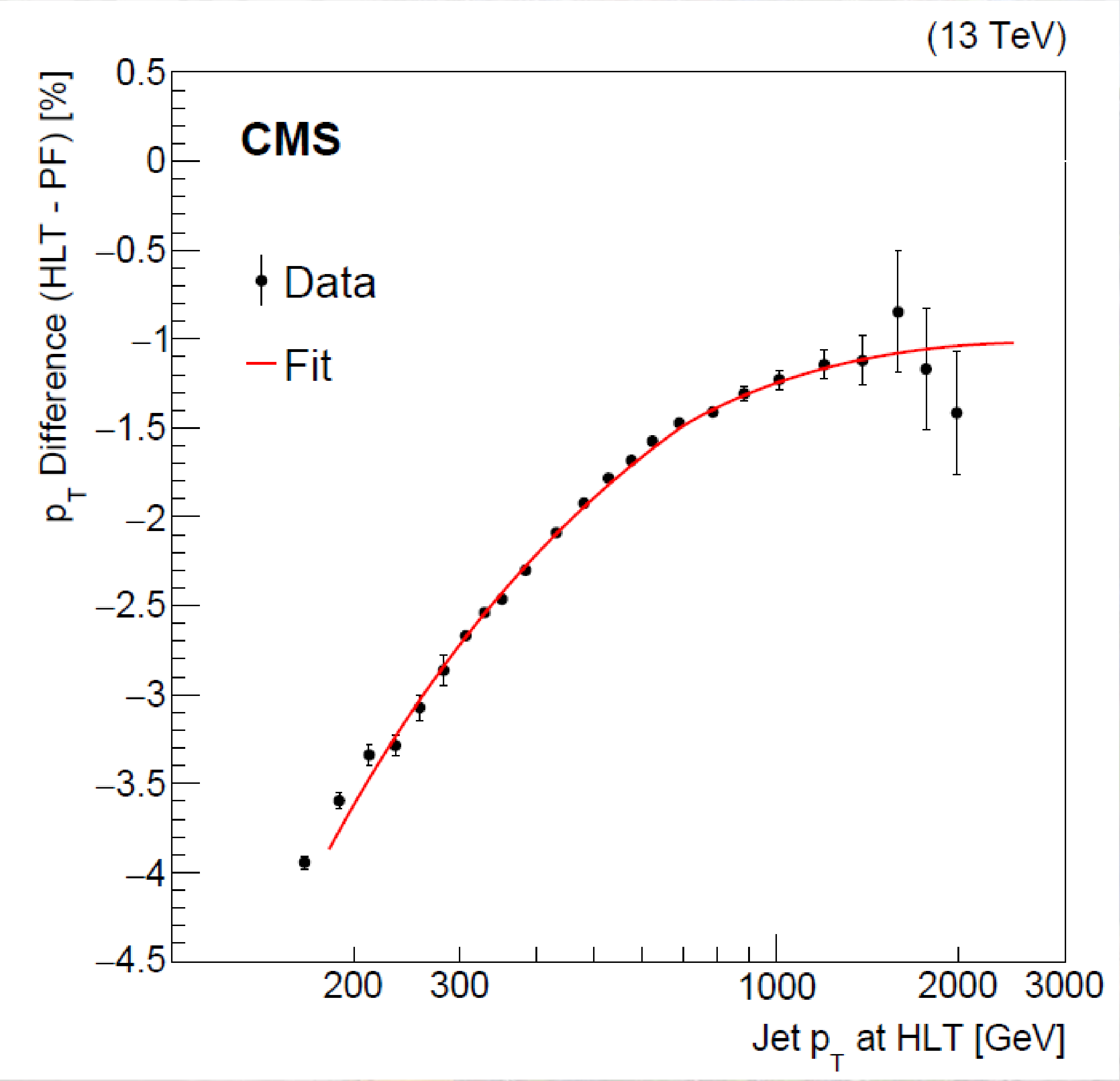


Calibration of Calo-Scouted Jets

Wide jets reconstructed from calo-jets at HLT are calibrated to have the same jet energy scale as the wide jets reconstructed from PF jets

A tag-and-probe technique is used on a small dataset of events reconstructed with both methods

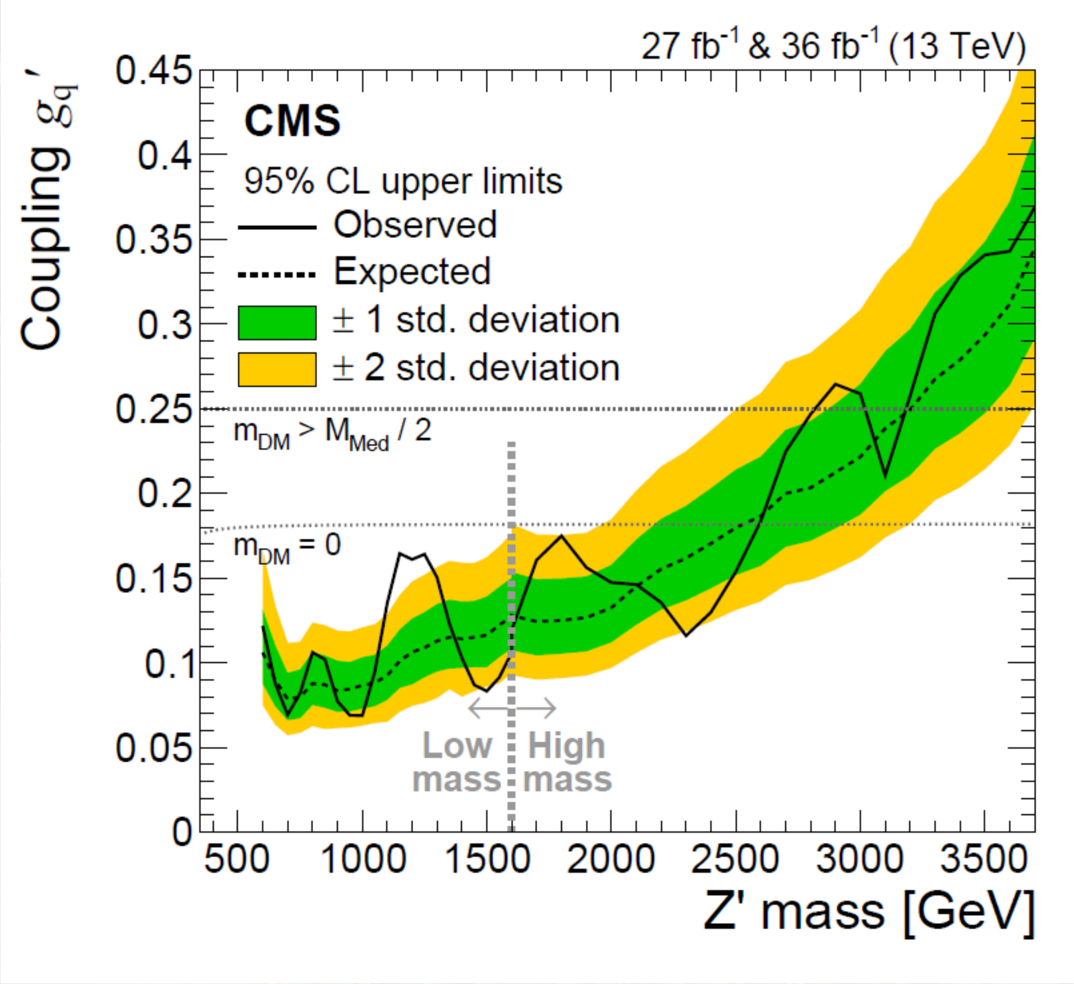
The fitted bias is used to correct the energy of calo-scouted jets such that jets in low and high-mass searches have same scale



Relationship of DM Limits With Z' Limits

For $M_{DM}>M_{med}/2$ the mediator cannot decay to DM particles, and the mediator cross section becomes equal to the one of a narrow leptophobic Z'[1]

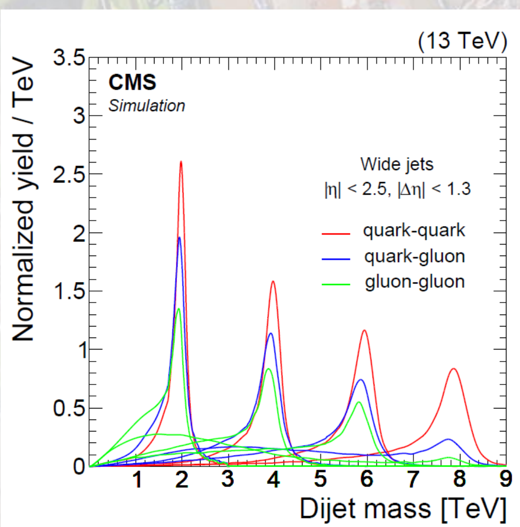
For $g_{q'}=0.182$ the equivalence of cross sections occurs if $M_{DM}=0$ when the number of active flavors contributing to the width of the resonance is $5+\sqrt{1-4m_{\mathrm{t}}^2/M_{\mathrm{Med}}^2}$

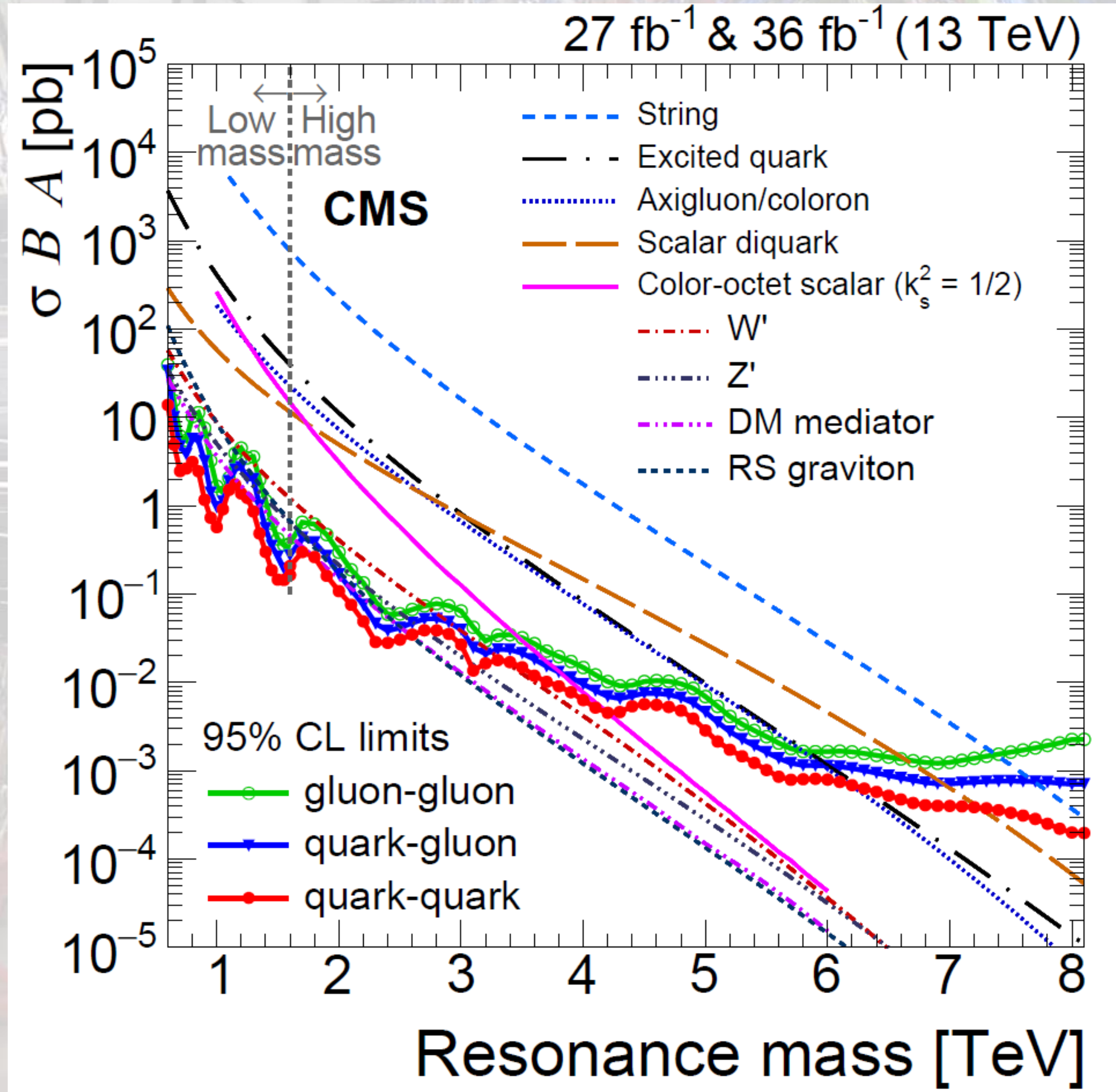


[1] B. A. Dobrescu and F. Yu, Phys. Rev. D **88** (2013) 035021

All Dijet Limits From Resonance Search

The figure compares the upper limits on the product of cross section, acceptance and branching fraction for resonances decaying to quark-quark, quark-gluon, and gluon-gluon final states to several models of new physics





Resonance Search: Effect of g_q

The effect of varying quark couplings can be seen in these temperature plots

The upper limit on g_q is drawn as a function of mediator and DM mass for g_{DM}=1 in the axial-vector (top) and vector (bottom) mediator scenarios

Limits decrease as m_{DM} increases, due to increased BR to quarks, until $m_{DM}=M_{med}$ (diagonal lines), then are constant