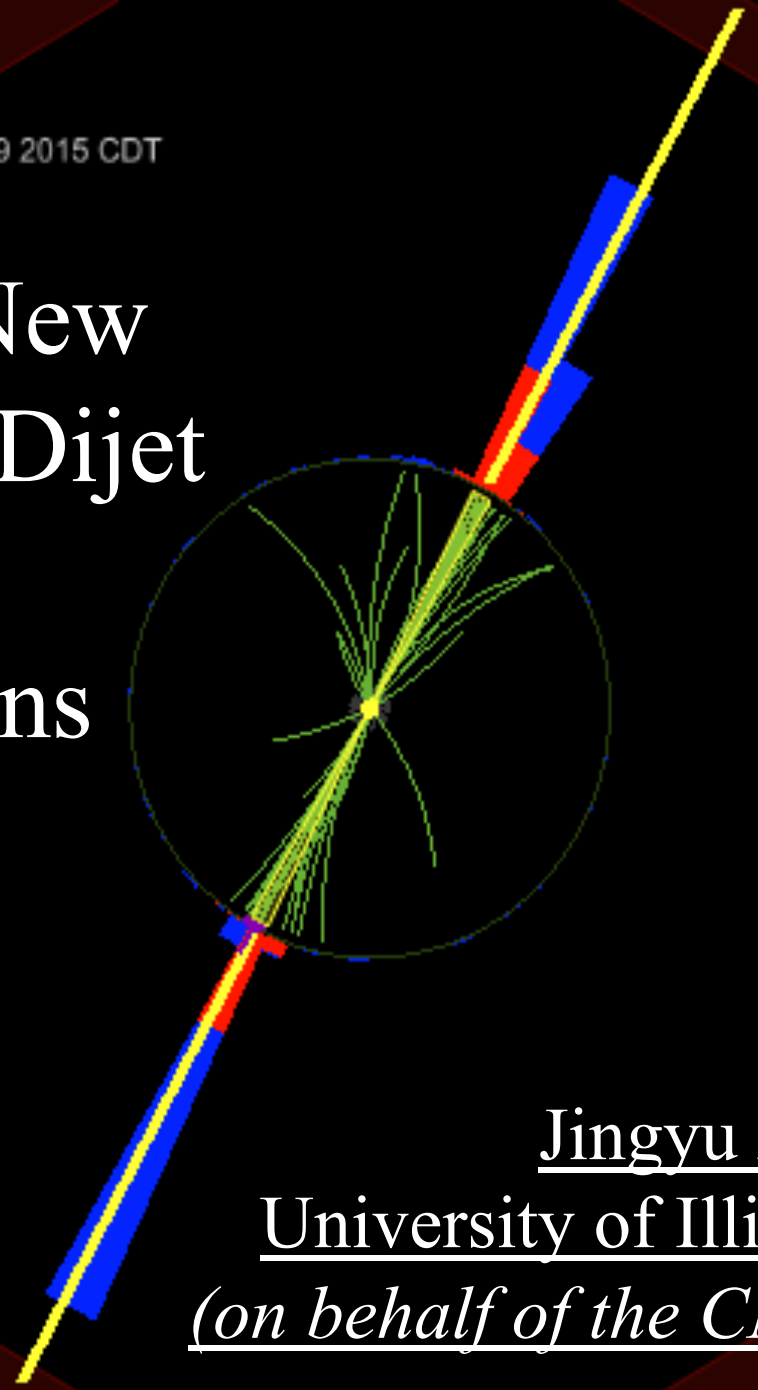
CMS Experiment at LHC, CERN
Data recorded: Sat Oct 31 01:41:49 2015 CDT
Run/Event: 260431 / 46326258
Lumi section: 27

Search for New Physics with Dijet Angular Distributions



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

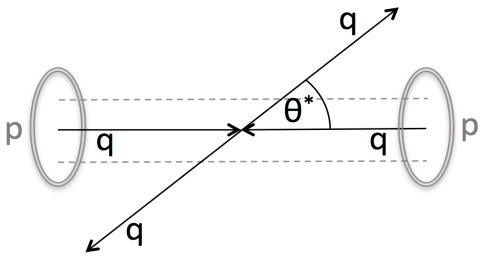
US LUA
LHCb
ATLAS
CMS
ALICE
US LHC Users Association

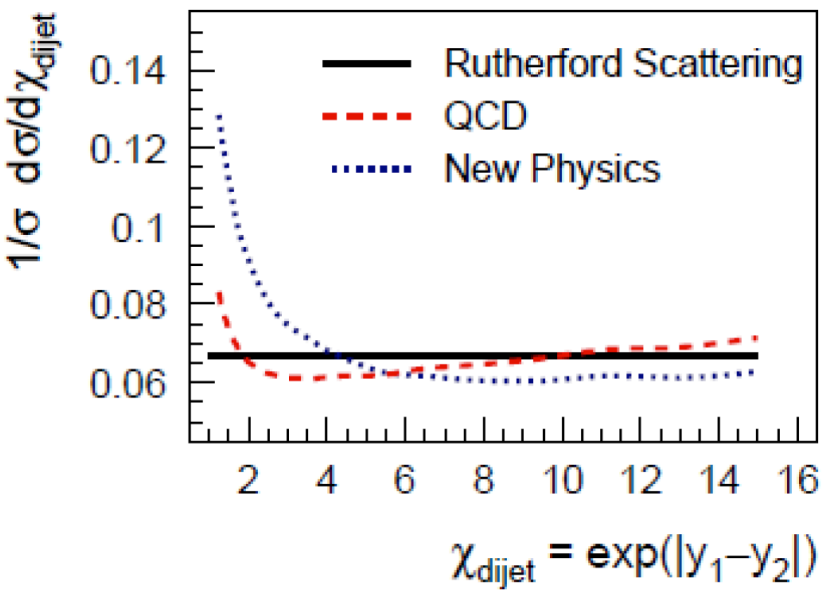
USLUA Annual Meeting
Fermilab, Batavia, IL
1-3 Nov. 2017

Dijet Angular Distributions

- Probe parton-parton scattering angle

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

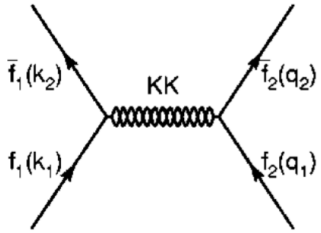


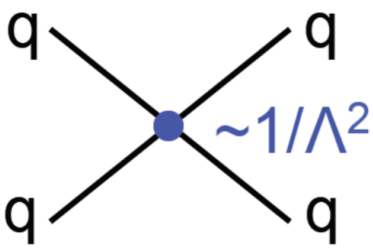


- New Physics will change the χ_{dijet} distribution at low χ_{dijet} at high M_{jj}

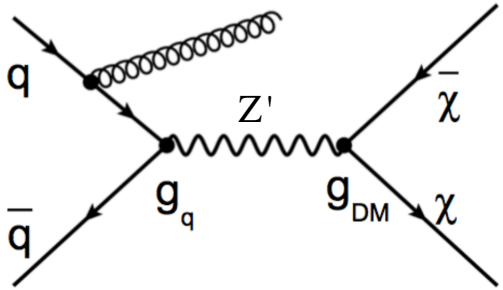
New Physics Models

- Quark Contact Interactions
  - 4 fermion contact interactions (CI) term
  - The quark compositeness
- Large Extra Spatial Dimension (ADD Model)
  - Proposed to solve the hierarchy problem
  - The plank scale in the 4+n dimensional space ~ TeV
  - Virtual Kaluza-Klein graviton exchange processes
- Quantum Black Holes
  - Two benchmark quantum black hole scenarios:
    ADD with $n_{ED} = 6$ and Randall-Sundrum (RS) with $n_{ED} = 1$
- Dark Matter Model
  - Dark mater particles interact with quarks via a spin-1 mediator
  - 4 parameters in the model:
    mediator mass (M_{Med}), dark matter mass (m_{DM}),
    quark coupling (g_q), and dark matter coupling (g_{DM})
  - Search for Dark Matter mediator

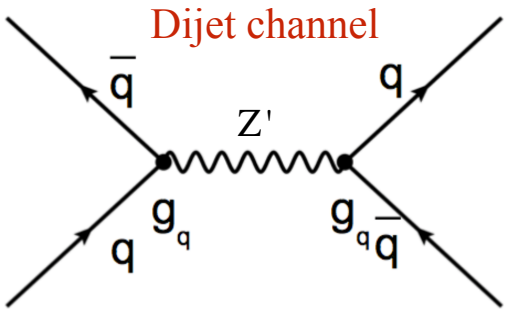




Mono-X channel



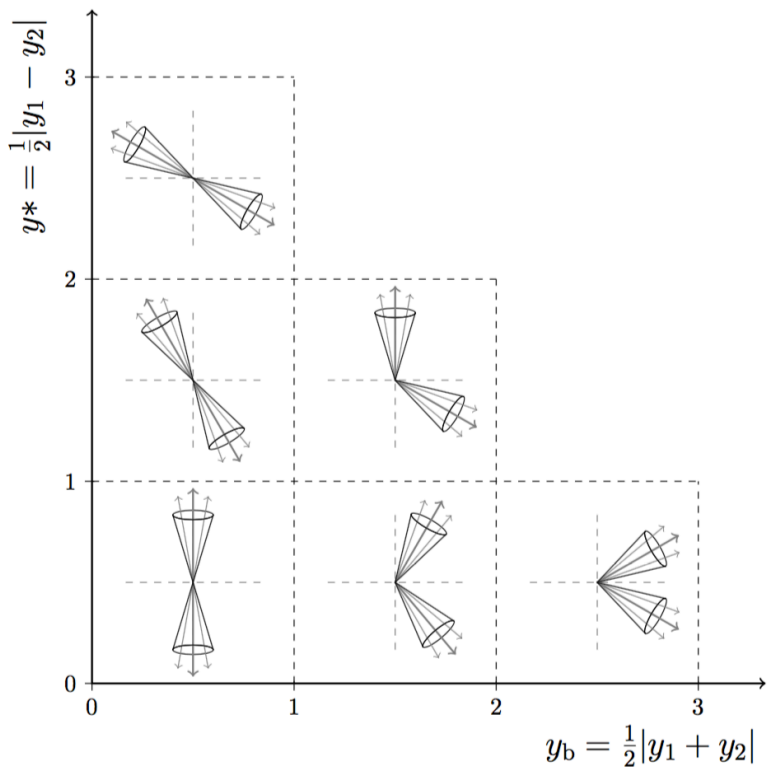
Dijet channel



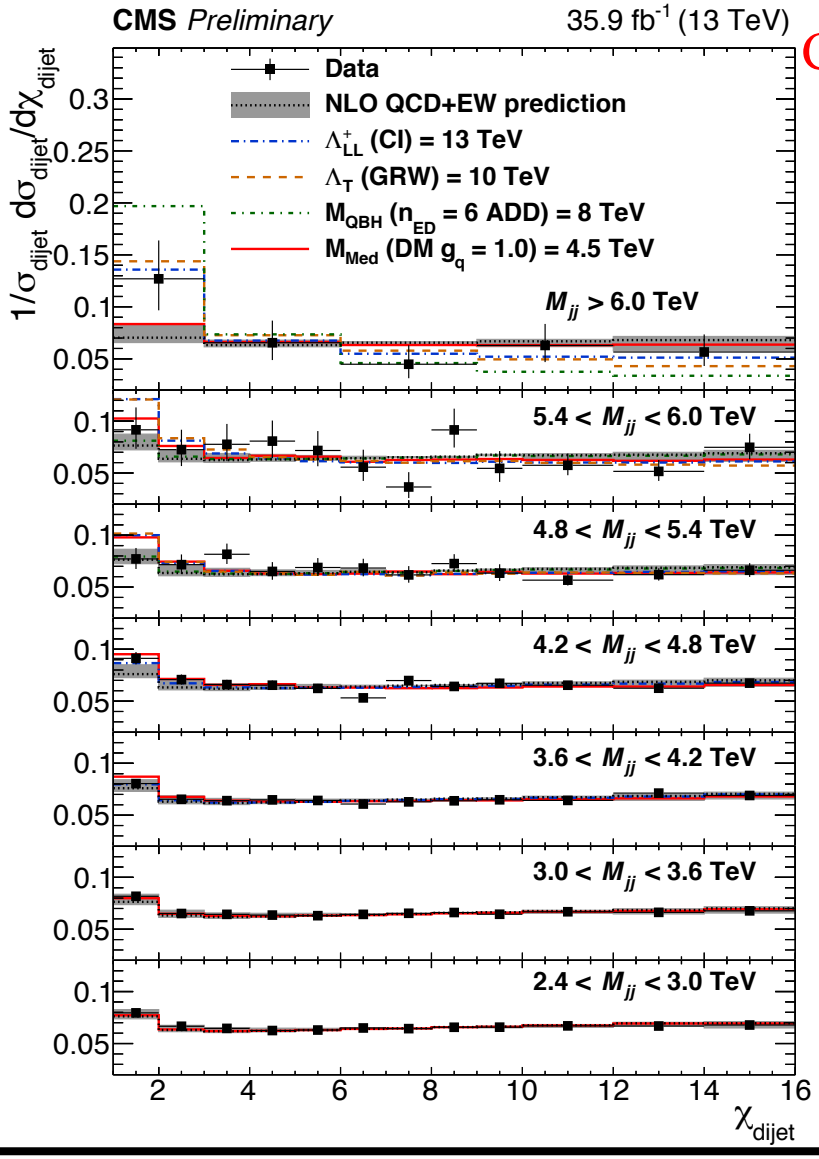
Data Analysis

- Event Selection
  - At least two AK4 jets with $p_T > 30$ GeV
  - $y_{boost} = \frac{1}{2}(y_1 + y_2) < 1.11 \quad y^* = \frac{1}{2}|y_1 - y_2| < 1.39$
  - $y < |2.5| \quad 1 < \chi_{dijet} < 16$

- Data are unfolded to particle level
  - Correct effect of event migrations between M_{jj} and χ_{dijet} bins due to finite jet p_T resolution
  - Data will be compared to theoretical predictions at **<u>particle level</u>**



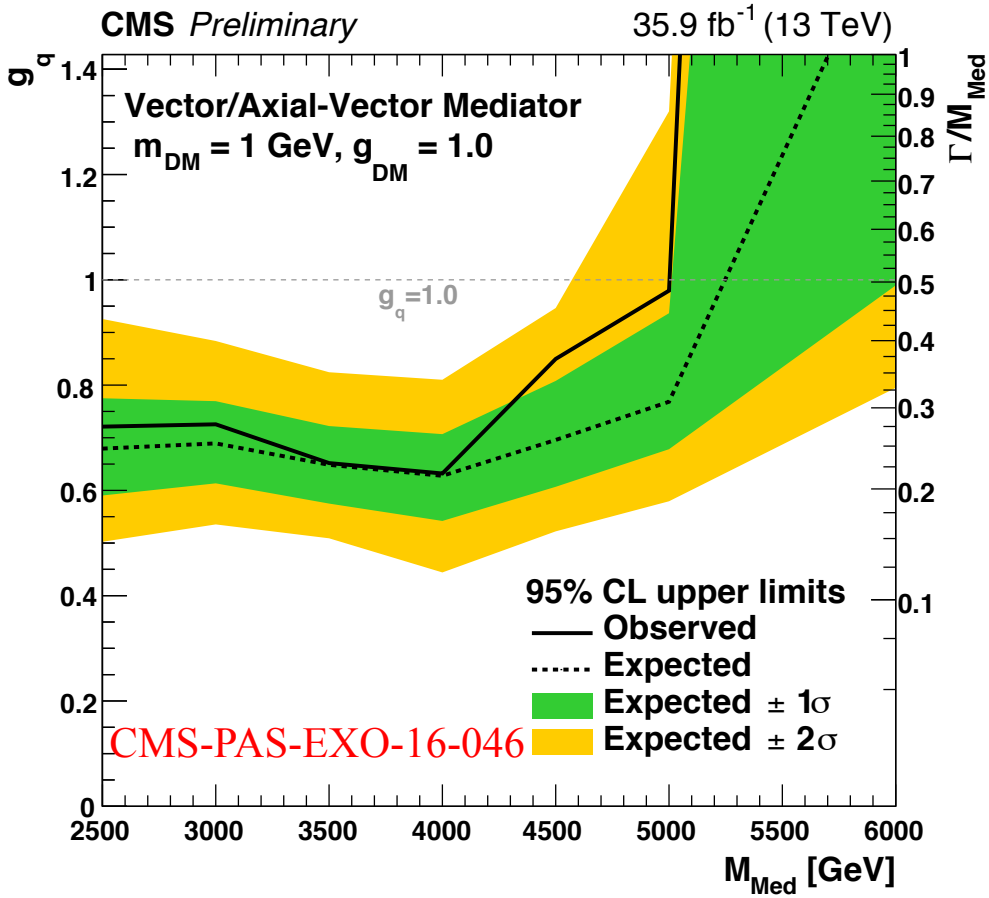
Results



CMS-PAS-EXO-16-046

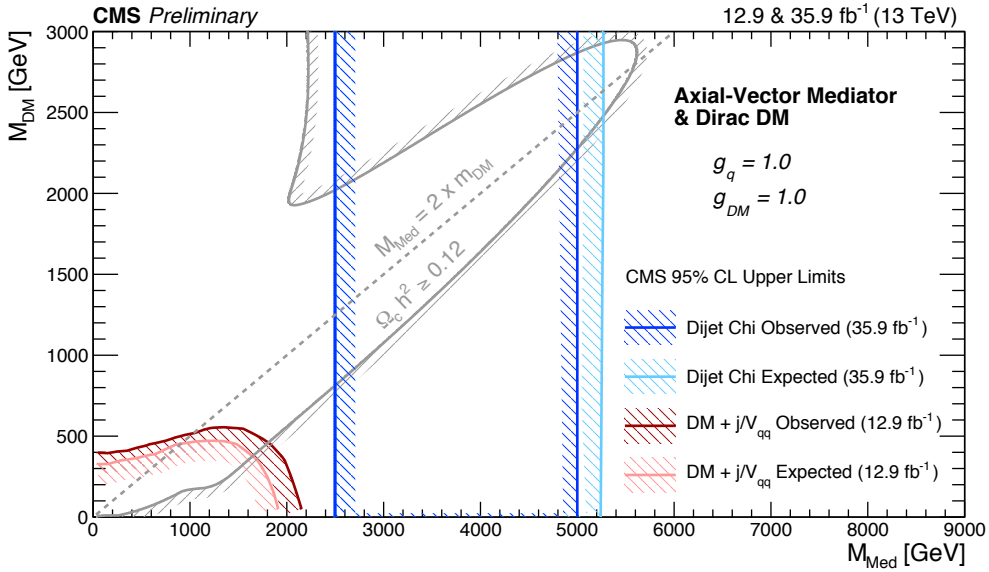
- Measured distributions are in agreement compare with QCD+EWK predictions
  - Largest upward fluctuations are found to be in the highest and 4th highest mass bin with ~2.0 sigma significance
- Observed (expected) limits for New Physics Models
  - Contact interactions
    - $\Lambda+$: 13.1 (15.2) TeV
    - $\Lambda-$: 14.7 (17.3) TeV
  - KK graviton exchange scale:
    - Λ_T : 10.6 (12.1) TeV
  - Minimum quantum black hole masses:
    - ADD QBH: 8.3 (8.7) TeV
    - RS QBH: 6.0 (6.5) TeV

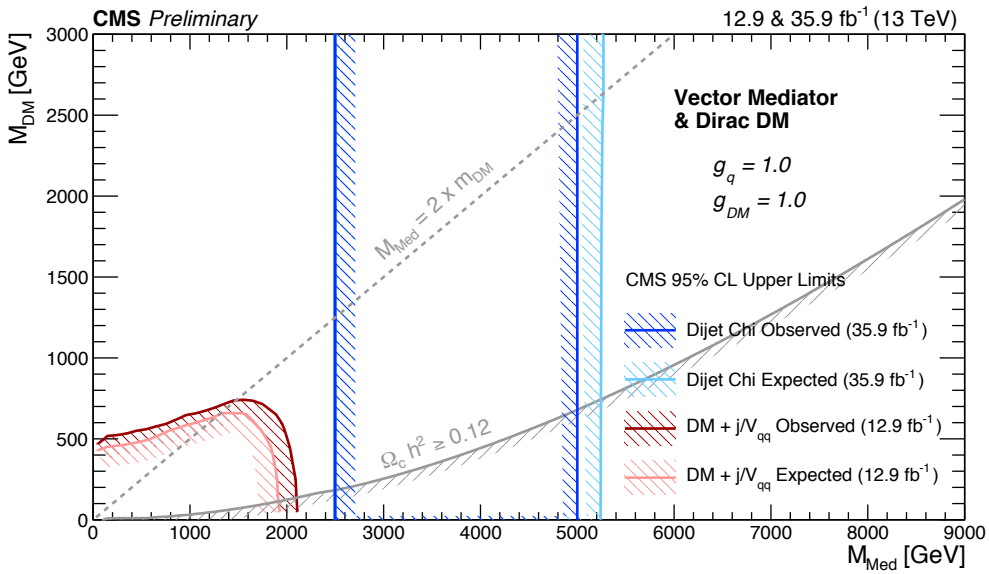
Dark Matter Interpretation



- The >1 sigma access for M_{Med}>4.5 TeV is due to the upward fluctuation in 4.2-4.8 and 6.0-13.0 TeV mass bins in the measured distributions

Dark Matter Interpretation

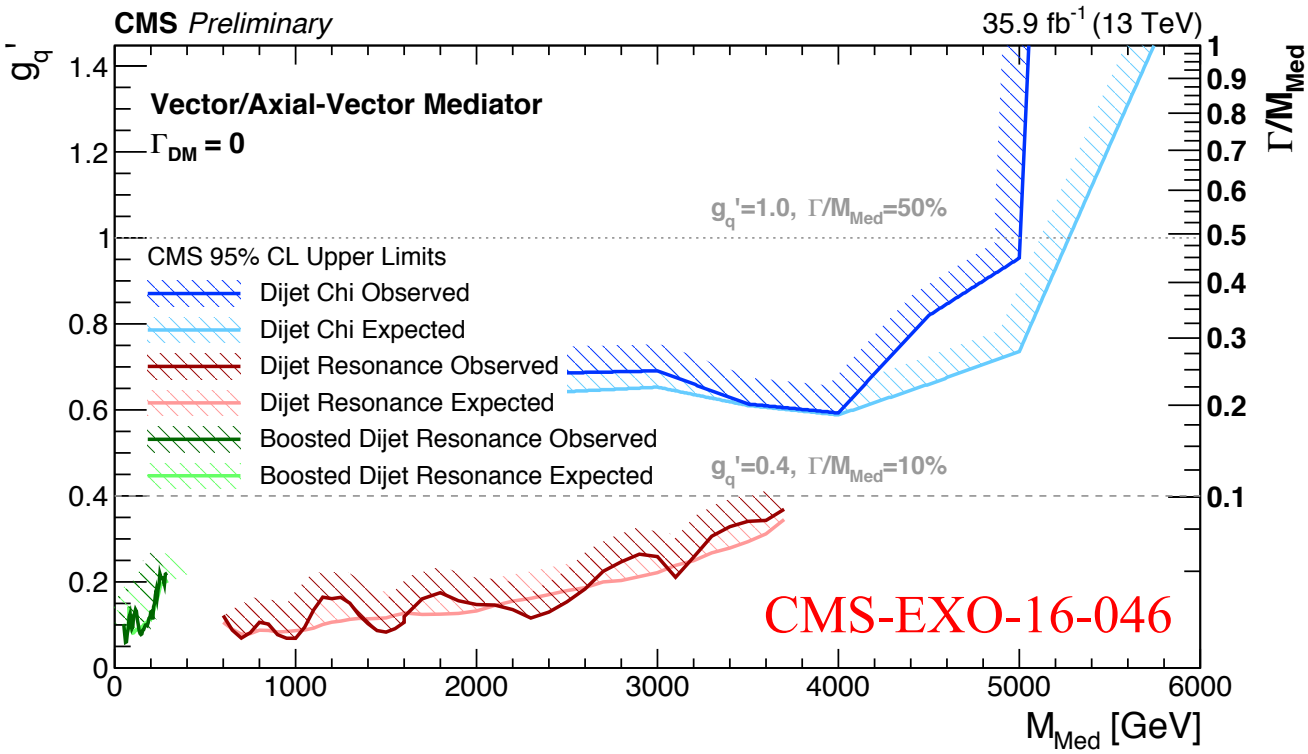




- Limits for m_{DM} vs M_{Med}
  - For g_q=1.0 and g_{DM}=1.0, quark decay dominate such that m_{DM} has little dependence on M_{Med}
- Limits are compared to constraints from the cosmological relic density of DM
- Also compared to the limits from monojet search with 12.9 fb^{-1} (CMS-EXO-16-037)
- This analysis extend the current CMS limits for g_q=1.0 and g_{DM} =1.0

CMS-EXO-16-046

Dark Matter Interpretation



- Limits for the DM mediator that only decays to quarks ($2m_{DM} > M_{Med}$) obtained from CMS dijet searches:
  - Boosted dijet resonance search (EXO-17-001)
  - Dijet narrow resonance search (EXO-16-056)
  - Dijet angular analysis (EXO-16-046)
- The sensitivity for dijet resonance searches fade away above $g_q' = 0.4$
- Dijet chi analysis is sensitive to large value of quark couplings and mediator widths

Conclusions

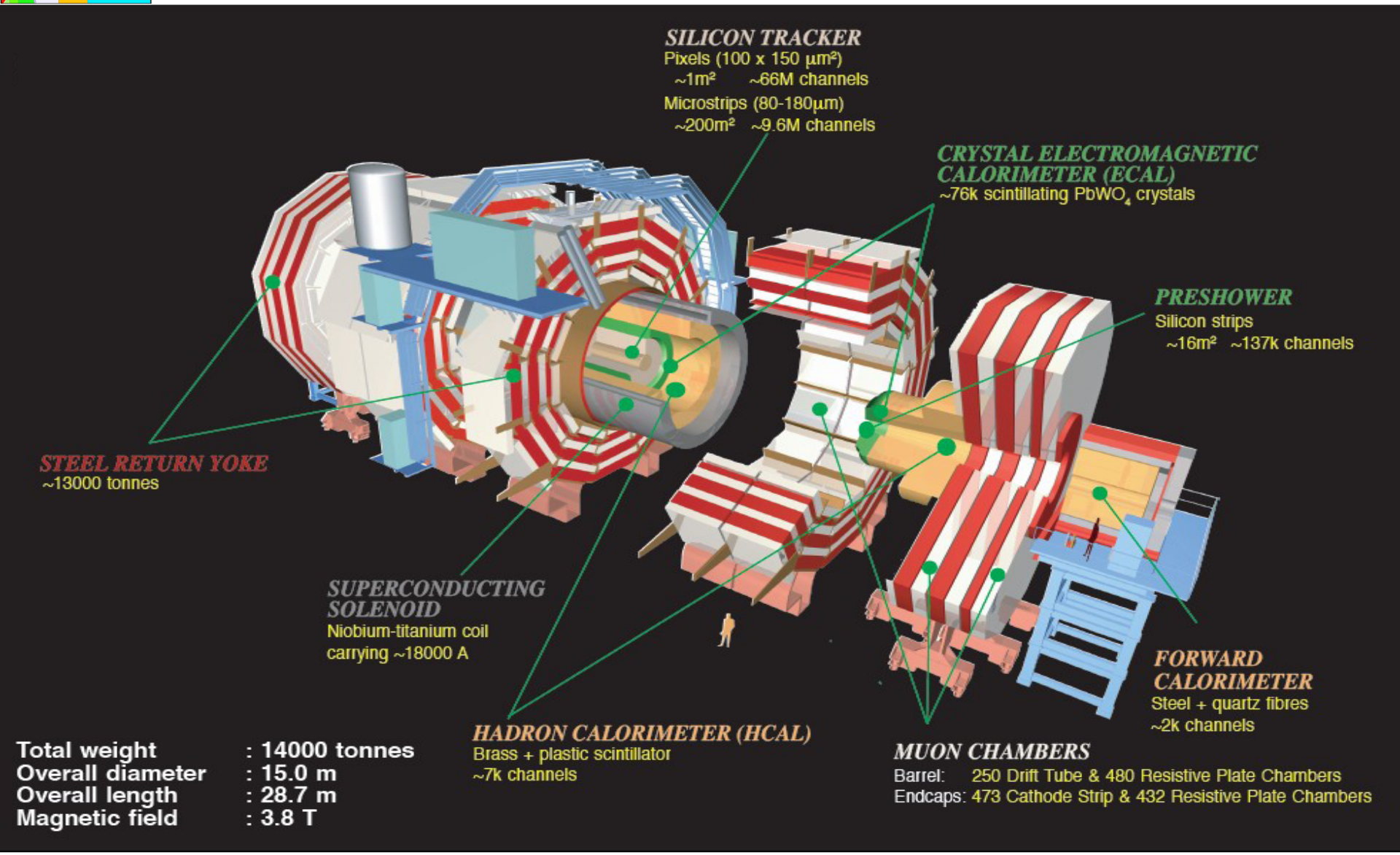
- Dijet angular distributions unfolded to particle level are measured using 35.9 fb^{-1}
  - Results are in good agreement with QCD+EW predictions

- Limits for New Physics models are extracted
  - Limits on CI, ADD, and QBH models:
    - $\Lambda_{LL}+$: 13.1 TeV
    - $\Lambda_{LL}-$: 17.4 TeV
    - ADD Λ_T : 10.6 TeV
    - ADD n_{ED}=6 M_{QBH}: 8.3 TeV
    - M_{Med} (g_q=1.0 and g_{DM}=1.0): 2.0-5.0 TeV

- Documentation: CMS-EXO-16-046

Back Up

The CMS Detector



Run 1 Results

4.2 TeV

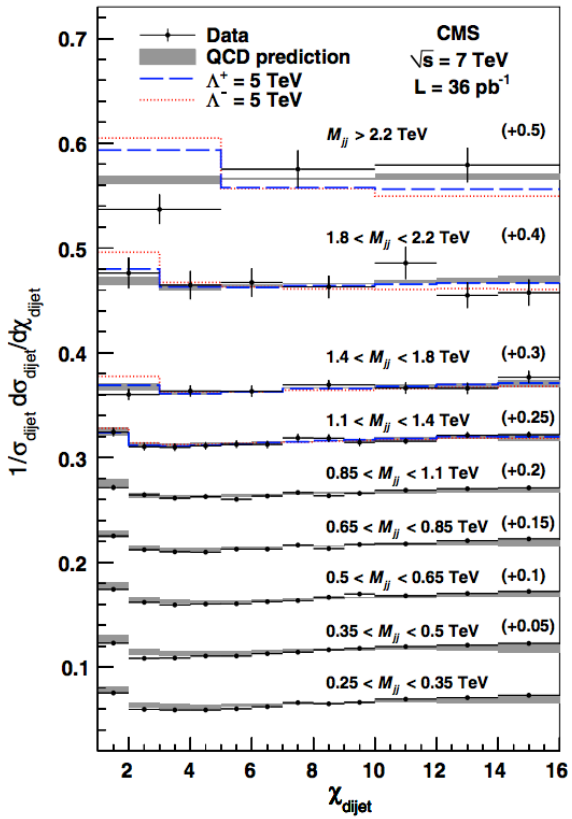
M_{jj}

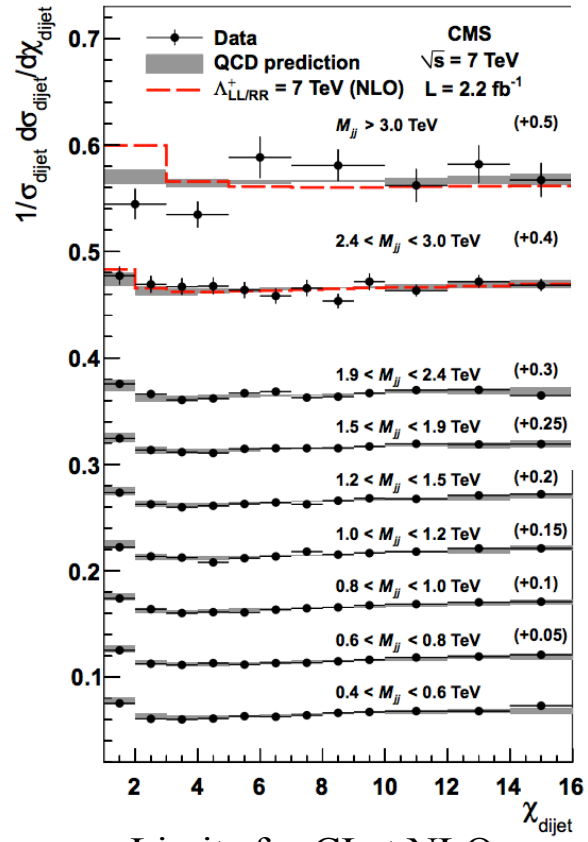
0.25 TeV

Limits on CI for at LO

PhysRevLett.106(2011)201804

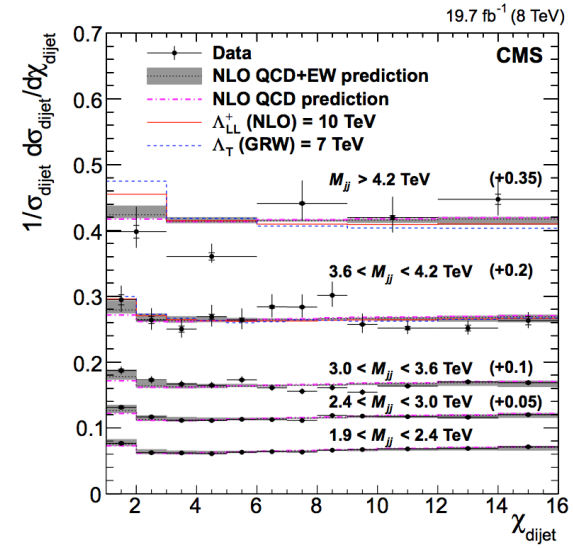
- Λ+: 5.6 TeV
- Λ-: 6.7 TeV





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

- Λ+: 7.5 TeV
- Λ-: 10.5 TeV



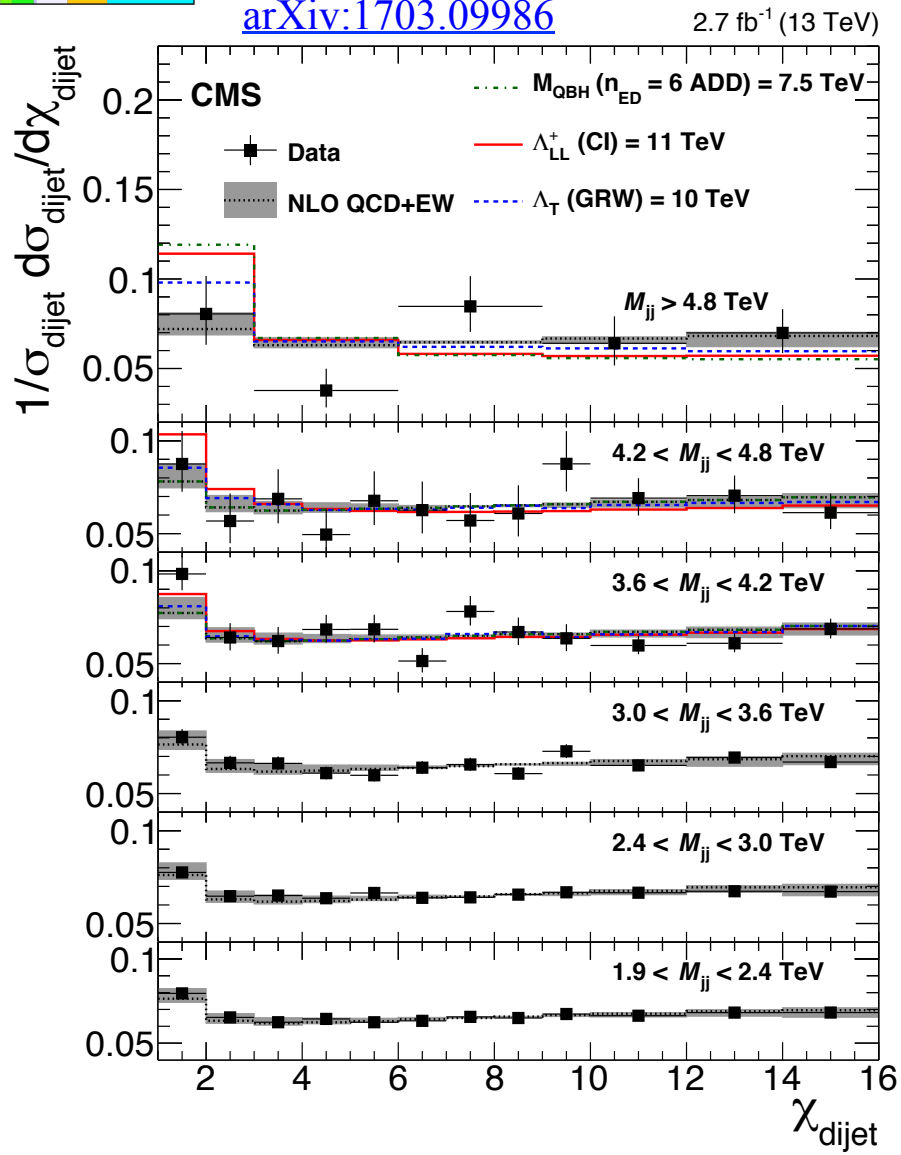
Limits on CI at NLO and ADD

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)

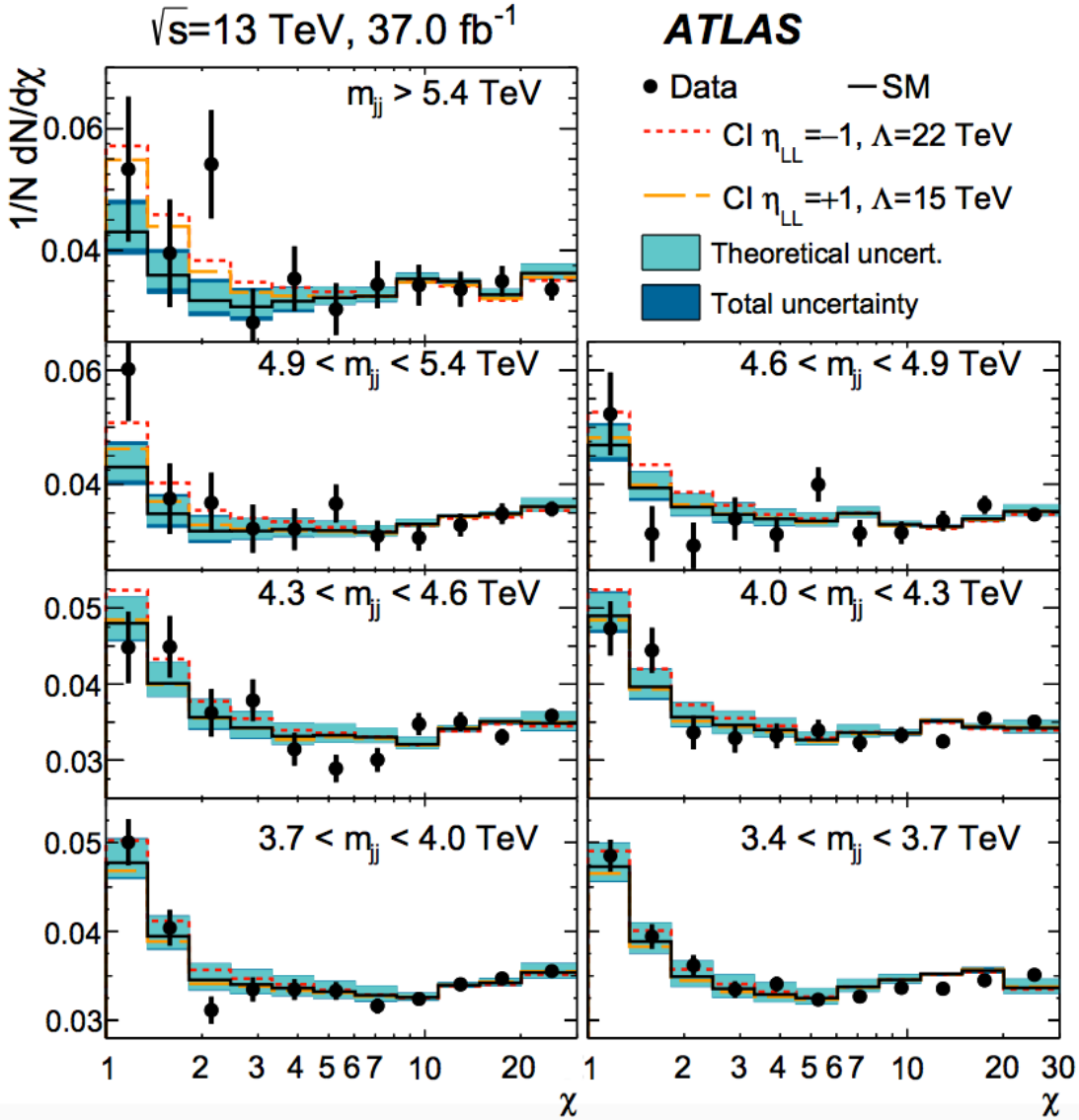
Previous Results

arXiv:1703.09986



- **Accepted by** JHEP (arXiv:1703.09986)
- Observed (expected) limits for Contact Interactions, Extra Dimensions, and Quantum Black Holes
  - Contact Interactions
    - Λ+ (NLO): 11.5 (12.1) TeV
    - Λ- (NLO): 17.4 (23.9) TeV
  - Extra Dimensions
    - Λ_T (GRW): 9.4 (9.8) TeV
  - Quantum Black Holes
    - ADD QBH: 7.8 (7.7) TeV
    - RS QBH: 5.3 (5.3) TeV
- Analysis extended to higher M_{jj} using **35.9 fb^{-1}** of data

ATLAS 13 TeV Results



- https://arxiv.org/abs/1703.09127
- **Expected** limits set for Contact Interactions
  - Sensitivity on CI
    - Λ+ : 15.0 TeV
    - Λ- : 28.3 TeV

Theoretical Predictions

- 13 TeV AK4 NLO QCD calculation with EWK correction
  - QCD scale uncertainty from 6 variations of μ_r and μ_f
  - PDF uncertainty from CT14 PDF set
  - EWK correction is 5% in highest mass bin

- CI predictions are calculated at LO and include QCD corrections at NLO
  - Scale and PDF uncertainties from CI have been taken into account and combined with those from NLO QCD

- Leading order ADD + leading order ADD and QCD interference predictions in GWR from Pythia8

- Quantum Black Hole production predictions from QBH generator version 3.0

- Dark Matter predictions from MadGraph
  - Samples with different M_{Med} and g_q are generated with fixed values of M_{DM} = 1 GeV and g_{DM}=1.0

Summary of Systematic Uncertainties

CMS-PAS-EXO-16-046

Source of uncertainty	$2.4 < M_{jj} < 3.0$ TeV	$M_{jj} > 6.0$ TeV
Statistical	0.7%	27%
Jet energy scale	3.6%	9.2%
Jet energy resolution (core)	1.0%	1.0%
Jet energy resolution (tails)	1.0%	1.5%
Unfolding, modelling	0.2%	1.5%
Unfolding, detector simulation	0.5%	1.0%
Pileup	<1%	<1%
Total experimental	4.1%	29%
QCD NLO scale (6 changes in μ_R and μ_F)	$^{+8.5\%}_{-3.0\%}$	$^{+19\%}_{-5.8\%}$
PDF (CT14 eigenvectors)	0.2%	0.6%
Non-perturbative effects	<1%	<1%
Total theoretical	8.5%	19%

- Experimental uncertainty dominated by statistical uncertainty
- Theoretical uncertainty dominated by QCD scale uncertainty

Limits

CMS-PAS-EXO-16-046

Model	Observed lower limit (TeV)	Expected lower limit (TeV)
$\Lambda^{+}_{\mathrm{LL/RR}}$ (NLO)	13.1	15.2 ± 0.9
$\Lambda^{-}_{\mathrm{LL/RR}}$ (NLO)	17.4	23.9 ± 3.0
$\Lambda^{+}_{\mathrm{VV}}$ (NLO)	15.1	17.3 ± 1.0
$\Lambda^{-}_{\mathrm{VV}}$ (NLO)	22.2	31.2 ± 3.8
$\Lambda^{+}_{\mathrm{AA}}$ (NLO)	15.2	17.3 ± 1.0
$\Lambda^{-}_{\mathrm{AA}}$ (NLO)	22.1	31.0 ± 3.8
$\Lambda^{+}_{(\mathrm{V-A})}$ (NLO)	9.1	11.7 ± 1.0
$\Lambda^{-}_{(\mathrm{V-A})}$ (NLO)	9.3	11.9 ± 1.1
ADD Λ_{T} (GRW)	10.6	12.1 ± 0.9
ADD M_{S} (HLZ) $n_{ED} = 2$	11.4	13.3 ± 1.0
ADD M_{S} (HLZ) $n_{ED} = 3$	12.6	14.4 ± 1.1
ADD M_{S} (HLZ) $n_{ED} = 4$	10.6	12.1 ± 0.9
ADD M_{S} (HLZ) $n_{ED} = 5$	9.6	10.9 ± 0.8
ADD M_{S} (HLZ) $n_{ED} = 6$	8.9	10.2 ± 0.8
QBH M_{QBH} (ADD $n_{ED} = 6$)	8.3	8.7 ± 0.3
QBH M_{QBH} (RS $n_{ED} = 1$)	6.0	6.5 ± 0.4
DM Vector/Axial-Vector M_{Med}	2.5–5.0	2.5–5.2

- The asymptotic LHC-style CLs method is used for limit calculation
- Observed limits smaller than expected due to upward fluctuation in the measured distributions