CMS Experiment at LHC, CERN
Data recorded: Sat Oct 31 01:41:49 2015 CDT
Run/Event: 260431 / 46326258
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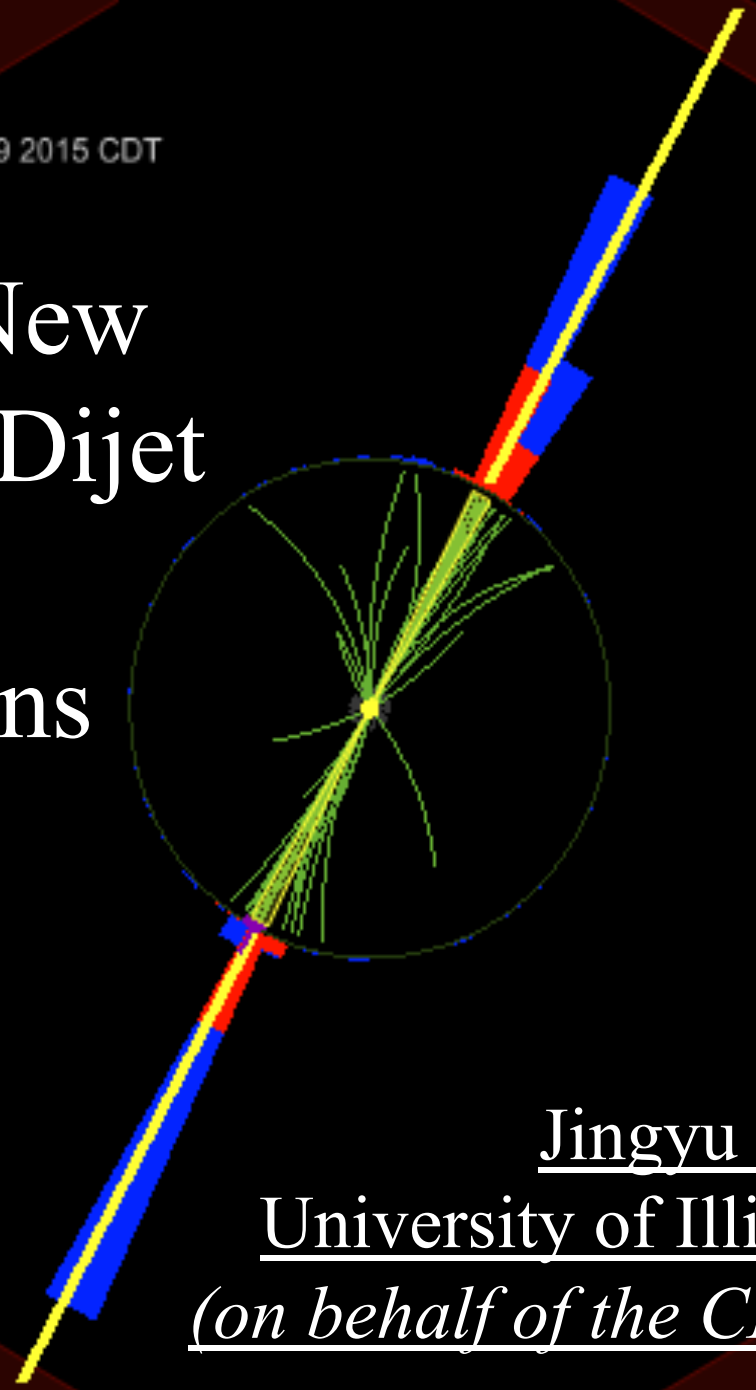
Search for New Physics with Dijet Angular Distributions



APS DIVISION OF PARTICLES & FIELDS
DPF 2017
MEETING OF THE AMERICAN PHYSICAL SOCIETY DIVISION OF PARTICLES AND FIELDS

DPF 2017
Fermilab, Batavia, IL
31 July- 4 August 2017

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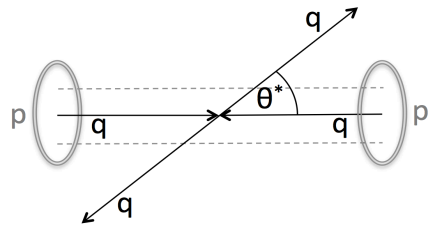
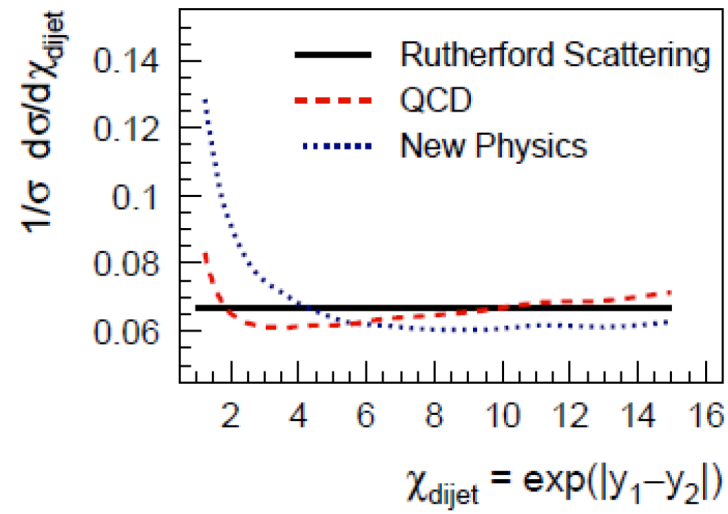
(on behalf of the CMS collaboration)

Dijet Angular Distributions

- Probe parton-parton scattering angle

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

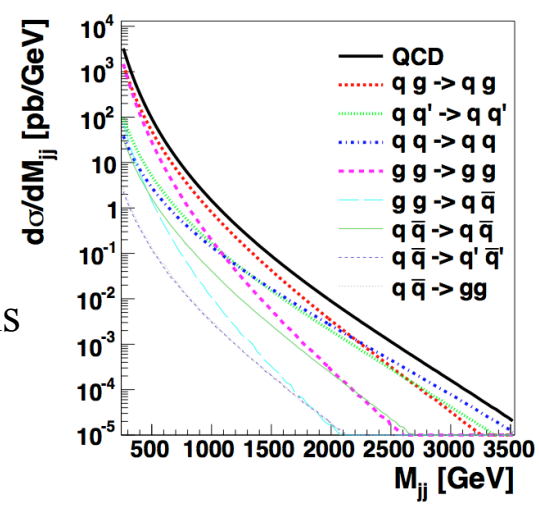


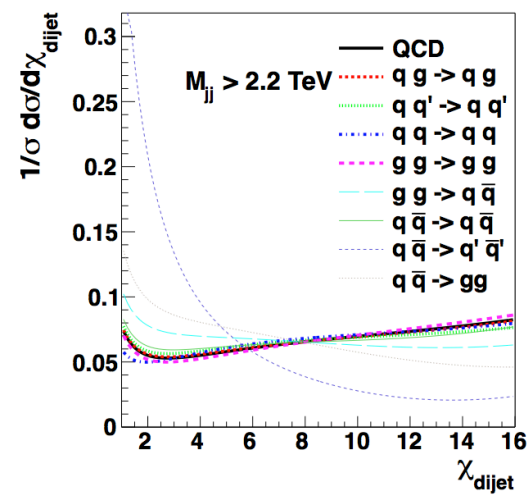


- New Physics will change the χ_{dijet} distribution at low χ_{dijet} at high M_{jj}

- χ_{dijet} is relatively flat for Leading QCD process (qg->qg, qq'->qq',gg->gg)
  - Small sensitivity to PDF uncertainties

- Observable: $1/\sigma d\sigma / d\chi_{dijets}$
  - Measure normalized distributions in bins of dijet mass
  - Reduced sensitivity to detector effects





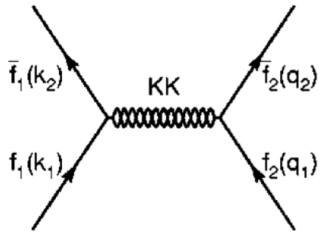
New Physics Models

- Quark Contact Interactions
  - 4 fermion contact interactions (CI) terms:

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

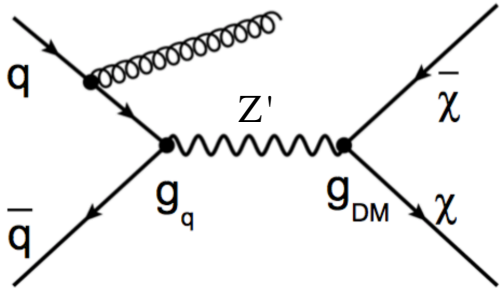
Λ	$(\eta_{LL}, \eta_{RR}, \eta_{RL})$
$\Lambda^{\pm}_{LL}$	$(\pm1, 0, 0)$
$\Lambda^{\pm}_{RR}$	$(0, \pm1, 0)$
$\Lambda^{\pm}_{VV}$	$(\pm1, \pm1, \pm1)$
$\Lambda^{\pm}_{AA}$	$(\pm1, \pm1, \mp1)$
$\Lambda^{\pm}_{(V-A)}$	$(0, 0, \pm1)$

- Large Extra Spatial Dimension (ADD Model)
  - Proposed to solve the hierarchy problem
  - Virtual Kaluza-Klein graviton exchange processes
  - Two parameterizations: GRW (Giudice, Rattazzi, Wells) and HLZ (Han, Lykken, Zhang)

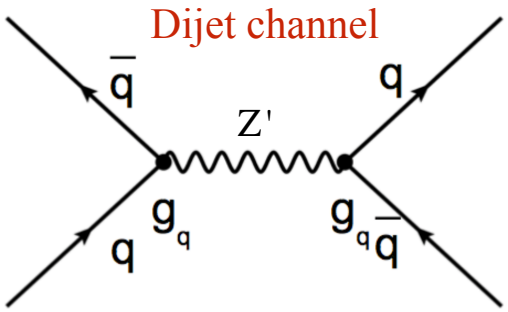


- Quantum Black Holes
  - Two benchmark quantum black hole scenarios: ADD with $n_{ED} = 6$ and RS with $n_{ED} = 1$
- Dark Matter Model
  - Dark mater particles interact with quarks via a spin-1 mediator
  - 4 parameters in the model: mediator mass (M_{Med}), dark matter mass (m_{DM}), quark coupling (g_q), and dark matter coupling (g_{DM})
  - Search for Dark Matter mediator

Mono-X channel

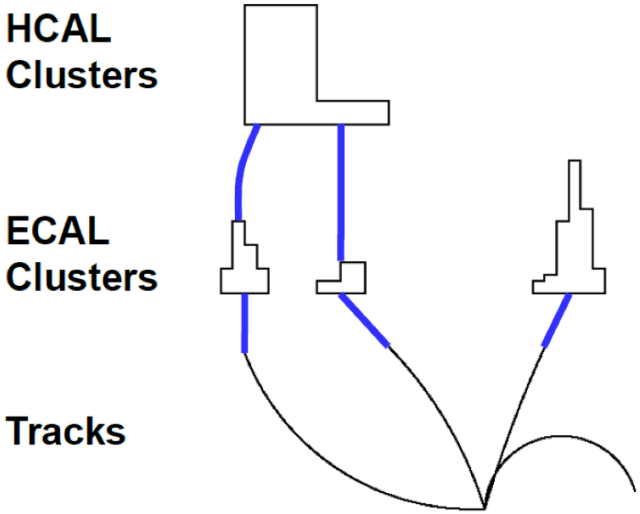


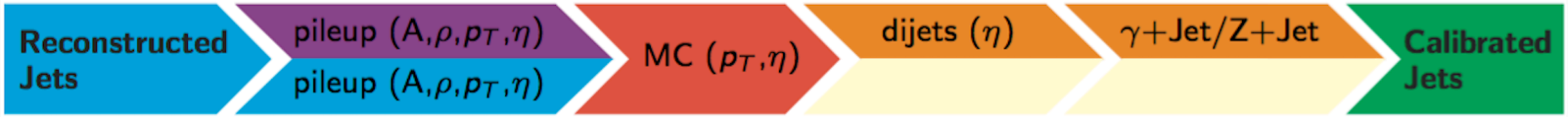
Dijet channel



Jet Reconstruction

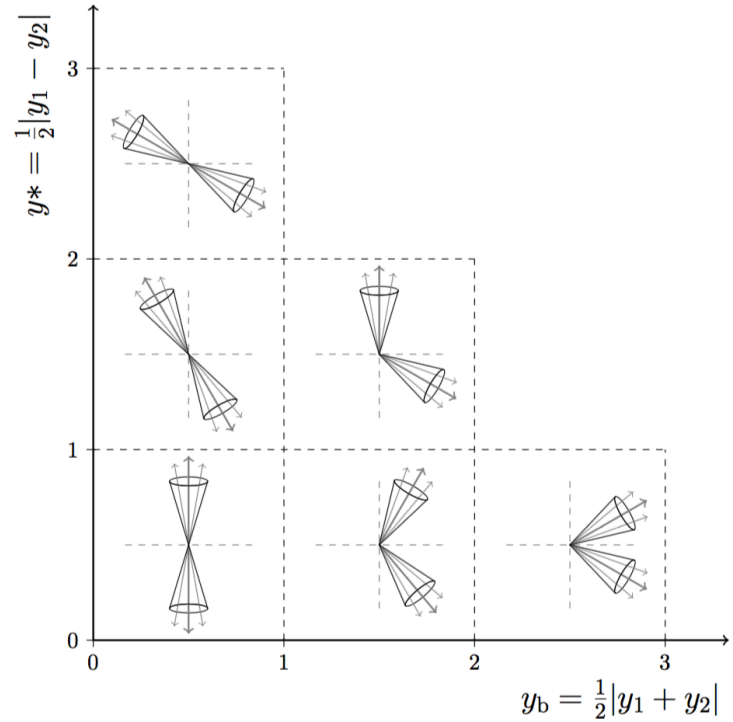
- Use "anti-k_T" clustering algorithm with jet size parameter R=0.4
- PF-jets are reconstructed and identified using particle flow technique, which utilizes an optimal combination of all information of CMS sub-detectors
- Jet energies are calibrated and corrected with a multilevel approach





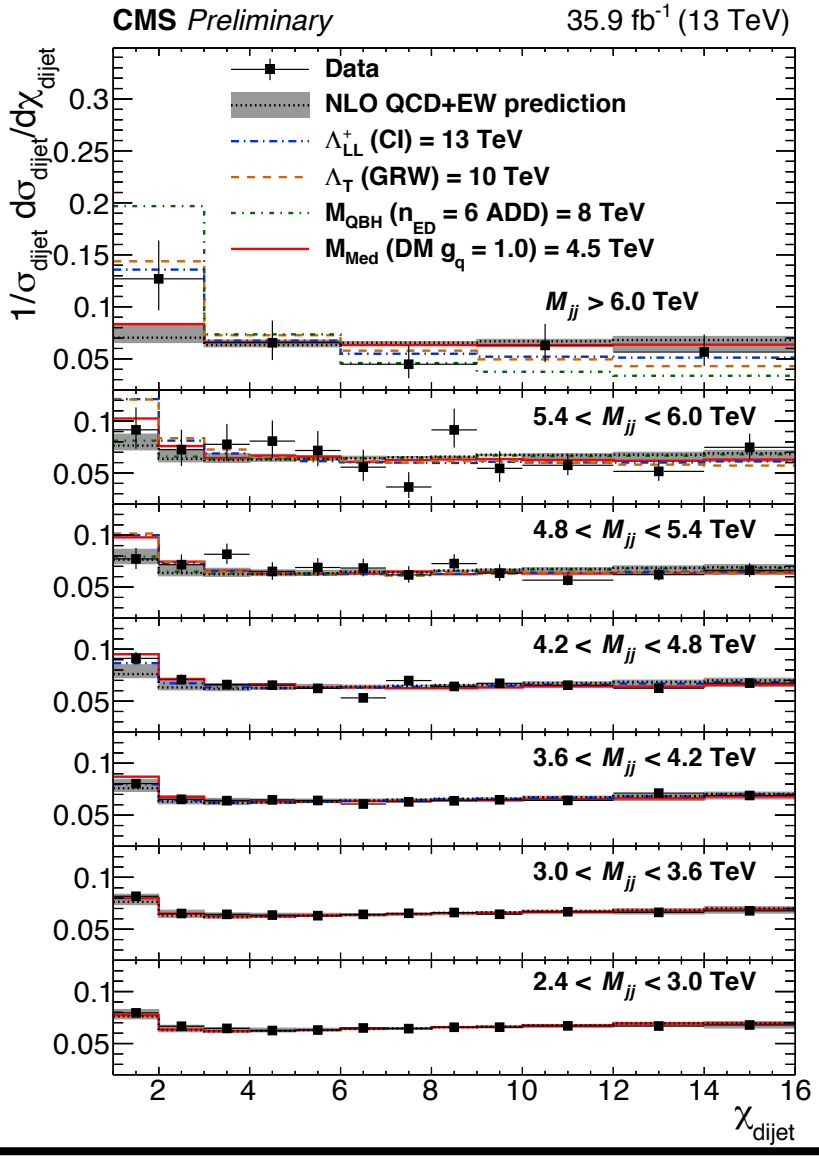
Data Analysis

- Online Selection
  - Single jet trigger with threshold at 450 GeV and HT trigger with threshold at 900 GeV
  - Fully efficient in the analysis phase space
- Offline Selection
  - Good primary vertex
  - Apply Jet ID requirements to remove fake jets
  - At least two jets with $p_T > 30$ GeV
  - Well understood calorimeter region: $y < |2.5|$
  - $y_{boost} = \frac{1}{2}(y_1 + y_2) < 1.11$, $y^* = \frac{1}{2}|y_1 - y_2| < 1.39$
  - $1 < \chi_{dijet} < 16$



- Data are unfolded to particle level using a 2D D'Agostini iterative method implemented in RooUnfold
  - 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 **particle level**

Results



CMS-PAS-EXO-16-046

- Dominant experimental uncertainties:
  - Statistical uncertainty: ~27% in the highest mass bin
  - Jet energy scale uncertainty: ~9% in the highest mass bin
- Dominant theoretical uncertainty:
  - QCD scale uncertainty: ~19% in the highest mass bin
- 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
  - Significance estimated using CI model in the log-likelihood

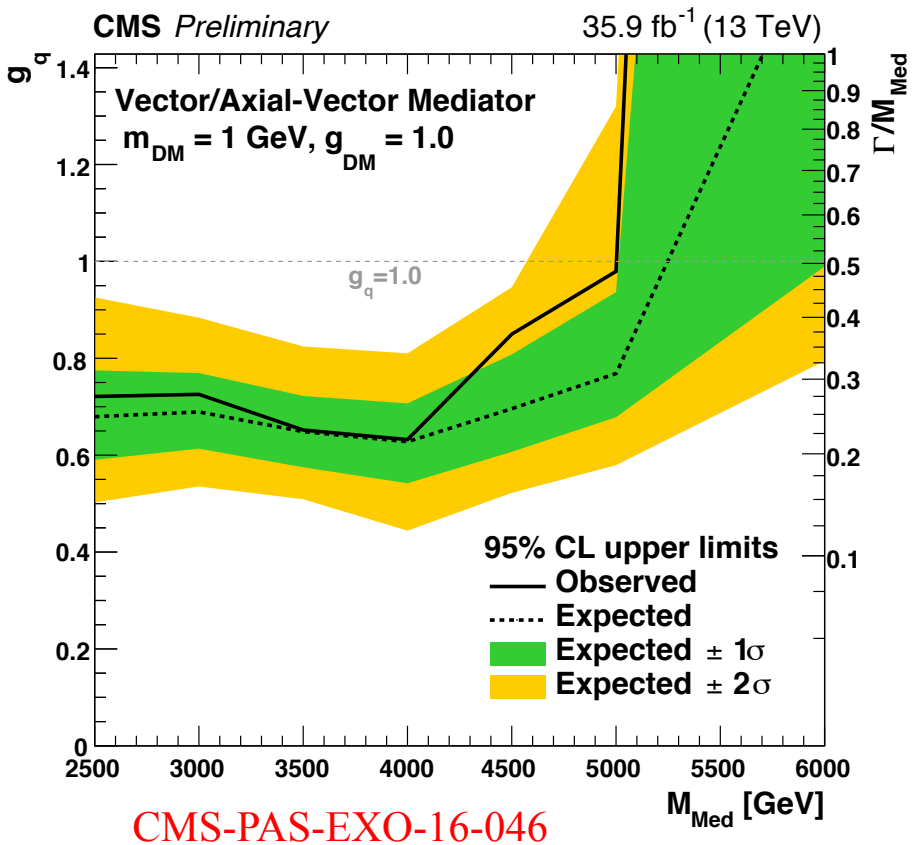
Limits

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

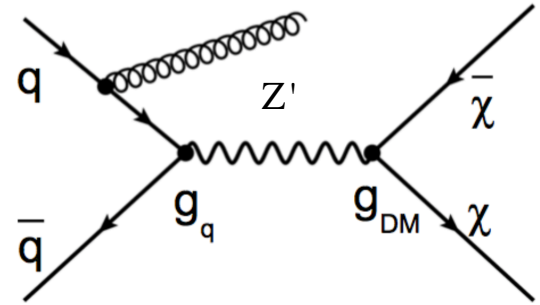
Dark Matter Interpretation



CMS-PAS-EXO-16-046

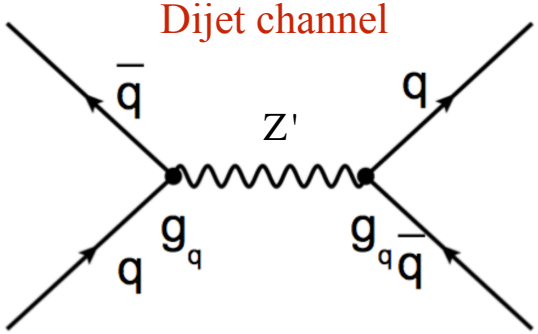
- The >1 sigma access for M_{Med}>4.5 TeV is due to the upward fluctuation in 4.2-4.8 and 6.0-13.0 TeV mass bins in the measured distributions

Mono-X channel



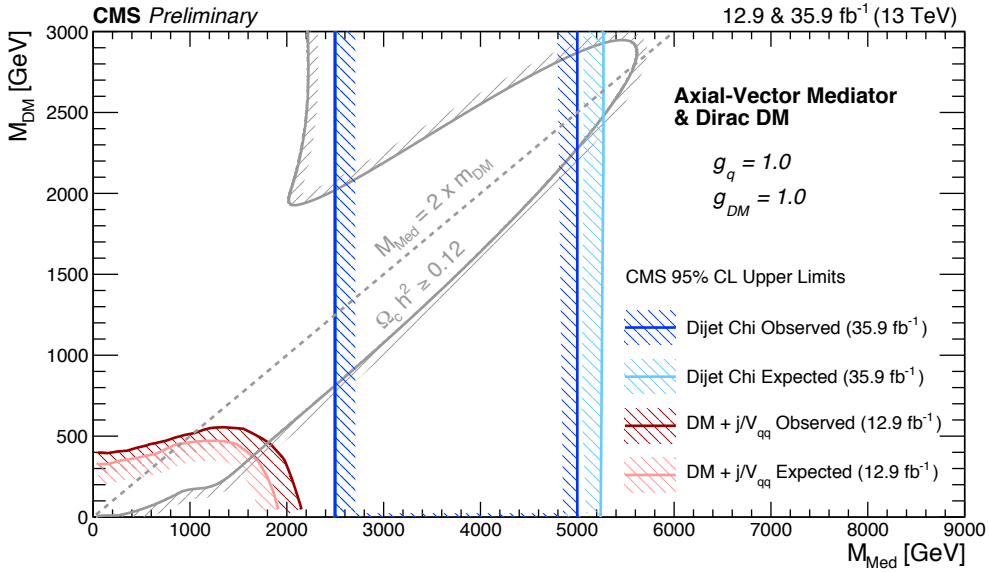
$$\Gamma^{\chi\bar{\chi}}_{\text{axial-vector}} = \frac{g^2_{DM} M_{Z'}}{12\pi}\left(1-4\frac{m^2_{DM}}{M^2_{Z'}}\right)^{3/2}$$

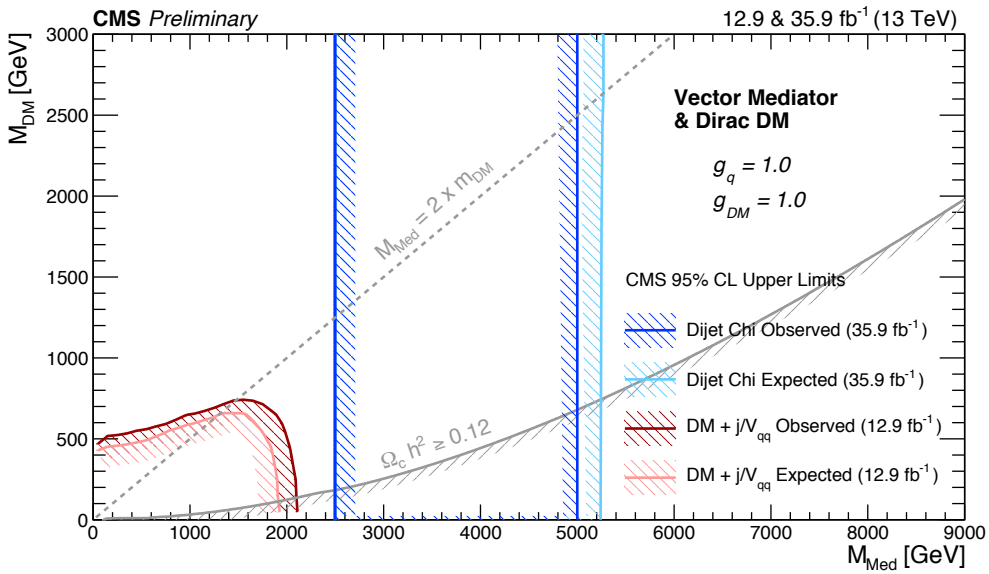
Dijet channel



$$\Gamma^{q\bar{q}}_{\text{axial-vector}} = \sum_{q=u,d,s,c,b,t} \frac{g^2_q M_{Z'}}{4\pi}\left(1-4\frac{m^2_q}{M^2_{Z'}}\right)^{3/2}$$

Dark Matter Interpretation

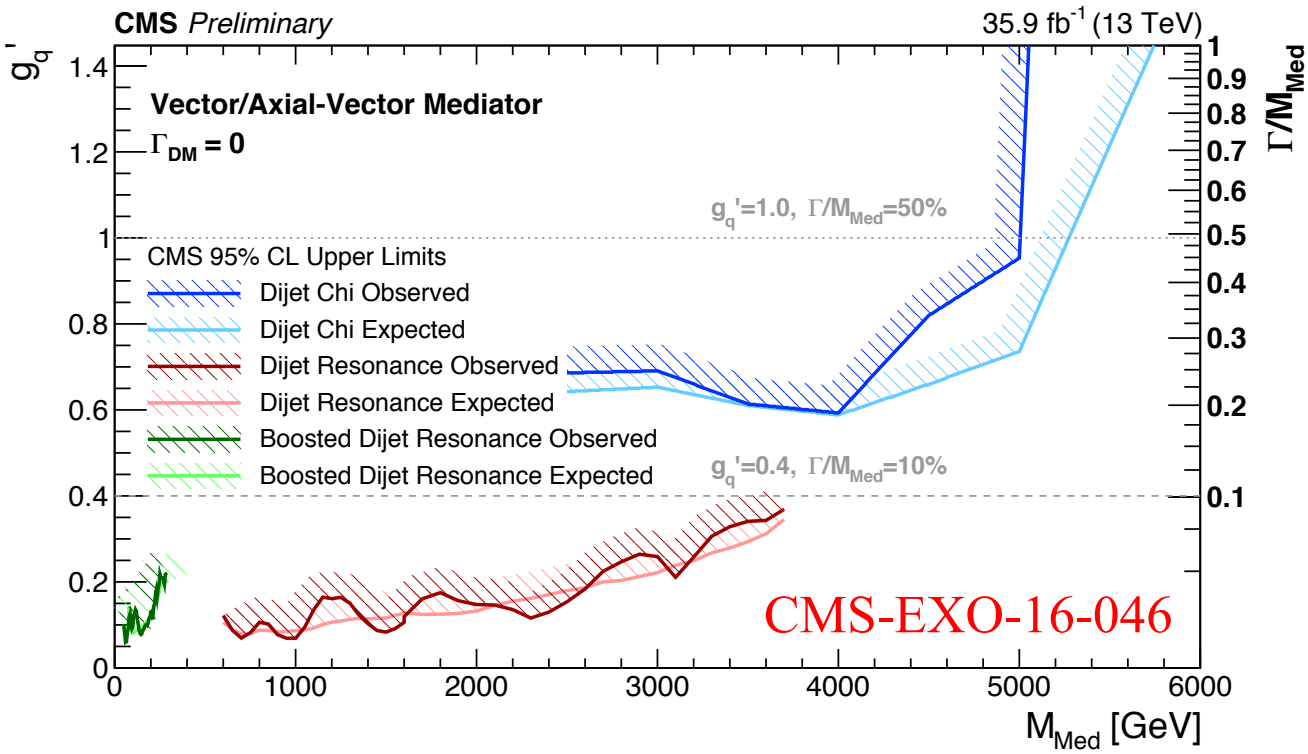




- Limits for m_{DM} vs M_{Med}
  - For g_q=1.0 and g_{DM}=1.0, quark decay dominate such that m_{DM} has little dependence on M_{Med}
- Limits are compared to constraints from the cosmological relic density of DM
- Also compared to the limits from monojet search with 12.9 fb^{-1} (CMS-EXO-16-037)
- This 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 fades away above $g_q' = 0.4$
- Dijet chi analysis is sensitive to large value of quark couplings and mediator widths

Conclusions

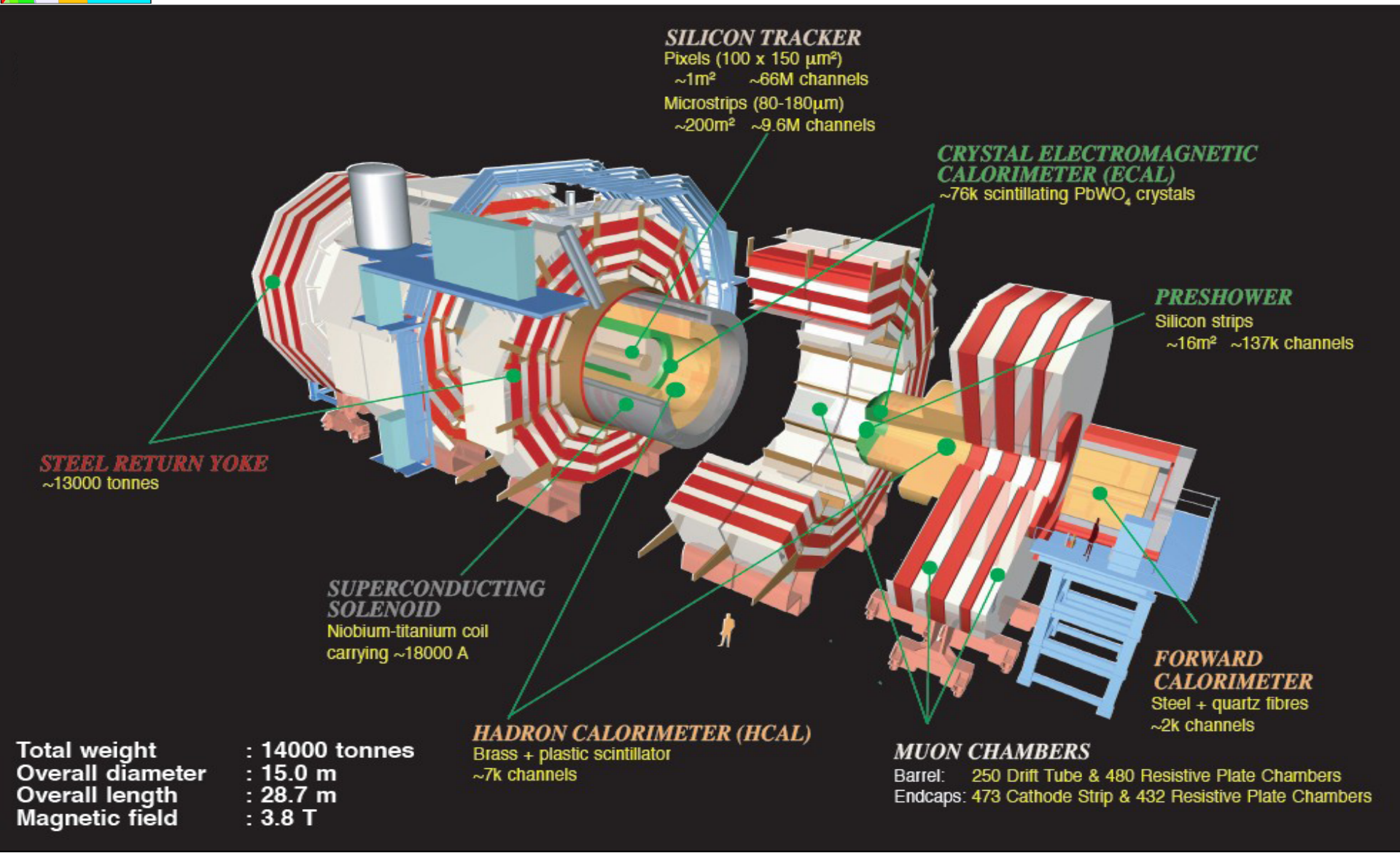
- Dijet angular distributions unfolded to particle level are measured using 35.9 fb^{-1}
  - Results are in good agreement with QCD+EW predictions

- Limits for New Physics models are extracted
  - Limits on CI, ADD, and QBH models:
    - Λ_{LL}+ (NLO): 13.1 TeV
    - Λ_{LL}- (NLO): 17.4 TeV
    - ADD Λ_T (GRW): 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

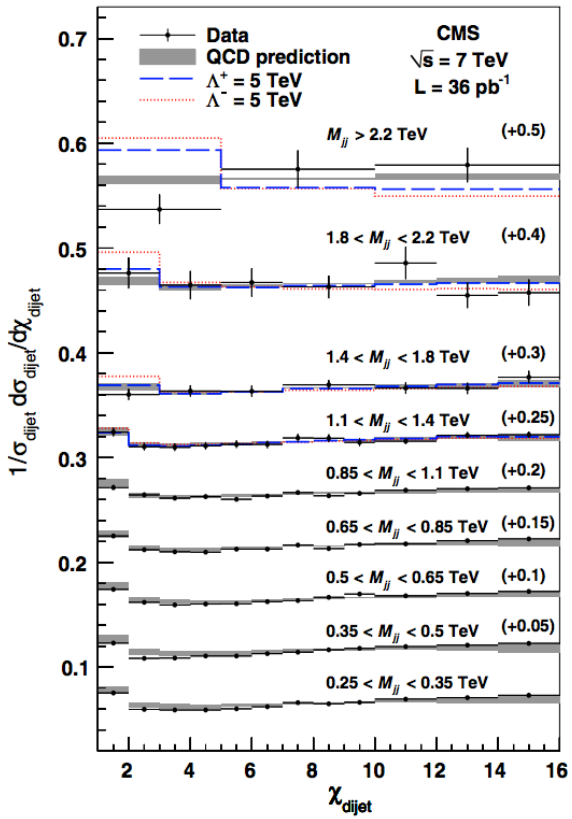
M_{jj}

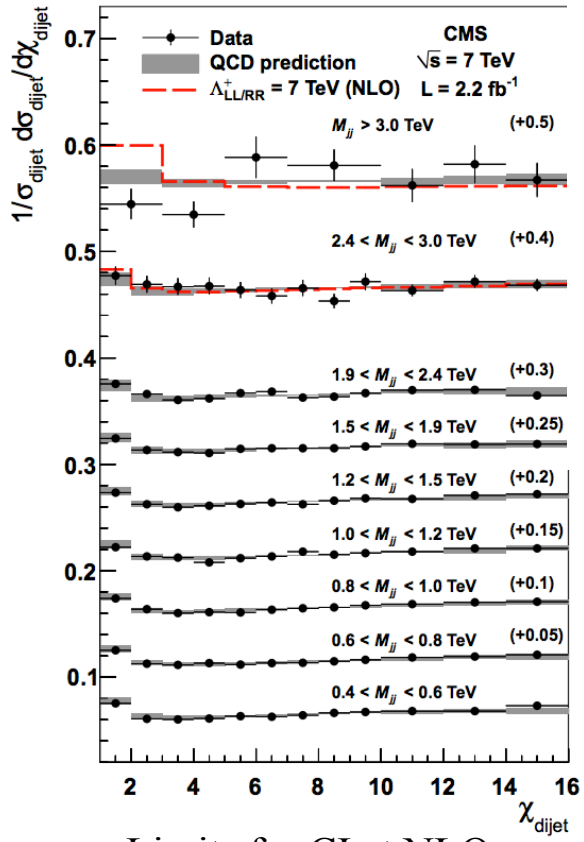
0.25 TeV

Limits on CI for at LO

PhysRevLett.106(2011)201804

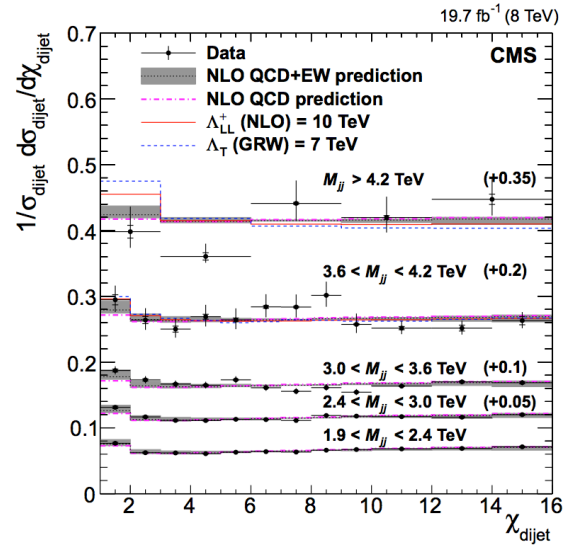
- Λ+: 5.6 TeV
- Λ-: 6.7 TeV





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

- Λ+: 7.5 TeV
- Λ-: 10.5 TeV



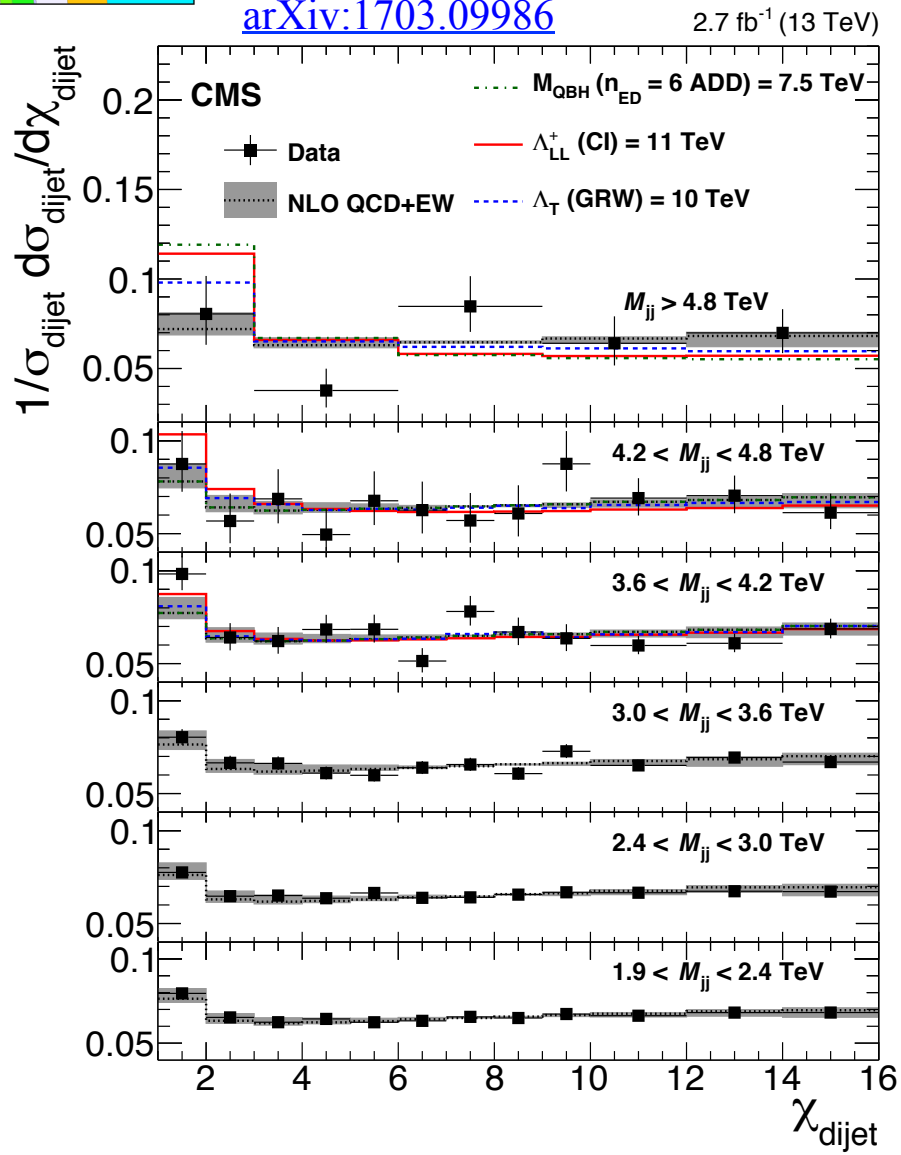
Limits on CI at NLO and ADD

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)

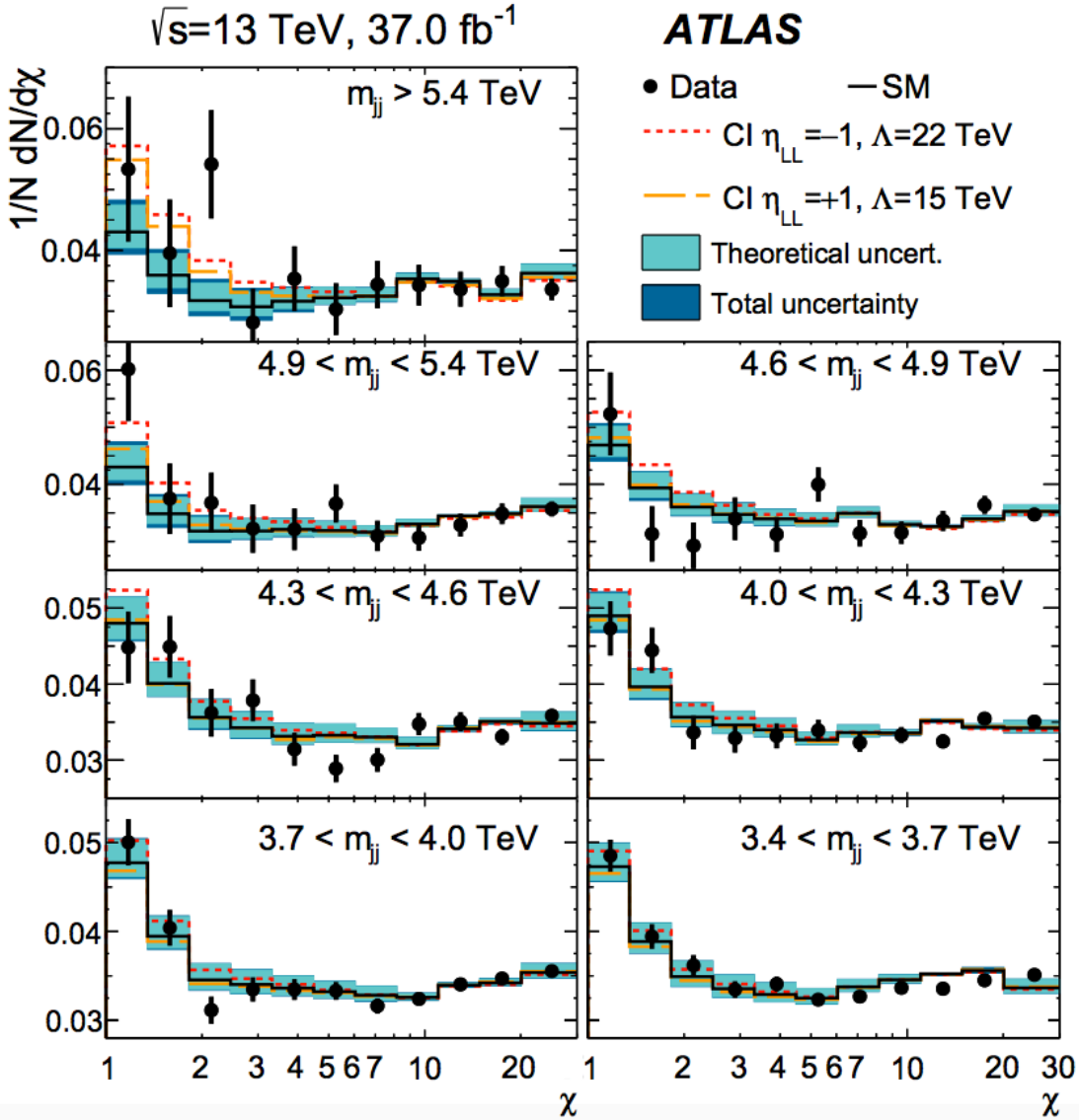
Previous Results

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): 14.7 (17.3) 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+ (NLO): 15.0 TeV
    - Λ- (NLO): 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