Searches for non-resonant new phenomena in final states with leptons, photons, and jets at CMS

Chris West
University of Alabama
on behalf of the CMS Collaboration

Overview

- Will describe three analyses sensitive to nonresonant new physics
- Interpreted in a large variety of new physics models!

Final state	Large extra dimensions	Clockwork model	Contact interactions	Quantum black holes	Dark matter
γγ EXO_17_017	✔	✔			
ee + μμ EXO_17_025	✔		✔		
Dijet EXO_16_046	✔		✔	✔	✔

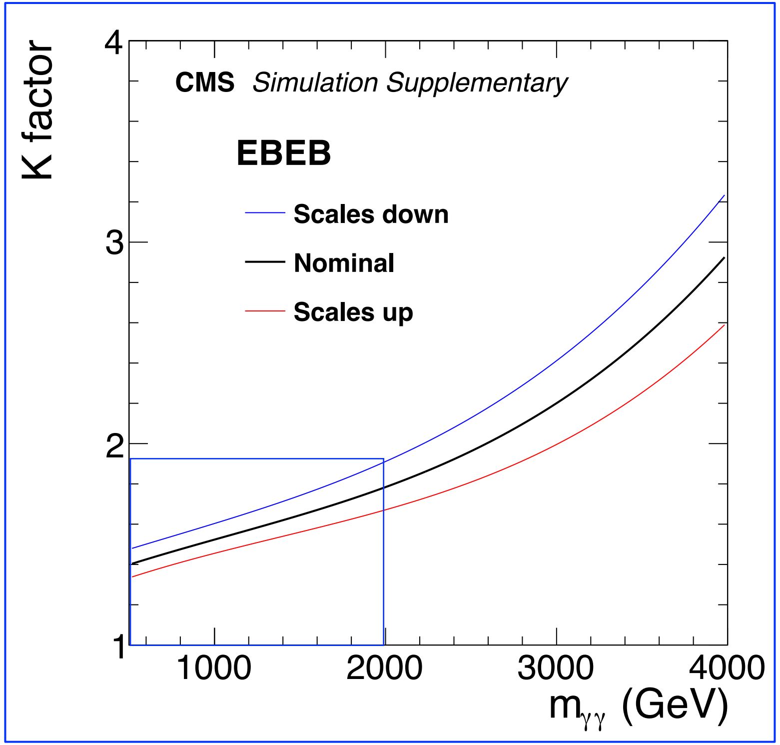
✔ = interpretation available in paper

This talk will focus mostly on large extra dimensions, contact interactions and dark matter

Analysis of diphoton channel

- Analysis selection
  - Photon $p_T > 75$ GeV
  - $m_{\gamma\gamma} > 500$ GeV
  - Two η categories
    - Two photons in ECAL barrel (EB)
    - 1 photon in barrel, 1 in ECAL endcap (EE)
- Background prediction
  - NNLO k-factor from MCFM 8.0 applied to real diphoton prediction from Sherpa γγ + 3 jets at LO
    - Both calculated with CT10 PDFs
    - Separate k-factors for barrel-barrel and barrel-endcap
    - NNLO/NLO difference taken as additional systematic
  - Fake photon contributions estimated from data sidebands
  - Fit allows floating EB-EB and EB-EE normalizations

Ratio of MCFM prediction to Sherpa LO



k-factor up to ~1.7 in region <2 TeV with nonzero data

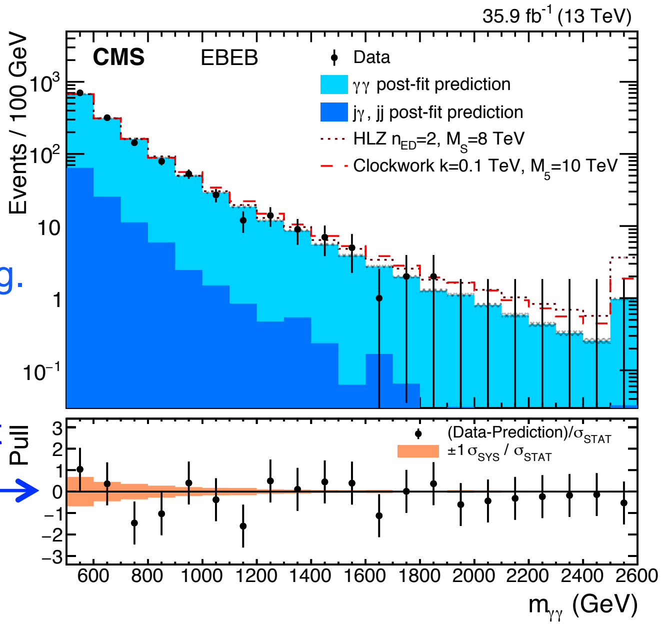
Post-fit γγ results

Prediction consistent within systematics prior to fit ⇒ perform fit

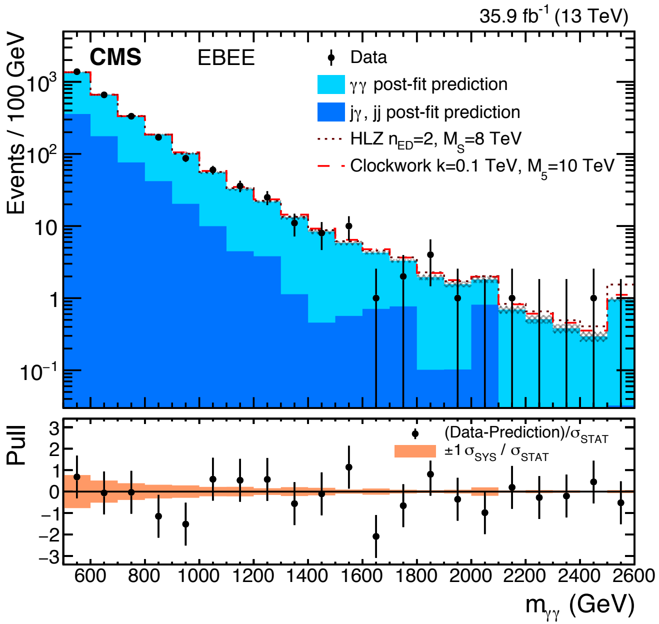
γγ

jγ + jj
<4% of total bkg.
above 1 TeV

Data consistent with fit



Barrel-barrel



Barrel-endcap

γγ

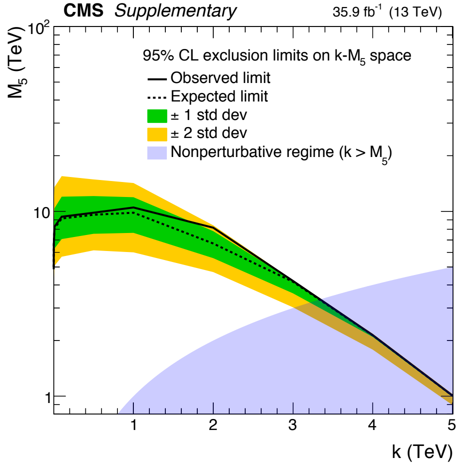
jγ + jj
<14% of total bkg.
above 1 TeV

Diphoton channel limits

- ADD model can be parameterized by convention-dependent higher dimension operator

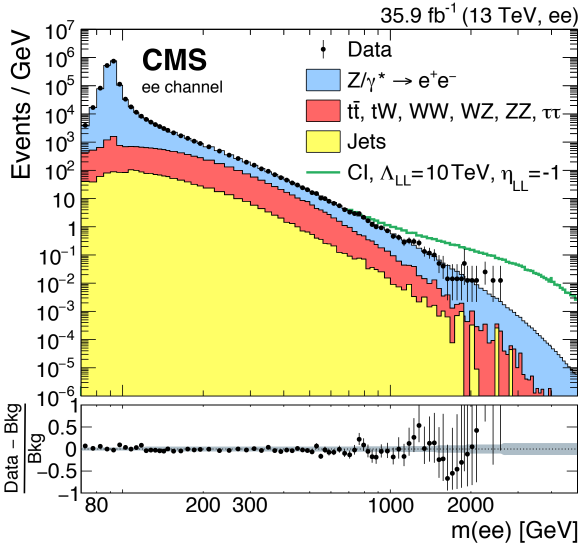
Signal	GRW	Hewett		HLZ					
		negative	positive	$n_{ED} = 2$	$n_{ED} = 3$	$n_{ED} = 4$	$n_{ED} = 5$	$n_{ED} = 6$	$n_{ED} = 7$
Expected	$7.1^{+0.7}_{-0.5}$	$5.5^{+0.1}_{-0.3}$	$6.3^{+0.6}_{-0.4}$	$8.4^{+1.3}_{-1.1}$	$8.4^{+0.8}_{-0.6}$	$7.1^{+0.7}_{-0.5}$	$6.4^{+0.6}_{-0.5}$	$6.0^{+0.6}_{-0.4}$	$5.6^{+0.6}_{-0.4}$
Observed	7.8	5.6	7.0	9.7	9.3	7.8	7.0	6.6	6.2

- Also exclude M_5 < 5 TeV in clockwork model for 0.2 < k < 2.0 TeV



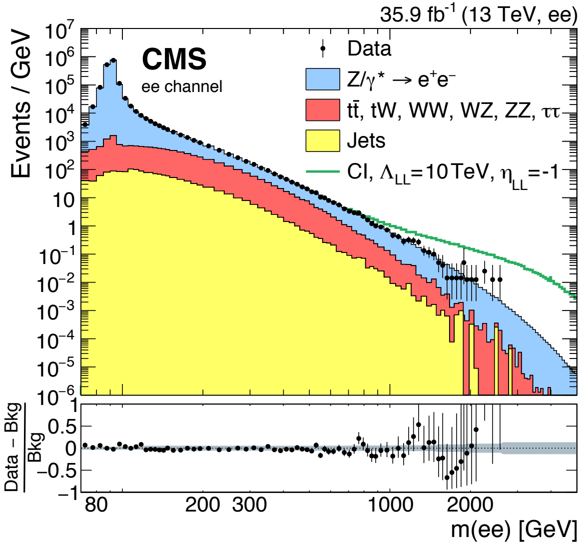
Dilepton channel background prediction

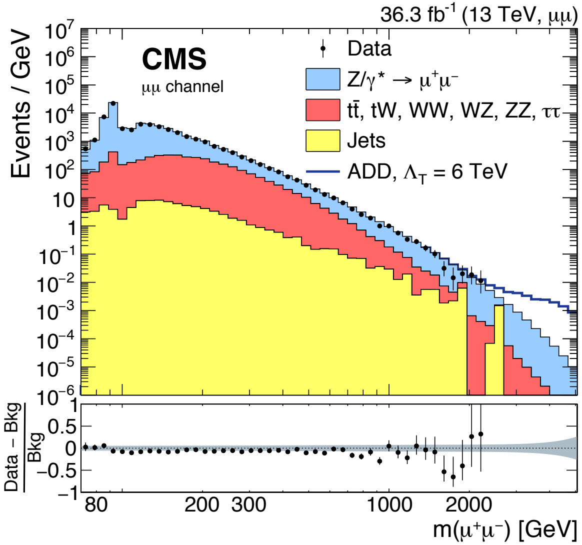
- Selection
  - p_T > 35 (53) GeV for electron (muon) candidates
  - Search region: $m_{\ell\ell}$ > 400 GeV
- Barrel-barrel and barrel-endcap combinations considered
- Drell-Yan k-factor calculated with `FEWZ 3.1b2` applied to $m_{\ell\ell}$ distribution
  - Calculated relative to `POWHEG V2`
  - Uses `PDF4LHC15` PDFs + `LUX` photon PDFs
- Jets misreconstructed as leptons evaluated from data
- Other backgrounds from MC normalized to SM cross section
  - ttbar – at NNLO + NNLL
  - Wt – NNLL
  - Other – up to NNLO with MCFM 6.6



Results

- No significant discrepancy between data observation and prediction
- In muon channel, data below prediction above $m_{\mu\mu}$ > 1.6 TeV (2.9σ local, 1.8σ global)
- Dominant uncertainties electron energy scale and PDFs





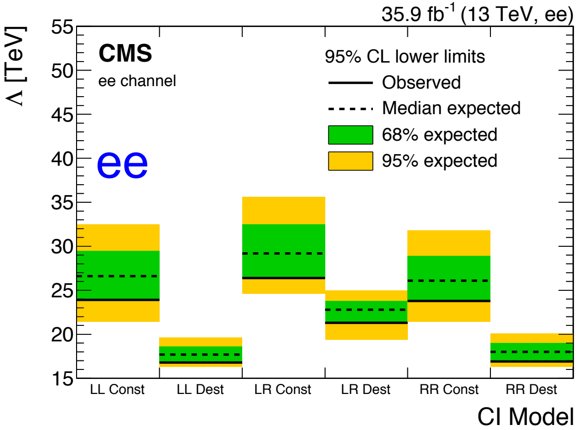
Barrel-barrel plus barrel-endcap

Limits on contact interactions

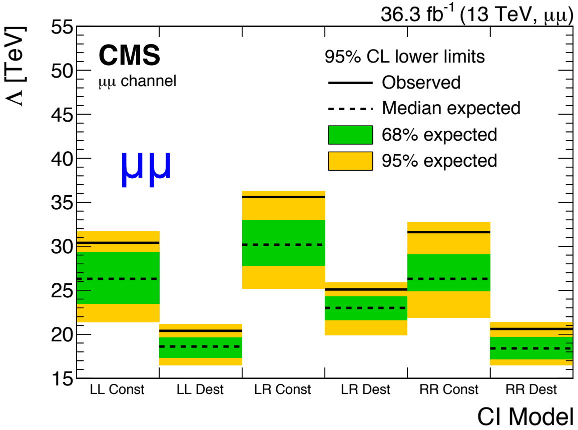
$$\mathcal{L}_{q\ell} = \frac{g^2_{\text{contact}}}{\Lambda^2}\left[\begin{array}{l}\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{\ell}_L\gamma_\mu\ell_L) + \eta_{RR}(\bar{q}_R\gamma^\mu q_R)(\bar{\ell}_R\gamma_\mu\ell_R) \\ +\eta_{LR}(\bar{q}_L\gamma^\mu q_L)(\bar{\ell}_R\gamma_\mu\ell_R) + \eta_{RL}(\bar{q}_R\gamma^\mu q_R)(\bar{\ell}_L\gamma_\mu\ell_L)\end{array}\right]$$

$$g^2_{\text{contact}}/4\pi = 1$$

- Limits set assuming only one non-zero η
  - Left-Left (η_{LL} = ± 1), Left-Right (η_{LR} = ± 1), Right-Right (η_{RR} = ± 1)
  - Destructive and constructive interference



LL		LR		RR	
+	-	+	-	+	-

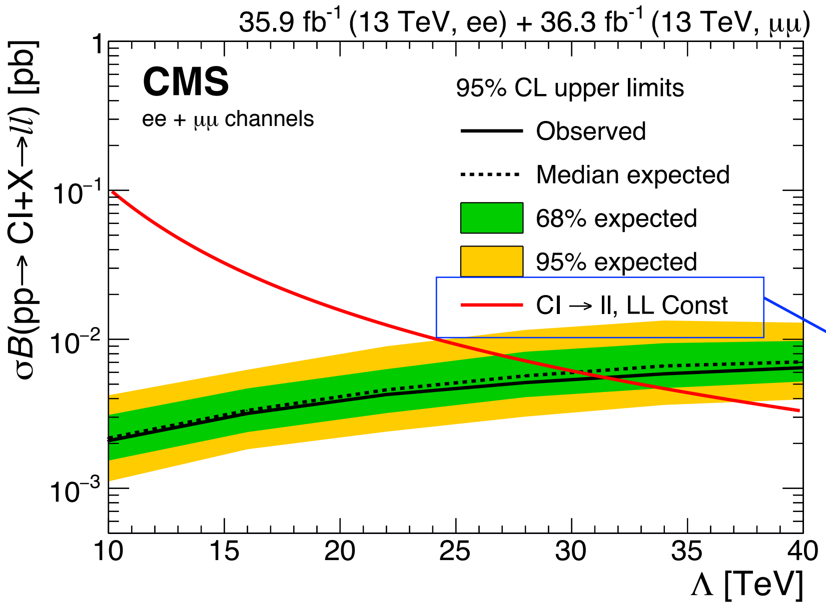


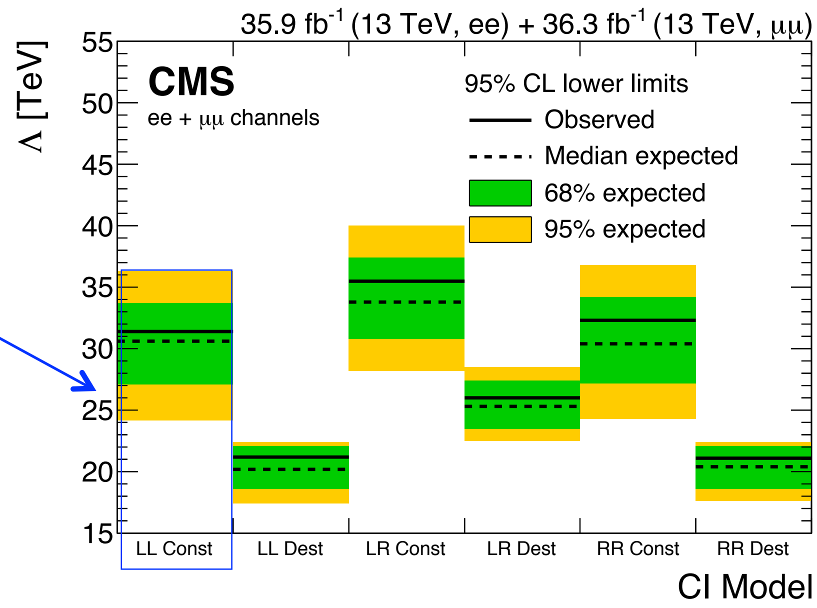
LL		LR		RR	
+	-	+	-	+	-

Observed limits < 2σ stronger than expected in dimuon channel

Combined ee + μμ limits on contact interactions

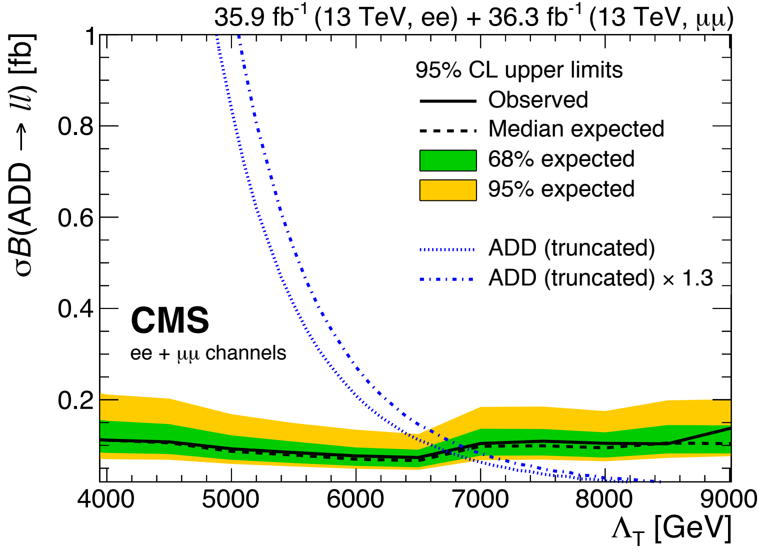
- Assuming electron-muon universality, no significant discrepancy between data and pred.
- Observed 95% CL limits from Λ_{LL} > 20 TeV (destr. case) to Λ_{RR} > 32 TeV (const. case)

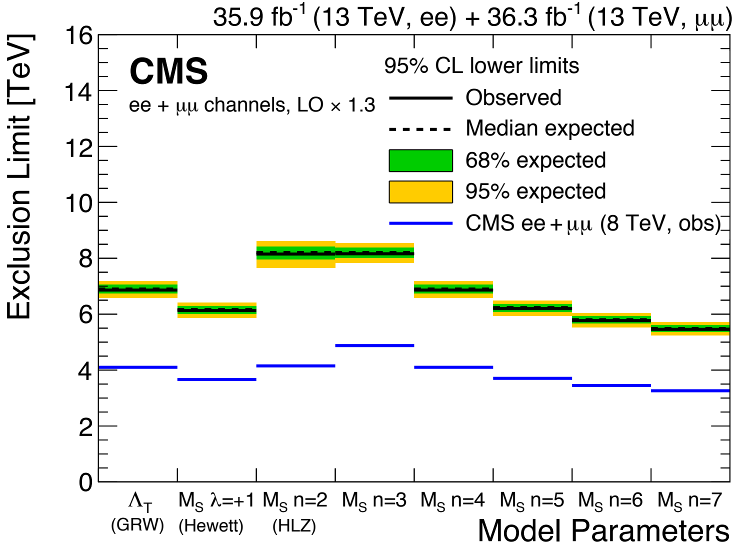




Combined ee+μμ limits on ADD model

- Combined limits significantly exceed 8 TeV results, comparable to 13 TeV diphoton limits
- Signal model assumes NLO k-factor and truncation of $m_{\gamma\gamma}$ spectrum above Λ_T (M_S)

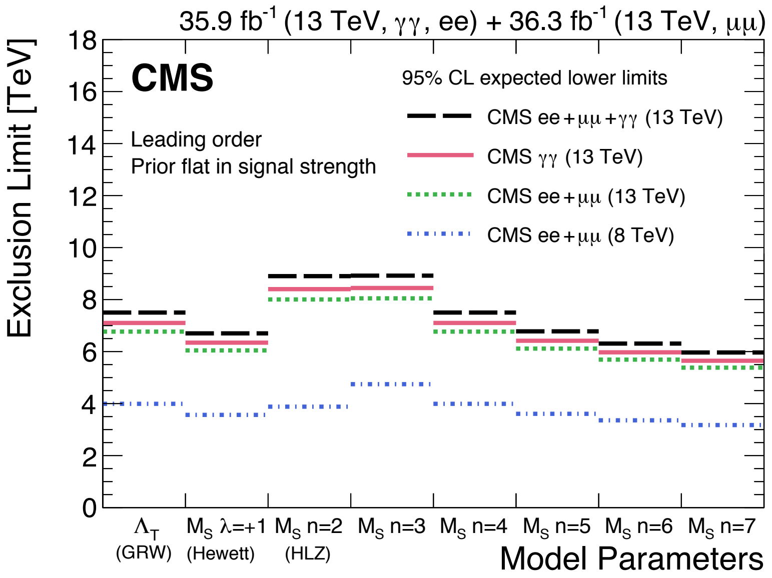




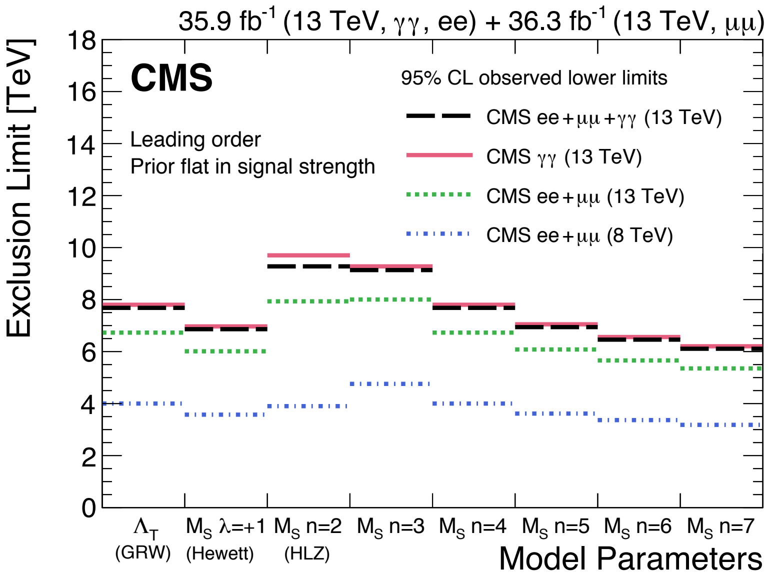
k-factor of 1.3 applied to signal

Combination of diphoton and dilepton constraints on extra dimensions

- Expected limits improve with γγ + ℓℓ combination
- Observed limits sometimes weaker due to stronger than expected γγ limit



Expected limits



Observed limits

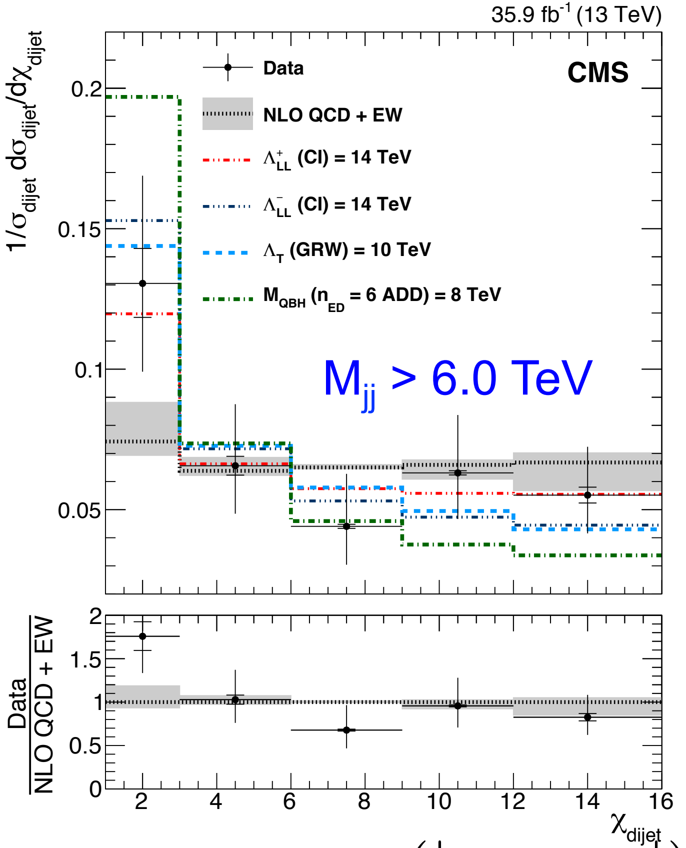
Dijet channel

- Uses additional background rejection variable

$$\chi_{\text{dijet}} = \exp(|y_1 - y_2|)$$

  - Exploits fact that new physics is likely to be more central than QCD background
- Bin with M_{jj} > 6.0 TeV most sensitive
  - Six lower mass bins starting at 2.4 TeV
  - Lower-mass bins also help to constrain systematic uncertainties
- Predictions based on NLOJET++ 4.13
- Jet energy scale (μ_F and μ_R scales) are the dominant experimental (theoretical) uncertainties

Data unfolded to particle level

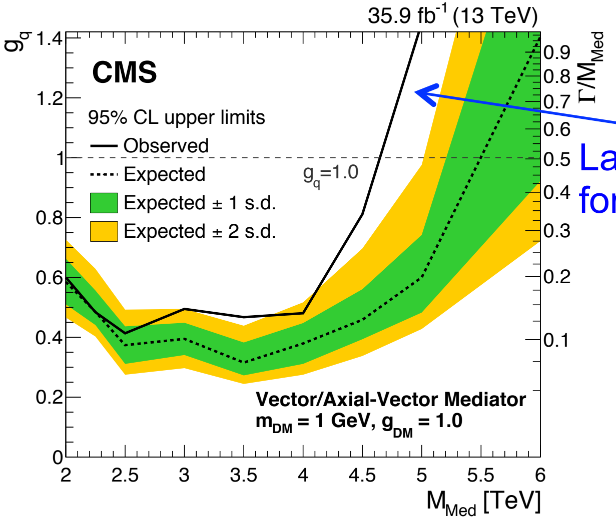


$$\chi_{\text{dijet}} = \exp(|y_1 - y_2|)$$

Dijet analysis limits on dark matter simplified models

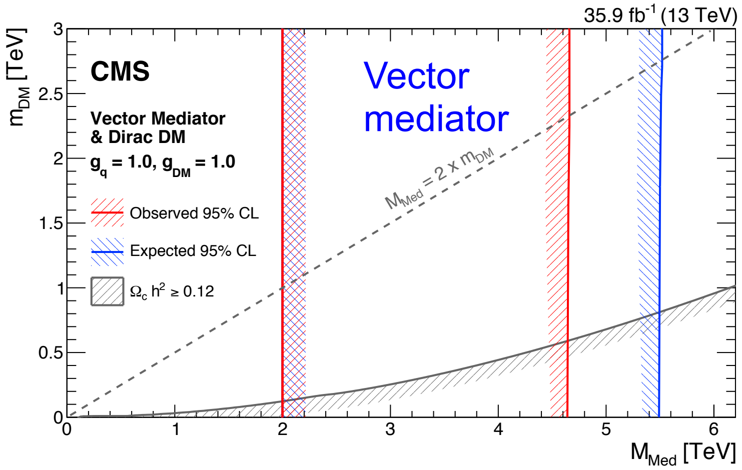
$$L_{\text{vector}} = -g_{\text{DM}} Z'_{\mu} \bar{\chi} \gamma^{\mu} \chi - g_{q} \sum_{q=u,d,s,c,b,t} Z'_{\mu} \bar{q} \gamma^{\mu} q,$$

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

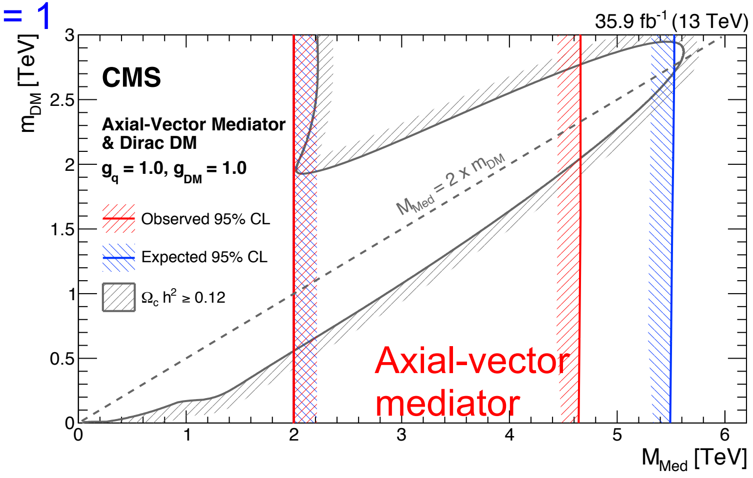


Largest significance 2.7-2.8σ for M_{med} = 4.5-6 TeV and g_q = 1

M_{med} exclusion range has little dependence on m_{DM} for $2m_{DM} << M_{med}$



Small differences between exclusion limits for vector and axial-vector mediators



Dijet analysis summary table

Limits derived by comparison of detector-level quantities

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

	Model	Observed lower limit (TeV)	Expected lower limit (TeV)
CI	$\Lambda^{+}_{LL/RR}$	12.8	14.6 ± 0.8
	$\Lambda^{-}_{LL/RR}$	17.5	23.5 ± 3.0
	Λ^{+}_{VV}	14.6	16.4 ± 0.8
	Λ^{-}_{VV}	22.4	30.7 ± 3.7
	Λ^{+}_{AA}	14.7	16.5 ± 0.8
	Λ^{-}_{AA}	22.3	30.6 ± 3.8
	$\Lambda^{+}_{(V-A)}$	9.2	11.5 ± 1.0
	$\Lambda^{-}_{(V-A)}$	9.3	11.8 ± 1.1
ADD	Λ_T (GRW)	10.1	11.4 ± 0.9
	M_S (HLZ) $n_{ED} = 2$	10.7	12.4 ± 1.0
	M_S (HLZ) $n_{ED} = 3$	12.0	13.6 ± 1.1
	M_S (HLZ) $n_{ED} = 4$	10.1	11.4 ± 0.9
	M_S (HLZ) $n_{ED} = 5$	9.1	10.3 ± 0.8
	M_S (HLZ) $n_{ED} = 6$	8.5	9.6 ± 0.8
QBH	M_{QBH} (ADD $n_{ED} = 6$)	8.2	8.5 ± 0.4
	M_{QBH} (RS $n_{ED} = 1$)	5.9	6.3 ± 0.7
DM	Vector/Axial-vector M_{Med}	2.0–4.6	2.0–5.5

Quantum black holes

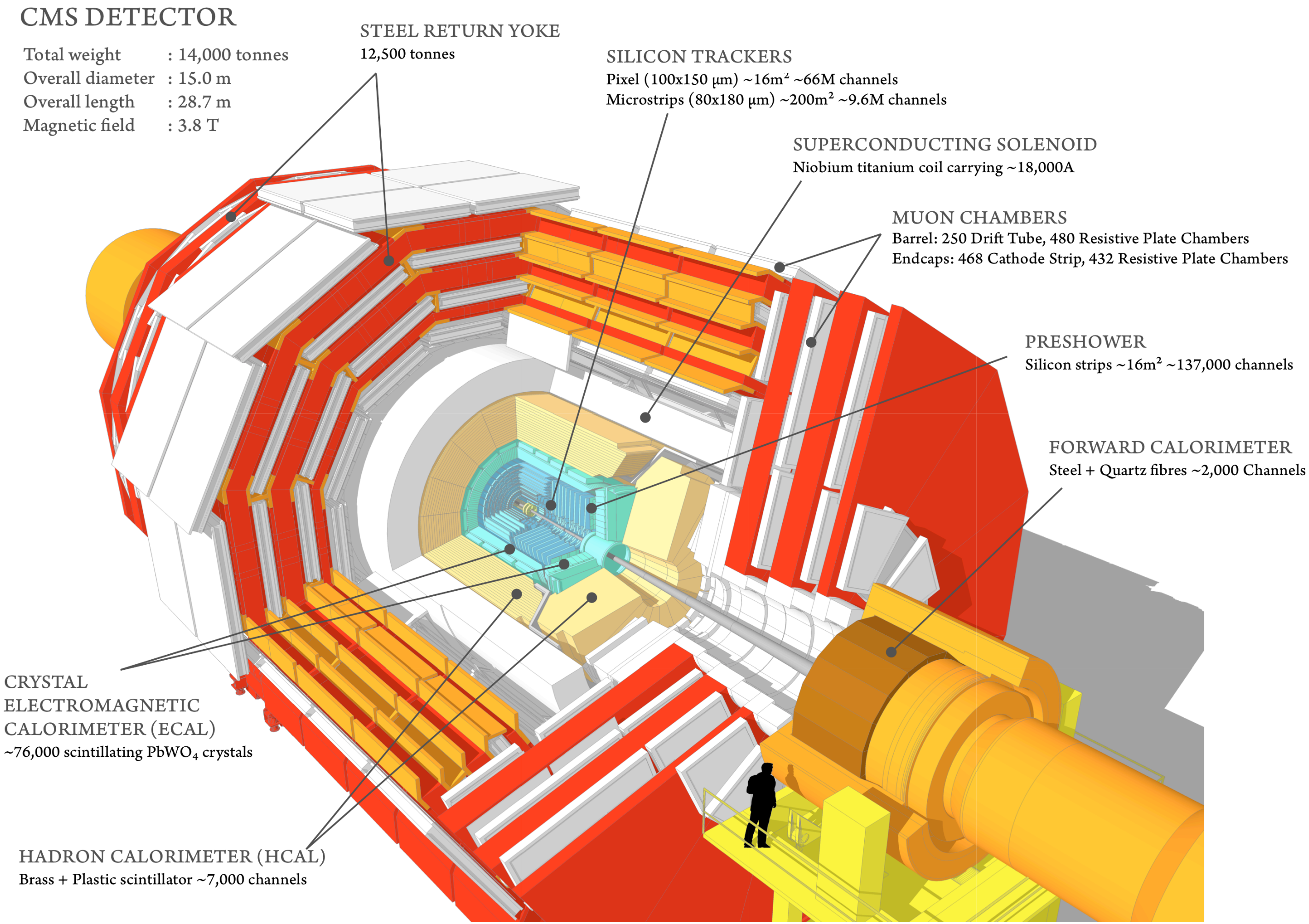
Observed limits ~2σ lower than expected

Strongest CMS limits on the ADD scenario

Summary

- New physics explored in diphoton, dilepton and dijet final states
- Limits set on a variety of models
  - Contact interactions
  - ADD model of extra dimensions
  - Clockwork model
  - Quantum black holes
  - Dark matter
- No significant deviations from SM
  - But full Run II dataset is 3.8 times that shown here!

Backup

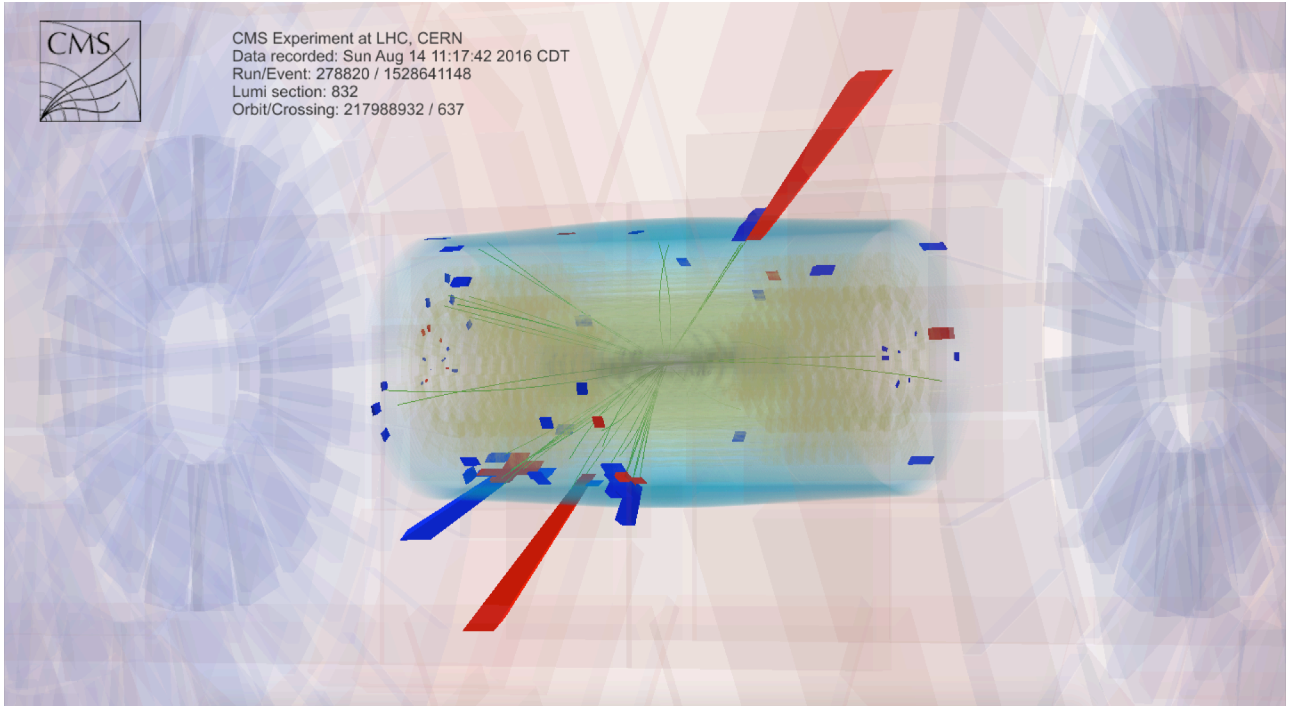

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

References

- EXO-17-017, arXiv:1809.00327, *Phys. Rev. D 98 (2018) 092001*
- EXO-17-025, arXiv:1812.10443, *JHEP 04 (2019) 114*
- EXO-16-046, arXiv:1803.08030, *Eur. Phys. J. C 78 (2018) 789*

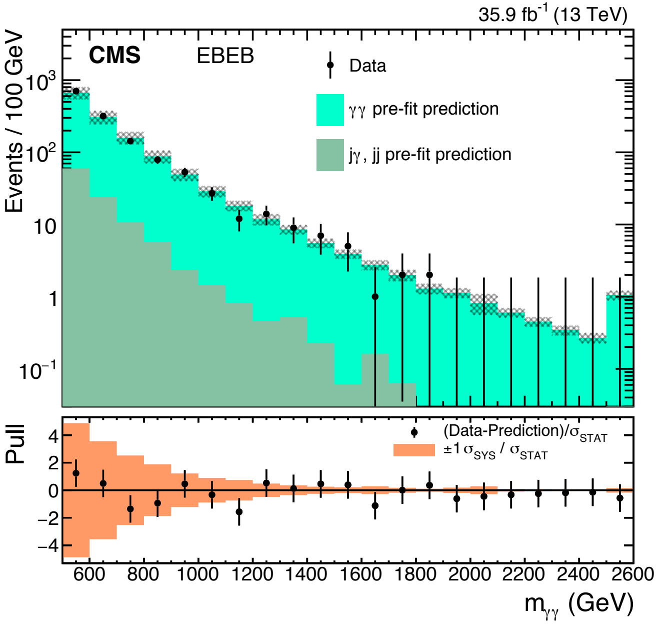
Diphoton analysis event display

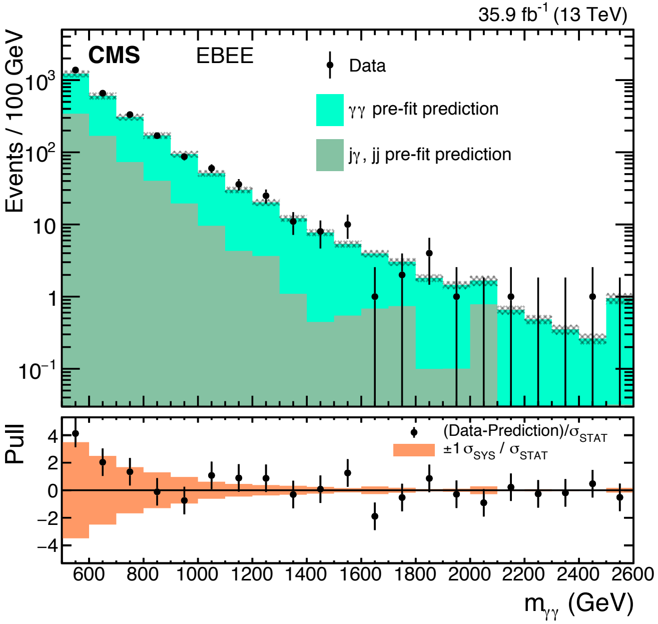
- Highest invariant mass diphoton mass recorded in 2016 in EB-EB category



Pre-fit results

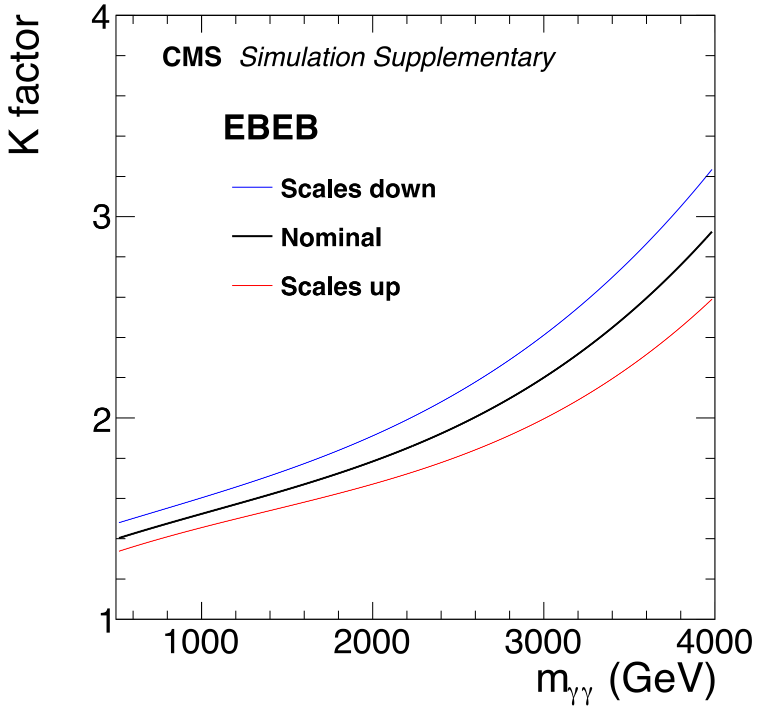
- Consistent with SM prediction

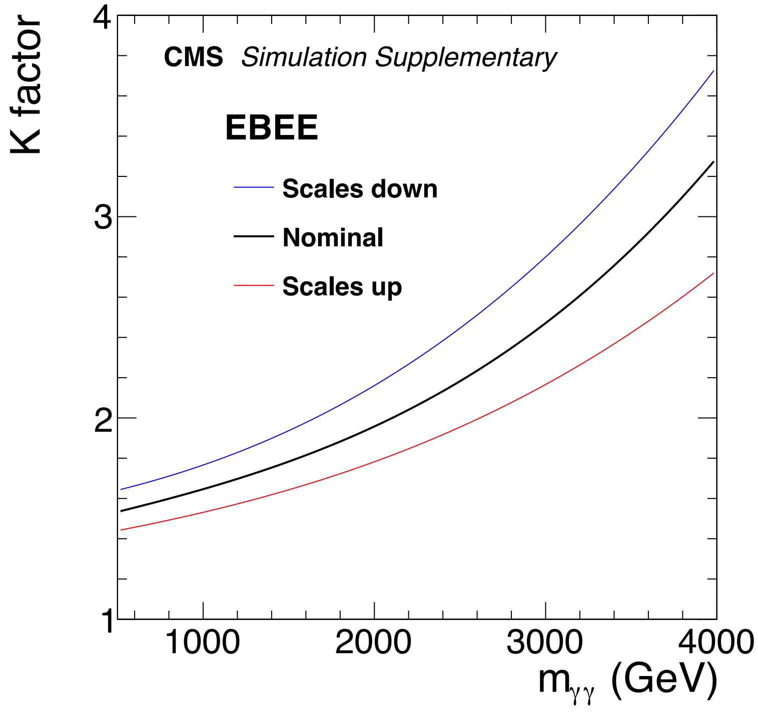




Diphoton analysis scale uncertainties

- Dominant pre-fit uncertainty

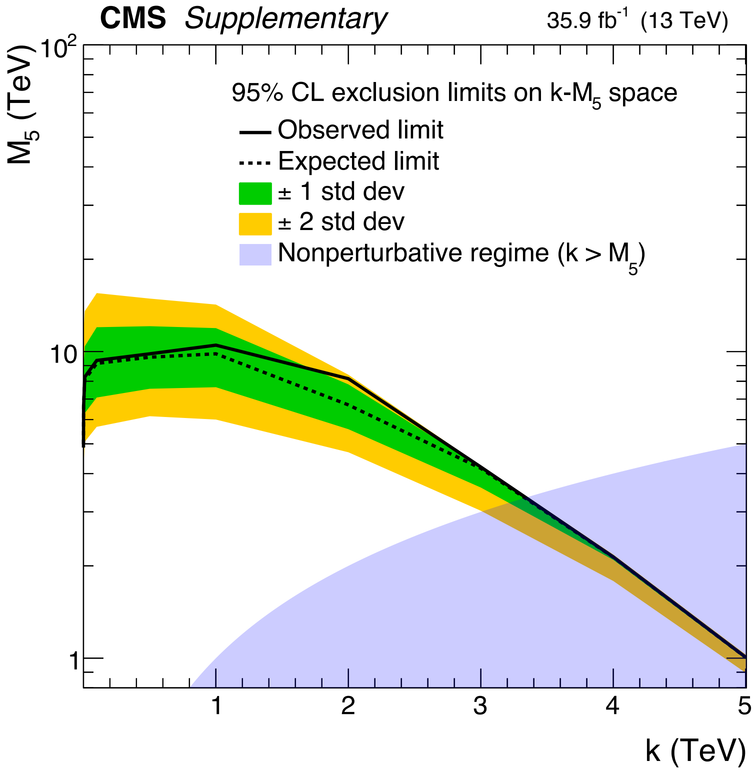




Diphoton channel: first limits on clockwork model

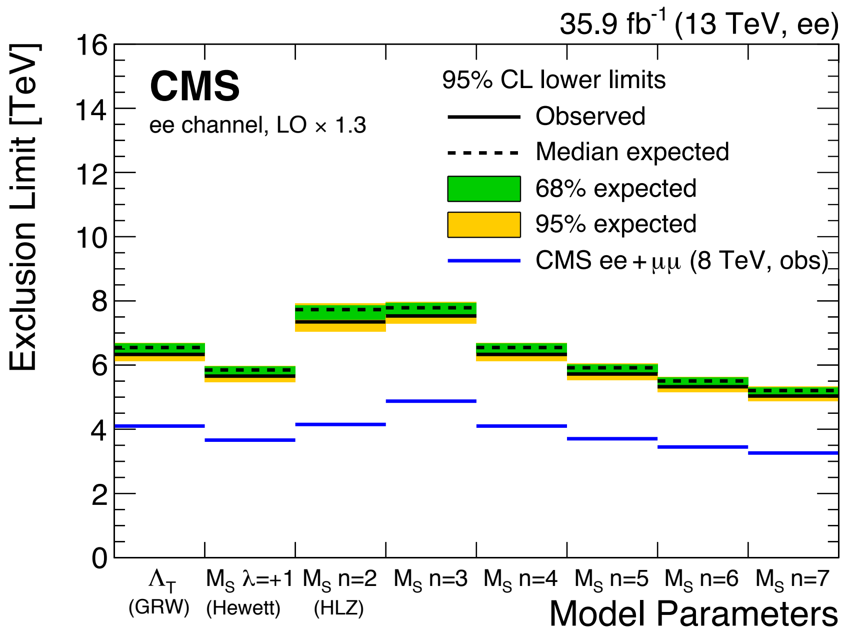
- Signal term from ADD model rescaled by

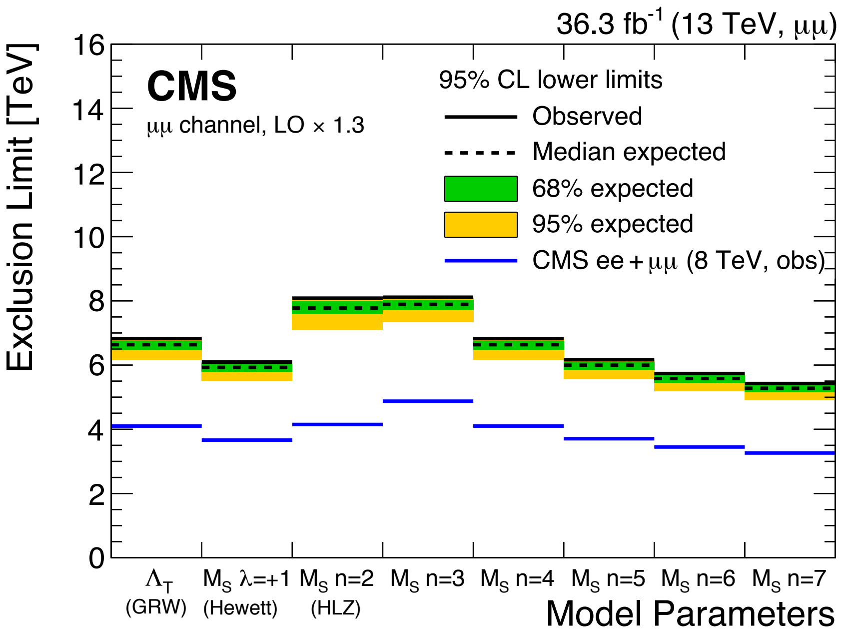
$$\theta(m_{\gamma\gamma}-k)\frac{30M_S^8}{283\pi M_5^3}\sqrt{1-\frac{k^2}{m_{\gamma\gamma}^2}}\frac{1}{m_{\gamma\gamma}^5}\left[1+\frac{(5^2)(7)(17)}{(283)(2^8)}\left(1-\frac{k}{m_{\gamma\gamma}}\right)^9\sqrt{\frac{m_{\gamma\gamma}}{k}}\right]^{-1}$$



Limits on ADD model: muon and electron channel combined

- Combined limits significantly exceed 8 TeV results, comparable to 13 TeV diphoton limits





Dilepton analysis systematic uncertainties

Uncertainty	Electrons $m_{ee} > 2\,\mathrm{TeV}$	Electrons $m_{ee} > 4\,\mathrm{TeV}$	Muons $m_{\mu\mu} > 2\,\mathrm{TeV}$	Muons $m_{\mu\mu} > 4\,\mathrm{TeV}$
Electron trigger + selection efficiency BB (BE)	6 (8)%		—	—
Electron energy scale BB (BE)	12.0 (6.7)%	21.7 (11.0)%	—	—
Muon trigger efficiency BB (BE)	—	—	0.3 (0.7)%	
Muon ID efficiency BB (BE)	—	—	0.8 (4.6)%	1.7 (7.6)%
Muon p_T resolution BB (BE)	—	—	0.8 (1.4)%	1.5 (2.3)%
Muon p_T scale BB (BE)	—	—	0.8 (2.8)%	4.1 (12.1)%
$t\bar{t}$/diboson cross section	7%		7%	
Z boson peak normalization	1%		5%	
PDF	5.7%	17.1%	5.7%	17.1%
Multijet BB (BE)	0.1 (1.3)%	0.1 (0.1)%	<0.1 (4.8)%	<0.1 (<0.1)%
Pileup reweighting BB (BE)	0.5 (0.7)%	0.4 (0.7)%	0.2 (0.1)%	0.2 (0.2)%
MC statistics BB (BE)	1.0 (1.8)%	0.7 (1.7)%	1.1 (1.3)%	1.0 (2.0)%

Dilepton analysis limits

Order	GRW Λ_T[TeV]	Hewett M_S[TeV] $\lambda = +1$	HLZ M_S[TeV] $n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
				ee for $m_{ee} > 1.8$ TeV				
LO	6.1 (6.4)	5.5 (5.7)	7.0 (7.5)	7.3 (7.6)	6.1 (6.4)	5.5 (5.8)	5.1 (5.4)	4.9 (5.1)
LO ×1.3	6.3 (6.5)	5.7 (5.8)	7.3 (7.7)	7.5 (7.8)	6.3 (6.5)	5.7 (5.9)	5.3 (5.5)	5.0 (5.2)
				$\mu\mu$ for $m_{\mu\mu} > 1.8$ TeV				
LO	6.7 (6.5)	6.0 (5.8)	7.9 (7.6)	7.9 (7.7)	6.7 (6.5)	6.0 (5.9)	5.6 (5.5)	5.3 (5.2)
LO ×1.3	6.8 (6.6)	6.1 (5.9)	8.1 (7.8)	8.1 (7.9)	6.8 (6.6)	6.2 (6.0)	5.7 (5.6)	5.4 (5.3)
				Combined ee and $\mu\mu$ for $m_{\ell\ell} > 1.8$ TeV				
LO	6.7 (6.8)	6.0 (6.0)	7.9 (8.0)	8.0 (8.0)	6.7 (6.8)	6.1 (6.1)	5.7 (5.7)	5.4 (5.4)
LO ×1.3	6.9 (6.9)	6.1 (6.2)	8.2 (8.2)	8.2 (8.2)	6.9 (6.9)	6.2 (6.2)	5.8 (5.8)	5.5 (5.5)
				Combined ee, $\mu\mu$, and $\gamma\gamma$ for $m_{\ell\ell} > 1.8$ TeV and $m_{\gamma\gamma} > 500$ GeV				
LO	7.7 (7.5)	6.9 (6.7)	9.3 (8.9)	9.1 (8.9)	7.7 (7.5)	6.9 (6.8)	6.5 (6.3)	6.1 (6.0)

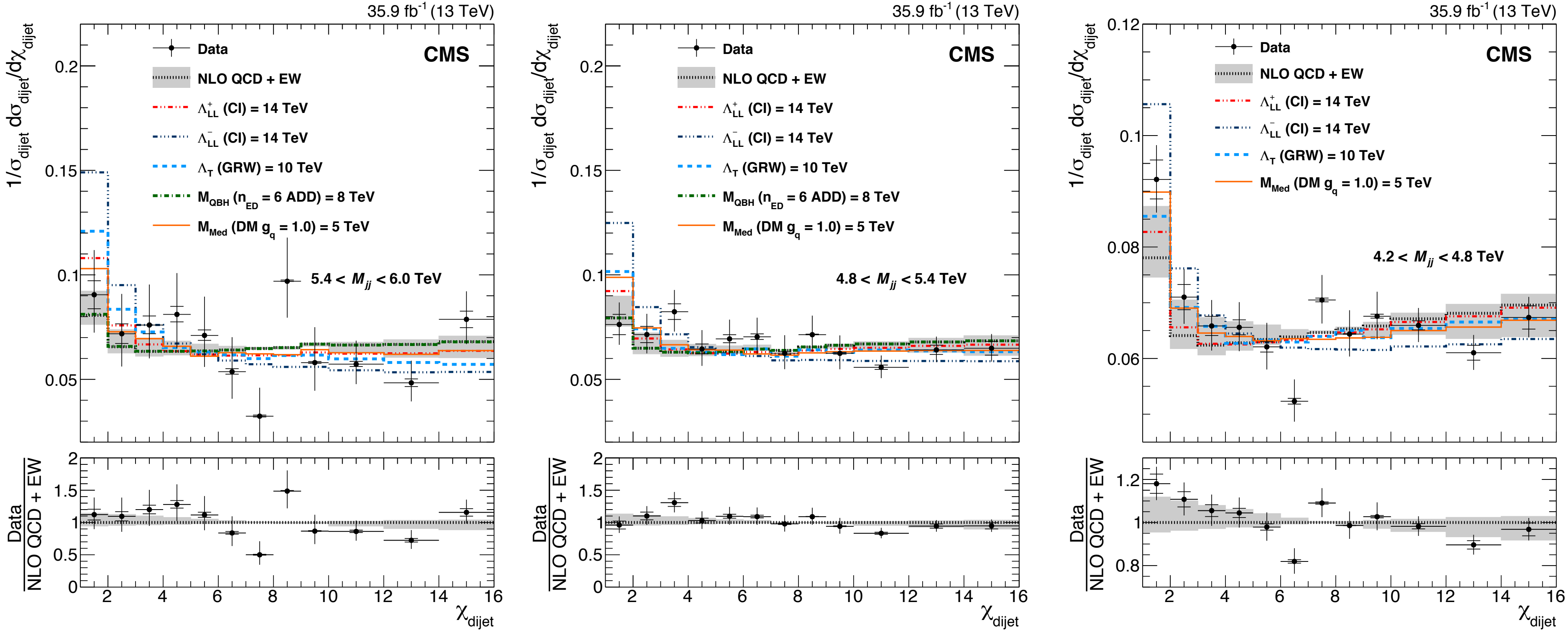
Dijet analysis—detailed selection

- $\chi_{dijet} < 16$
- $y_{boost} = |y_1 + y_2|/2 < 1.11$
- $M_{jj} > 2.4$ TeV
- These selections result in:
  - $|y_1| < 2.5$
  - $|y_2| < 2.5$
  - Jet $p_T > 200$ GeV
  - Trigger efficiency > 99%

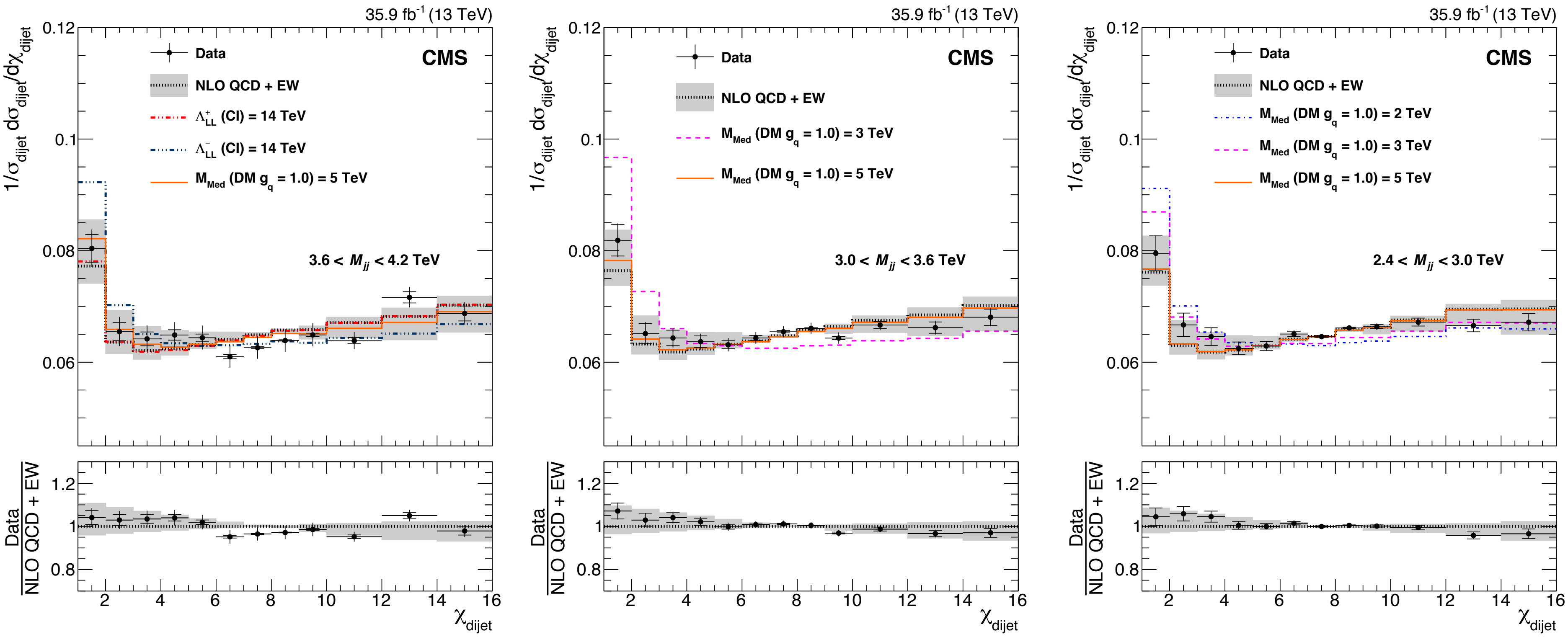
Dijet analysis—event yields

M_{jj} selection [TeV]	Yield
2.4—3.0	353025
3.0—3.6	71832
3.6—4.2	16712
4.2—4.8	4287
4.8—5.4	1153
5.4—6.0	330
> 6.0	95

Dijet analysis—high mass bins



Dijet analysis—low mass bins



Dijet analysis uncertainties

Source of uncertainty	$2.4 < M_{jj} < 3.0\,\text{TeV}$	$M_{jj} > 6.0\,\text{TeV}$
Statistical	0.7	27
JES	3.6	9.2
Jet p_T resolution (core)	1.0	1.0
Jet p_T resolution (tails)	1.0	1.5
Detector response model	0.5	1.0
Unfolding, model dependence	0.2	1.5
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
Total theoretical	8.5	19

Contact interactions

- Motivated by models of quark and lepton compositeness

In notation of EXO-17-025: $$\mathcal{L}_{q\ell} = \frac{g^2_{\mathrm{contact}}}{\Lambda^2}\left[\begin{array}{l} \eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{\ell}_L\gamma_\mu\ell_L) + \eta_{RR}(\bar{q}_R\gamma^\mu q_R)(\bar{\ell}_R\gamma_\mu\ell_R) \\ +\eta_{LR}(\bar{q}_L\gamma^\mu q_L)(\bar{\ell}_R\gamma_\mu\ell_R) + \eta_{RL}(\bar{q}_R\gamma^\mu q_R)(\bar{\ell}_L\gamma_\mu\ell_L) \end{array}\right]$$

$$g^2_{\mathrm{contact}}/4\pi = 1$$

In notation of EXO-16-046: $$\mathcal{L}_{qq} = \frac{2\pi}{\Lambda^2}\left[\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) + \eta_{RR}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_R\gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_L\gamma_\mu q_L)\right]$$

- May interfere constructively or destructively with SM contribution

$$\frac{d\sigma_{X\to\ell\ell}}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} + \eta_X\mathcal{I}(m_{\ell\ell}) + \eta_X^2\mathcal{S}(m_{\ell\ell})$$

$$\eta_X = -\frac{\eta_{ij}}{\Lambda^2_{ij}}$$

Large extra dimensions: ADD model

- Potential resolution to hierarchy problem
- Spacetime extended with *n* additional compactified spatial dimensions of size *L*
- Gravity can propagate in all dimensions
- All SM particles confined to four-dimensional subspace. Fundamental and 4-D Planck scale related by

$$M_{\mathrm{D}}^{2+n} = M_{\mathrm{Pl}}^{2} / L^{n}$$

- ADD model can be parameterized by convention-depenent higher dimension operator with coefficient $\mathcal{F}$

$$\mathcal{F} = \begin{cases} 1 \quad \text{(GRW)}, \\ \begin{cases} \log\left(\frac{M_{\mathrm{S}}^2}{\hat{s}}\right), \text{ if } n_{\mathrm{ED}} = 2 \\ \frac{2}{n_{\mathrm{ED}}-2}, \text{ if } n_{\mathrm{ED}} > 2 \end{cases} \quad \text{(HLZ)}, \\ \pm\frac{2}{\pi} \quad \text{(Hewett)}, \end{cases}$$

$$\eta_{\mathrm{G}} = \mathcal{F} / M_{\mathrm{S}}^{4}$$