Searches for New Heavy Resonances in Final States with Leptons, Photons and Jets

Norbert Neumeister
PURDUE UNIVERSITY
On behalf of the CMS Collaboration

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Introduction

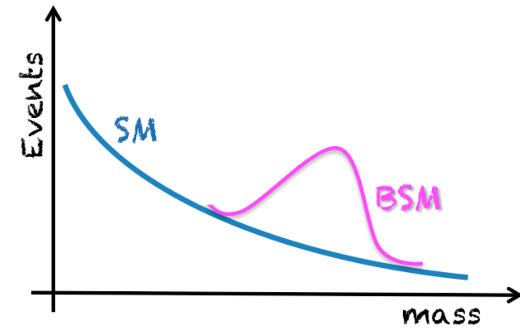
- There are strong motivations for physics beyond the standard model
  - Not clear at what energy scale new particles/phenomena will appear
- High energy and large integrated luminosity give sensitivity for searches in unexplored phase space
  - High energy: Particularly important for searches for high mass resonances
  - Large statistics: About 150 fb^{-1} from Run 2
- A multitude of searches target anomalous production of resonant di-leptons, di-jets and di-photons motivated by a wide range of theoretical models
  - Distinct signature with low SM backgrounds
  - Simple signatures allow for largely model-independent searches
  - Due to the large Lorentz boost decay products may be merged into a single object (jet)

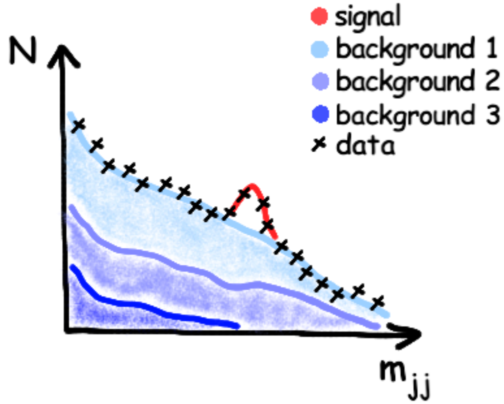
Extended Gauge Symmetries

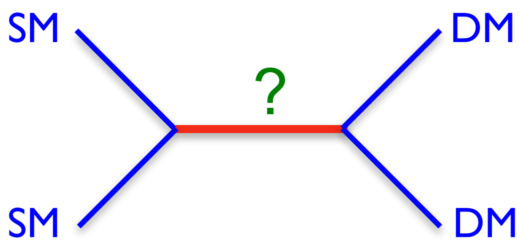
- New gauge bosons predicted by many extensions of the Standard Model with extended gauge symmetries
  - Sequential Standard Model Z_{SSM} with same coupling as in the SM
  - Z'_ψ , Z'_χ , Z'_η models from E6 and SO(10) GUT groups
  - Left-Right symmetry model (LRM) and Alternative LRM (ALRM)
  - The Kaluza-Klein model (KK) from Extra Dimensions
- No precise prediction for mass scale of gauge bosons
- Differentiating between different models requires measurement of
  - Cross section, mass, width, angular distributions

Resonance Searches

- Search for new resonances in the tails of the SM distributions
- Backgrounds
  – relatively clean with good S/B
  – most SM backgrounds can be modeled from data
- Experimental challenges
  – understanding detector resolution is key
  – 1.3% – 2.4% for electrons and 7% for muons at 1 TeV
- Resonance searches can also be interpreted in terms of Dark Matter models







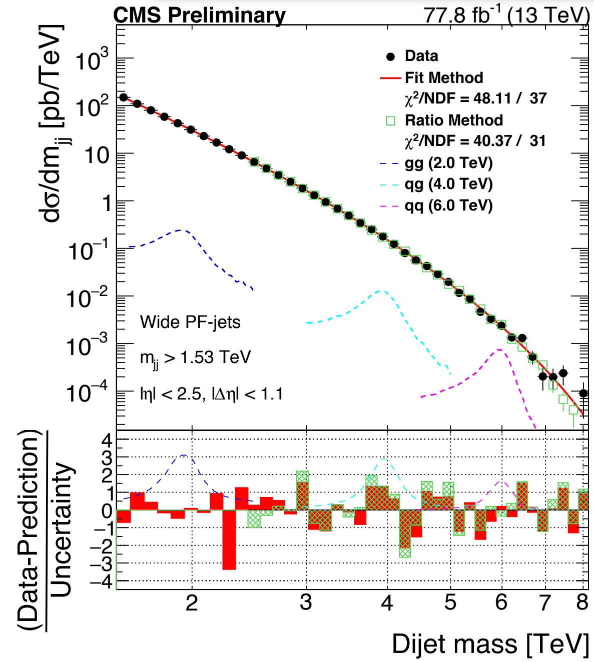
Di-jet Resonances

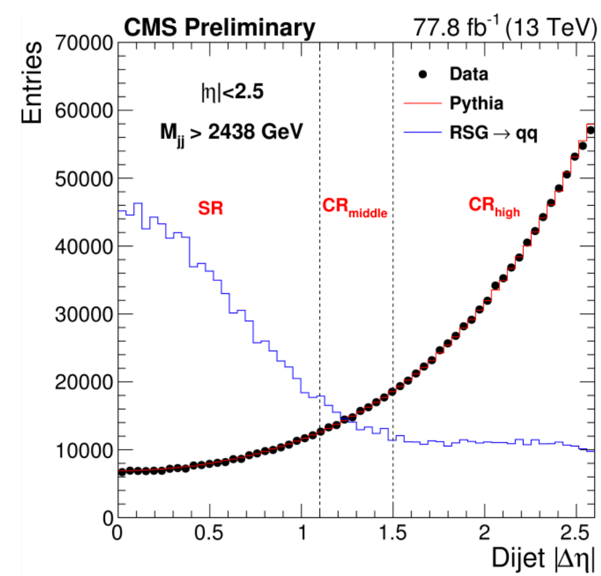
CMS-PAS-EXO-17-026

- Search for high mass di-jet resonances using wide PF-jets (78 fb^{-1})
  - ΔR < 1.1: reduce sensitivity to gluon radiation from the final-state partons
  - Search for bumps in di-jet mass spectrum
    - compare binned m_{jj} data to the fitted background estimate
- Fit smoothly falling di-jet background (full mass range) with:

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}} \quad \text{with } x = m_{jj}/\sqrt{s}$$

- Data-driven method via a |Δη| sideband
  - Create SR and CR in $|\Delta\eta|$ of two wide-PF jets
  - Background in SR is estimated from CR
    - from MC: R=N(CR,mjj)/N(SR,mjj)

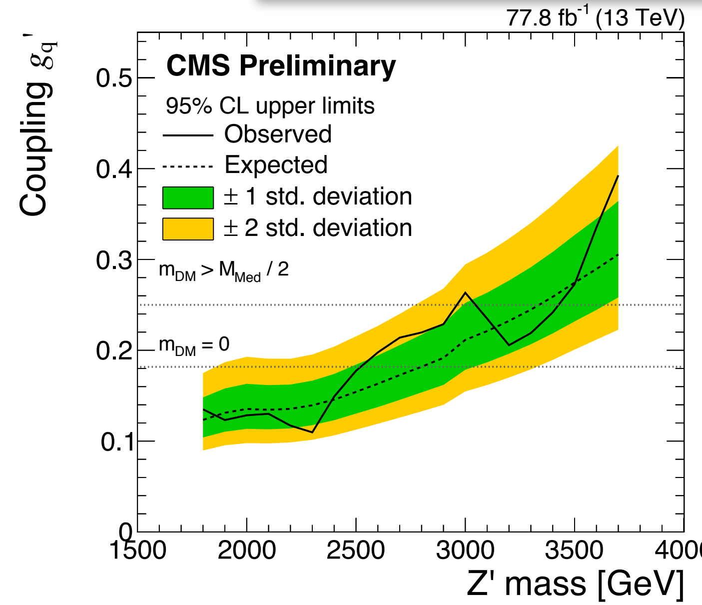




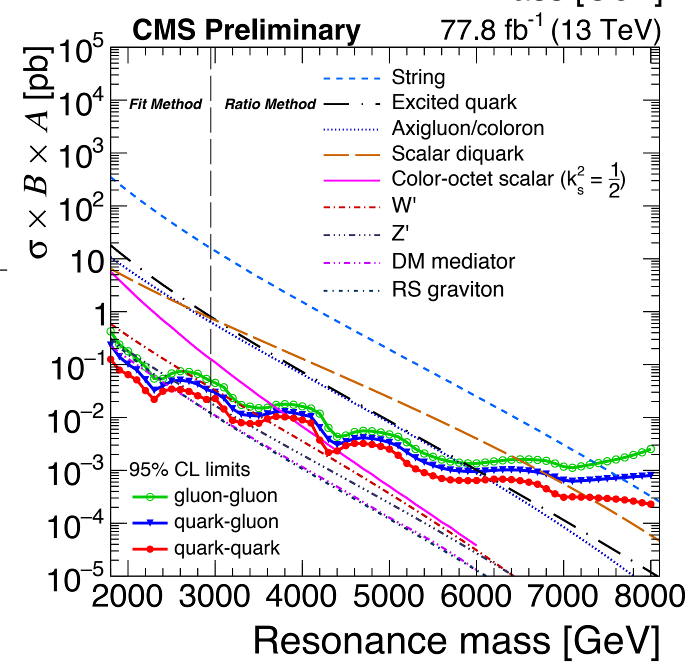
Di-jet Resonances

CMS-PAS-EXO-17-026

- Global significance is computed with pseudo experiments
- Upper limits on nine benchmark models
- No significant excess observed
- Finals states with gluons have more FSR and wider resonances → Limit depends on final state
  - Different signal shapes for qq, qg, gg final states



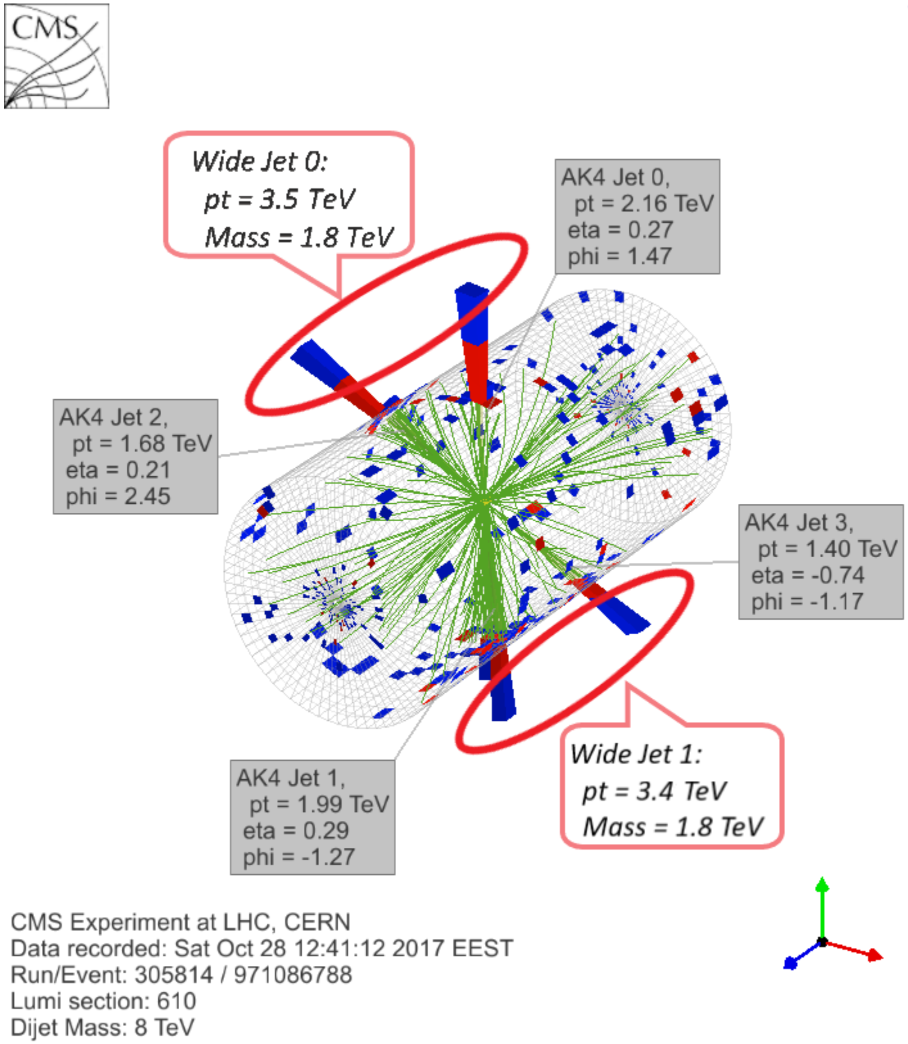
Model	Final State	Observed (expected) mass limit [TeV] $36\ fb^{-1}$ 13 TeV	$77.8\ fb^{-1}$ 13 TeV
String	qg	7.7 (7.7)	7.6 (7.9)
Scalar diquark	qq	7.2 (7.4)	7.3 (7.5)
Axigluon/coloron	$q\bar{q}$	6.1 (6.0)	6.2 (6.3)
Excited quark	qg	6.0 (5.8)	6.0 (6.0)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4 (3.6)	3.7 (3.8)
W′	$q\bar{q}$	3.3 (3.6)	3.6 (3.8)
Z′	$q\bar{q}$	2.7 (2.9)	2.9 (3.1)
RS graviton ($k/M_{PL} = 0.1$)	$q\bar{q}$, gg	1.8 (2.3)	2.4 (2.4)
DM mediator ($m_{DM} = 1$ GeV)	$q\bar{q}$	2.6 (2.5)	2.5 (2.8)

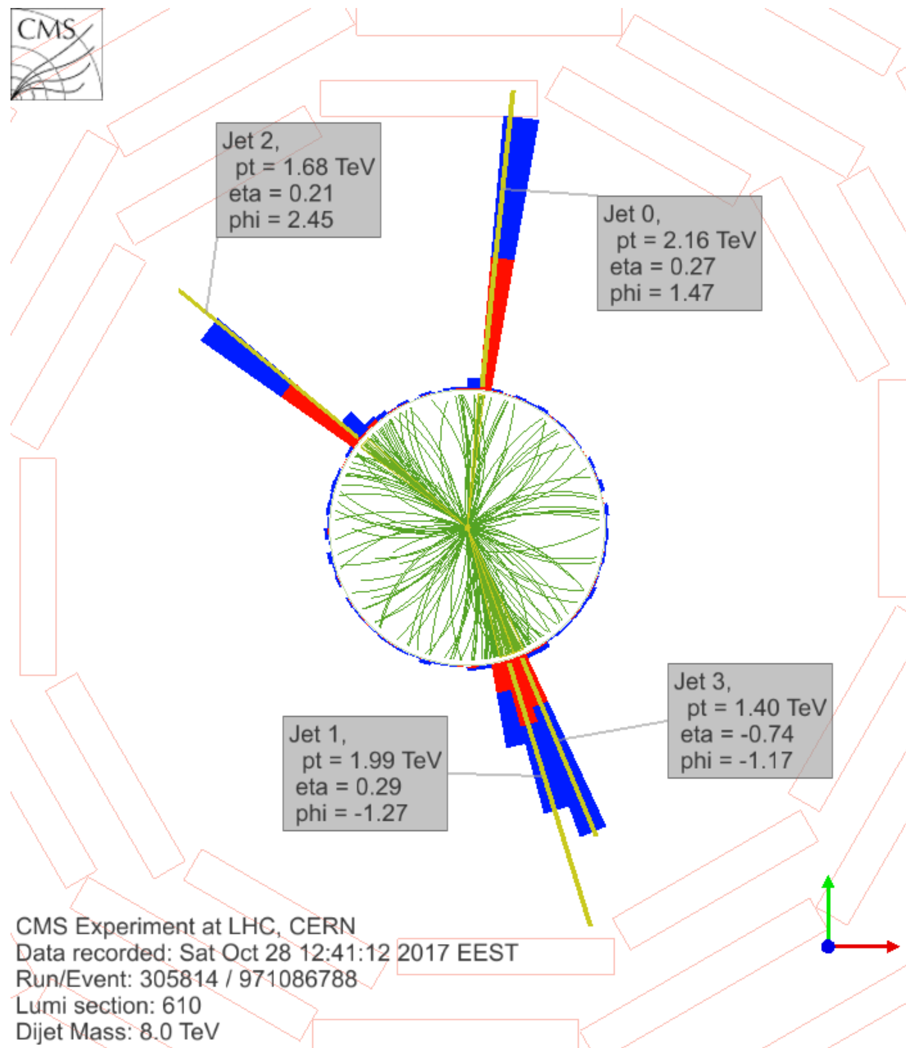


Di-jet Resonances

CMS-PAS-EXO-17-026

Event display of the event with the highest di-jet invariant mass at 8 TeV

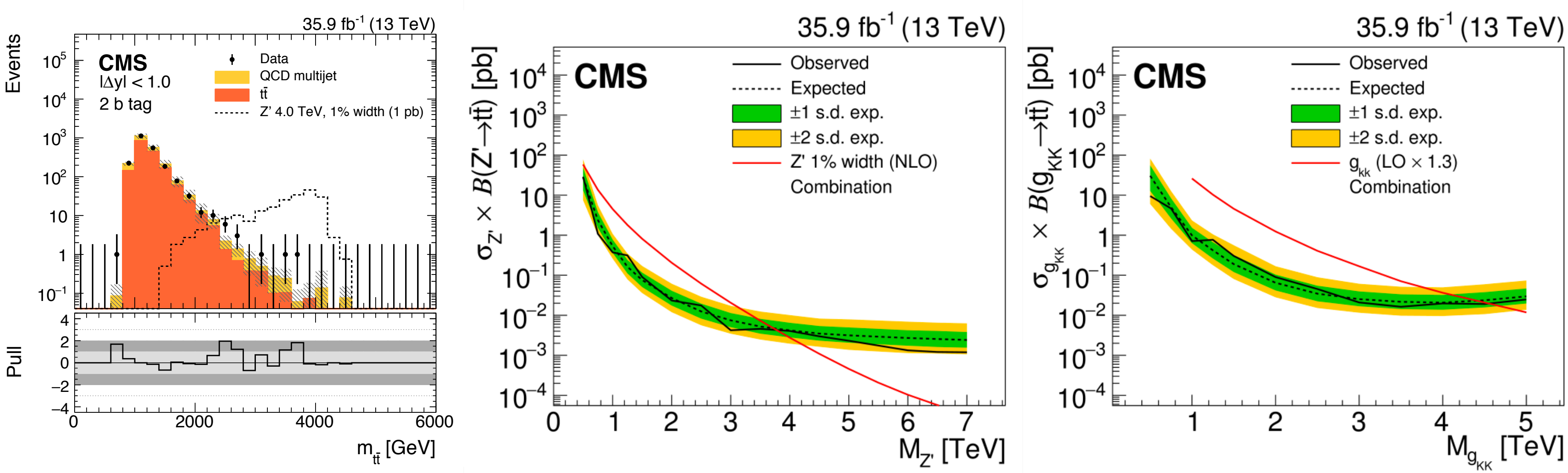




$Z' \rightarrow t\bar{t}$

CMS-B2G-17-007

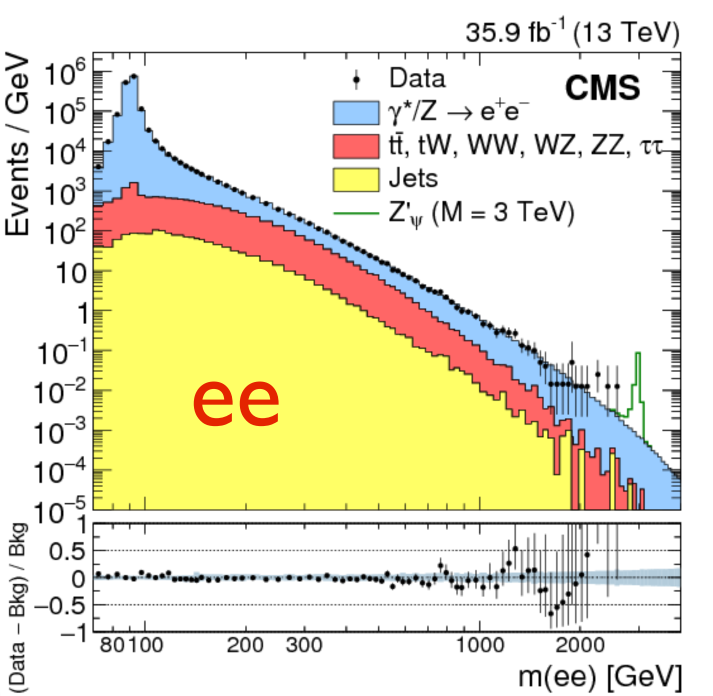
- Search for a heavy spin-1 resonance decaying to a top quark and antiquark pair
  - no interference with SM $t\bar{t}$ production assumed
  - $t\bar{t}$ modes: fully-leptonic, semi-leptonic, hadronic (*leptons*=e, μ)
- Optimized for top-quarks with high Lorentz boost
  - requires non-isolated leptons and jet substructure techniques
- Limits on leptophobic topcolor Z' with widths of 1, 10, and 30%, relative to the mass of the resonance: 3.80, 5.25, and 6.65 TeV, respectively.
- Kaluza-Klein excitations of the gluon in the RS model are excluded up to 4.55 TeV.

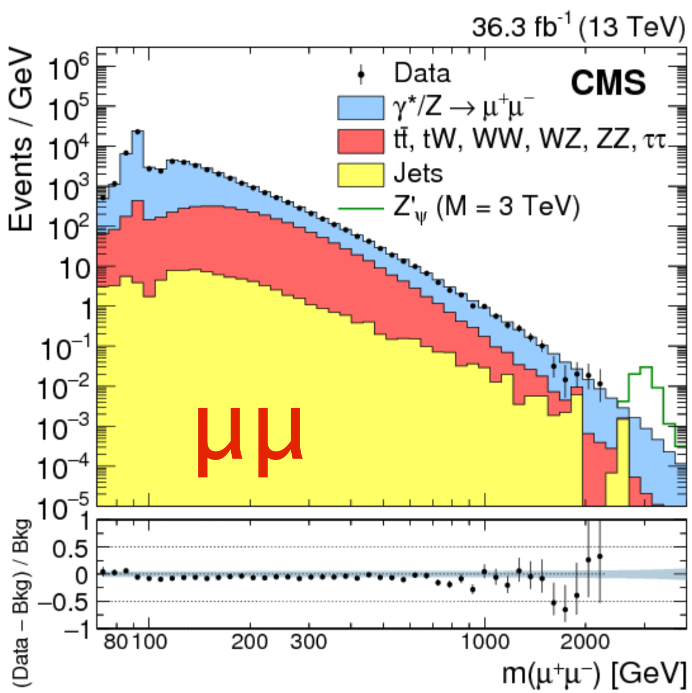


$Z' \to \ell^+\ell^-$

CMS-EXO-16-047

- Search for narrow resonances in $m_{\ell\ell}$ (ℓ = e,μ) distributions above SM background using 36 fb^{-1} (2016) of data
- Dominant background: Drell-Yan
  - Estimated from mass-dependent POWHEG, corrected with NNLO(NLO) QCD(EWK) k-factors
- The amount of jet background is estimated from data

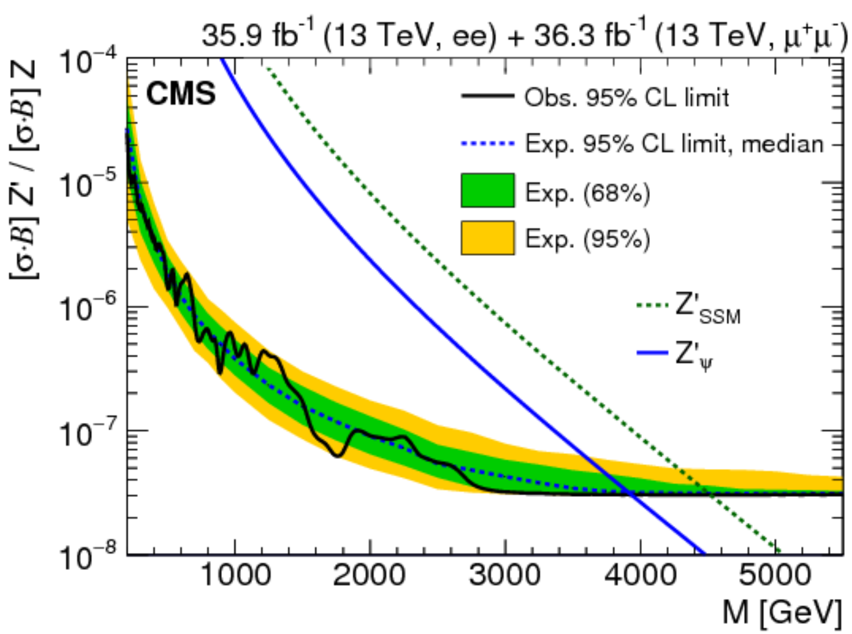


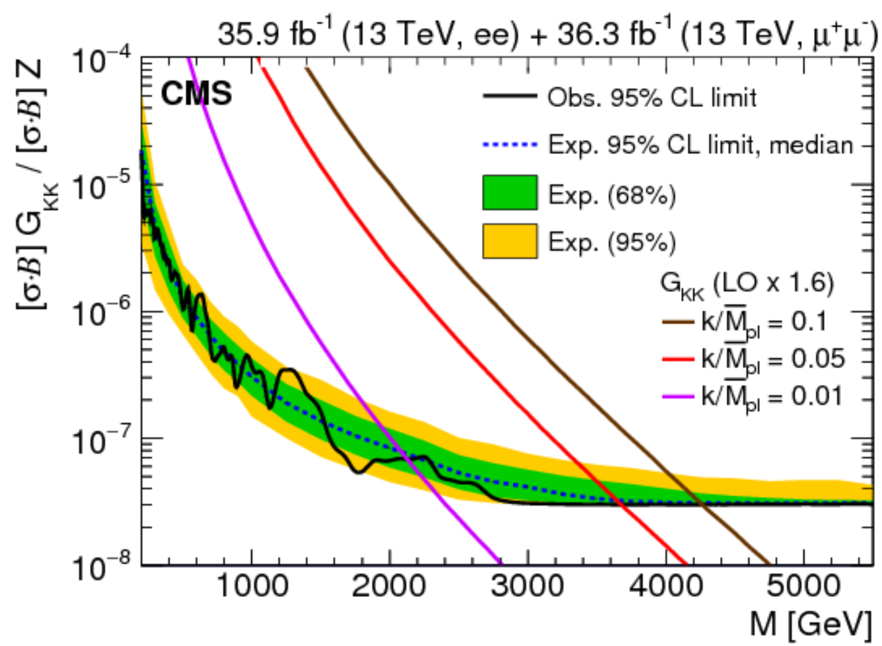


$Z' \rightarrow \ell^{+}\ell^{-}$

CMS-EXO-16-047

- Exclusion limits are set on the ratio σ(Z')/σ(Z) using an unbinned maximum likelihood fit to the data
- Limits set on Z'/Z cross section ratio using Bayesian calculations
- Spin-1: $m(Z'_{\psi}) > 3.9$ TeV, $m(Z'_{SSM}) > 4.5$ TeV
- Spin-2: $k/M_{Pl} = 0.01$: m > 2.10 TeV
  $k/M_{Pl} = 0.05$: m > 3.65 TeV
  $k/M_{Pl} = 0.1$: m > 4.25 TeV

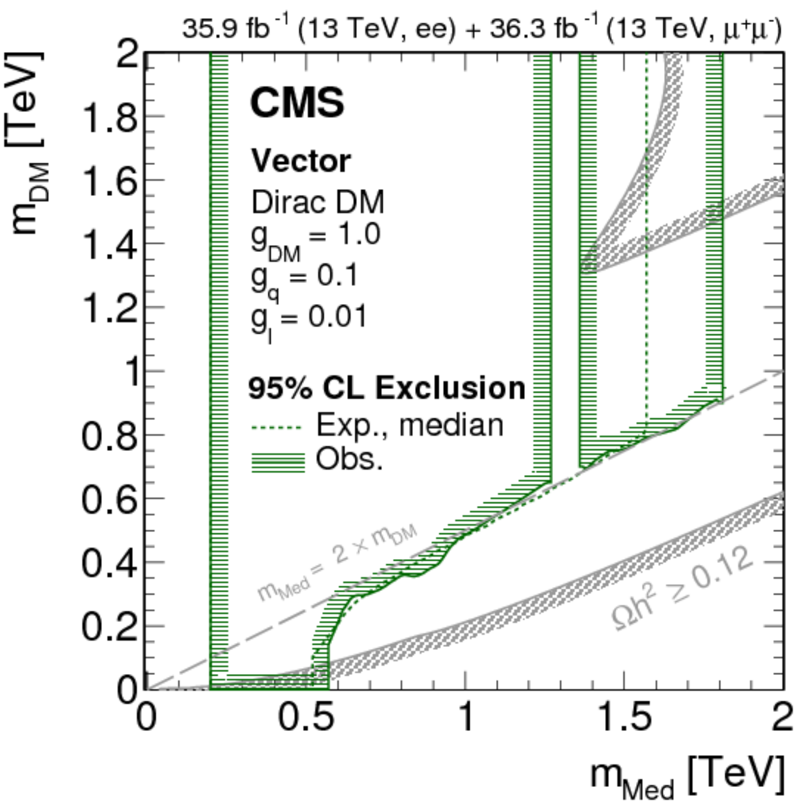


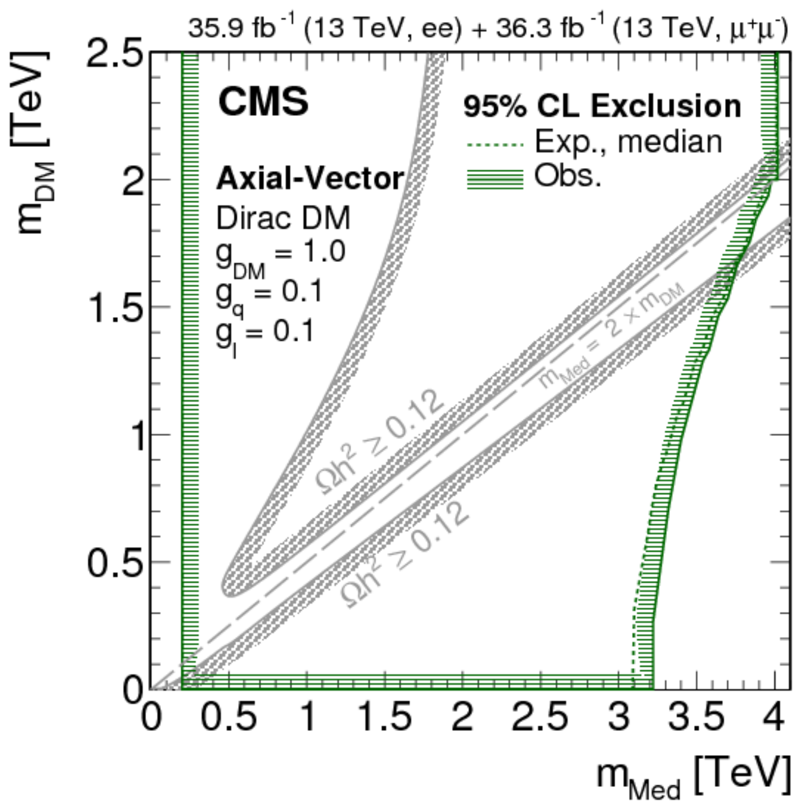


$Z' \to \ell^+\ell^-$

CMS-EXO-16-047

- In a simplified model of dark matter production via a vector or axial vector mediator, limits at 95% confidence level are obtained on the masses of the dark matter particle and its mediator.
- The width of the mediator is taken into account in the limit calculation.

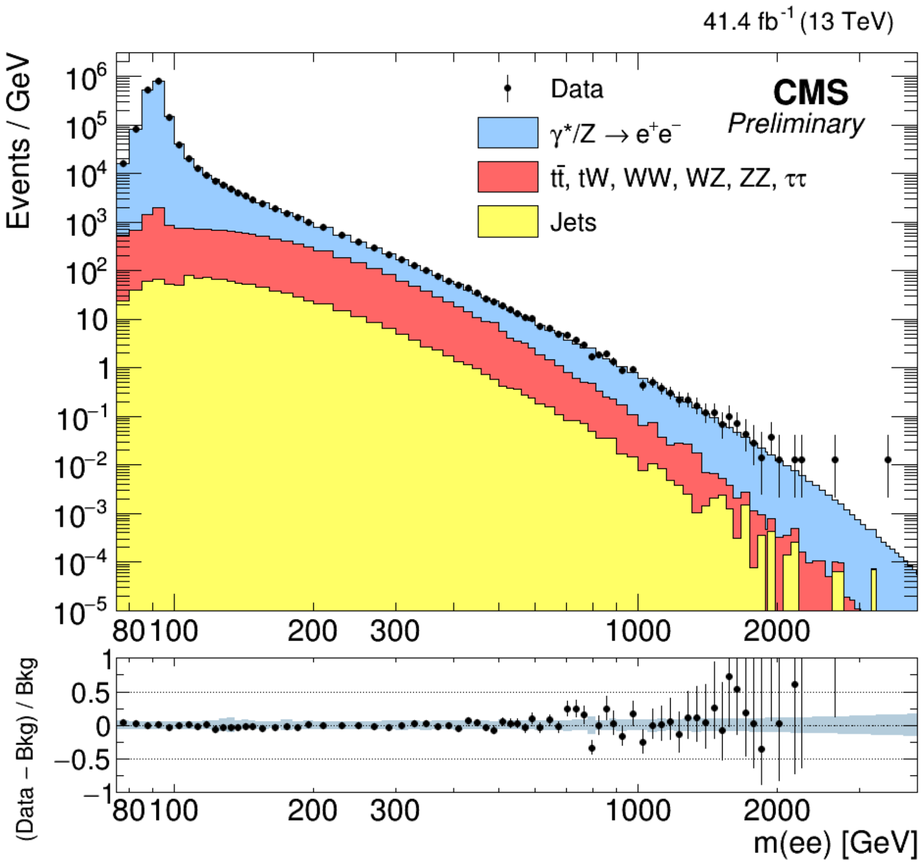




$Z' \rightarrow e^+e^-$

CMS-PAS-EXO-18-006

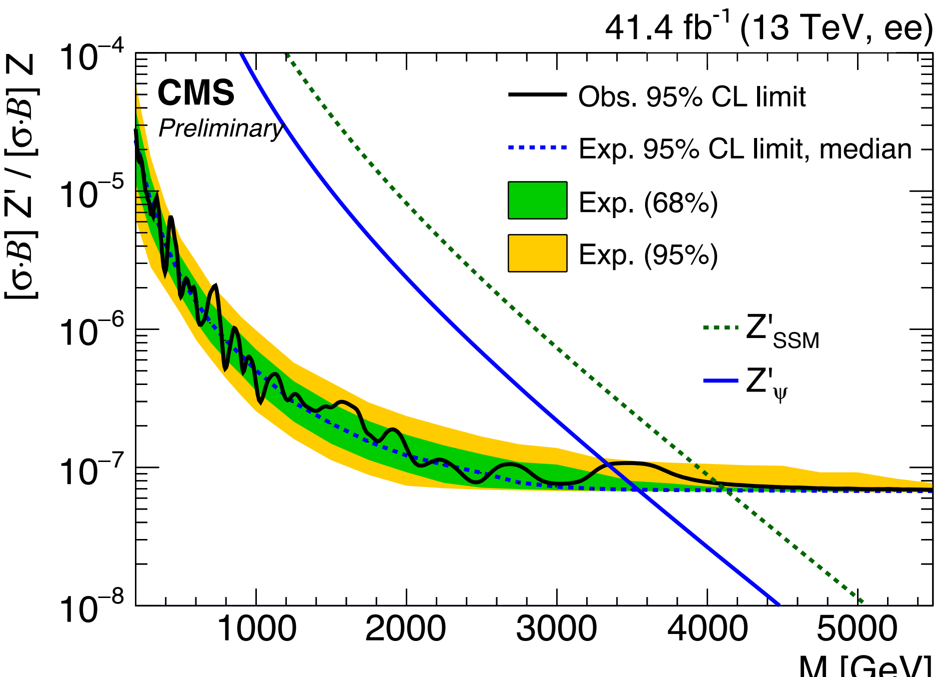
- A search for high mass resonances in the dielectron final state is performed using 41.4 fb^{-1} of data collected in 2017.
- The analysis selects two well reconstructed and isolated electrons, with $E_T > 35$ GeV
- Electrons are selected in the barrel region using $|\eta| < 1.44$ or in the endcap region $1.56 < |\eta| < 2.5$
- The dielectron pair is formed with the highest p_T electrons.
- Main background: Drell-Yan

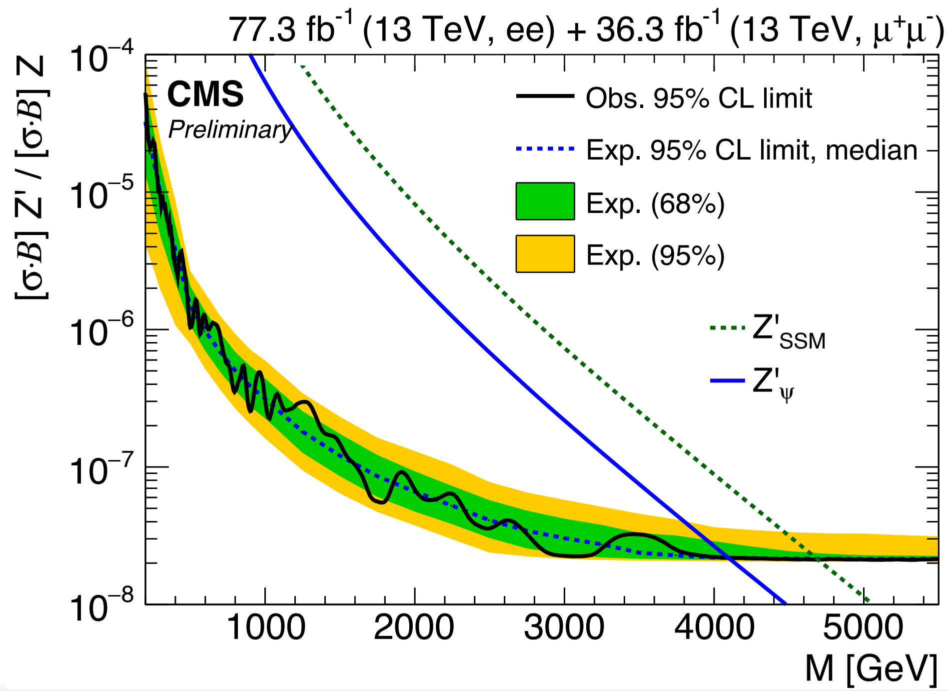


$Z' \rightarrow e^+e^-$

CMS-PAS-EXO-18-006

- The statistical analysis from the electron channel (41 fb^{-1}) and muon channel (36 fb^{-1}) are combined in order to place stronger limits on the lower bounds of the Z' mass
- Lower mass limits:
  - For the Z'_{SSM} m > 4.7 TeV
  - For the Z'_{ψ} m > 4.1 TeV

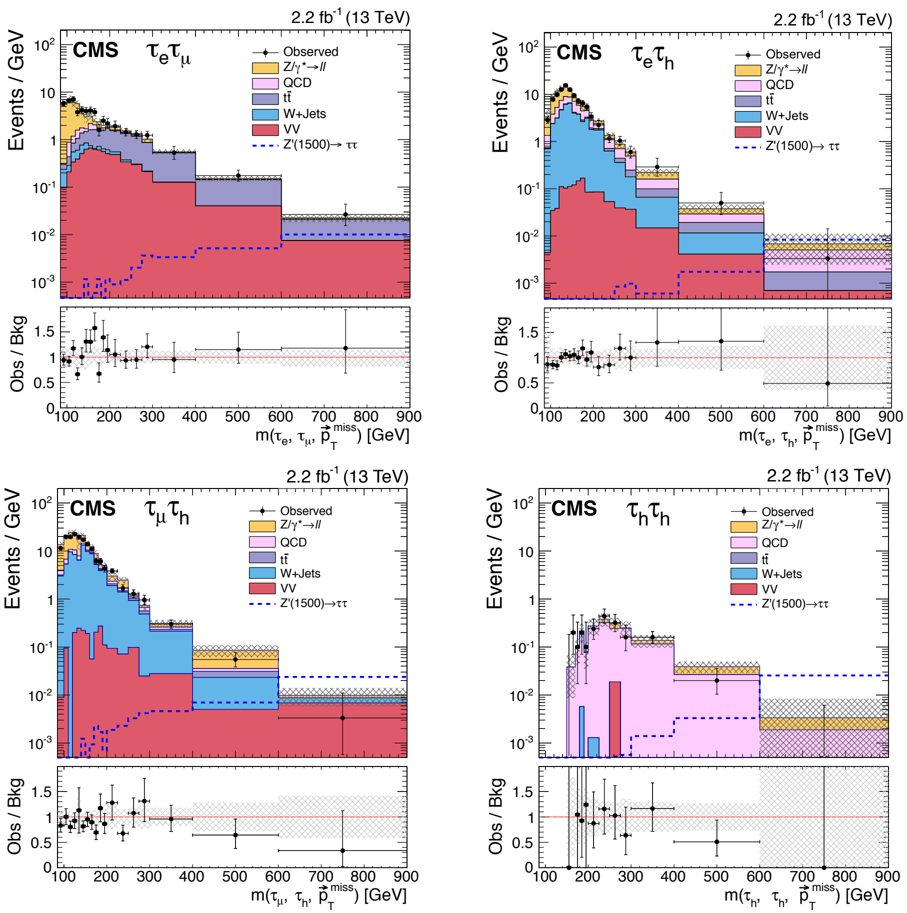


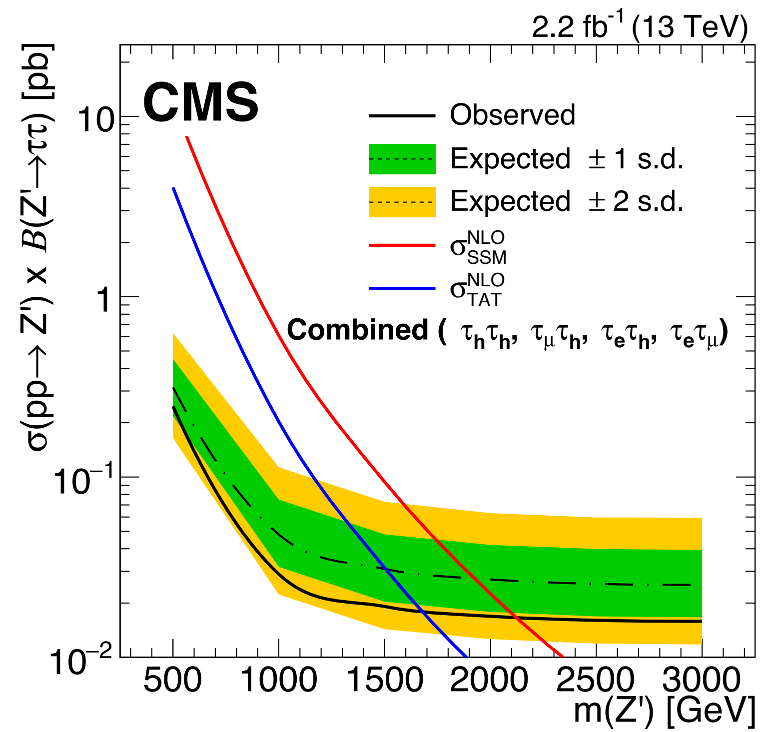


Z’→ $\tau\tau$

CMS-EXO-16-008

- Search for a Z’ also performed in decay to $\tau\tau$
- Especially motivated by models preferring Z’ couplings to the third generation
- Consider both hadronic and leptonic τ decays

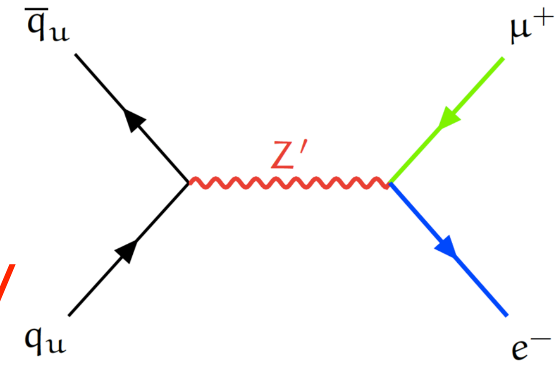




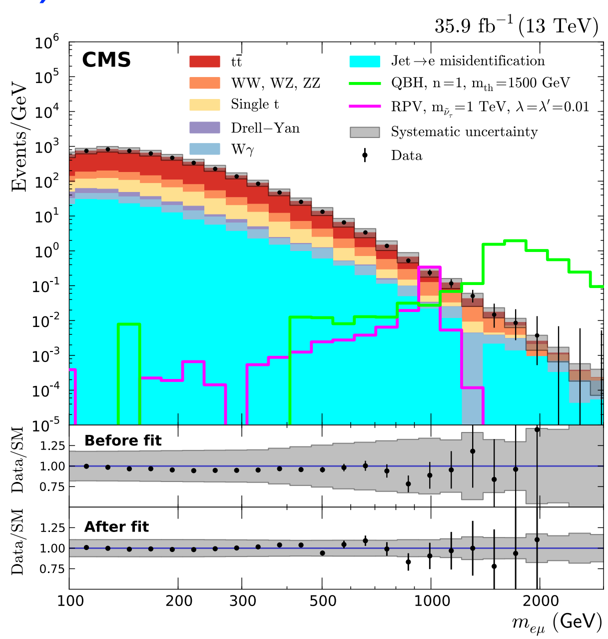
- Combining all four final states the exclusion limit for a SSM Z’ is 2.1 TeV.

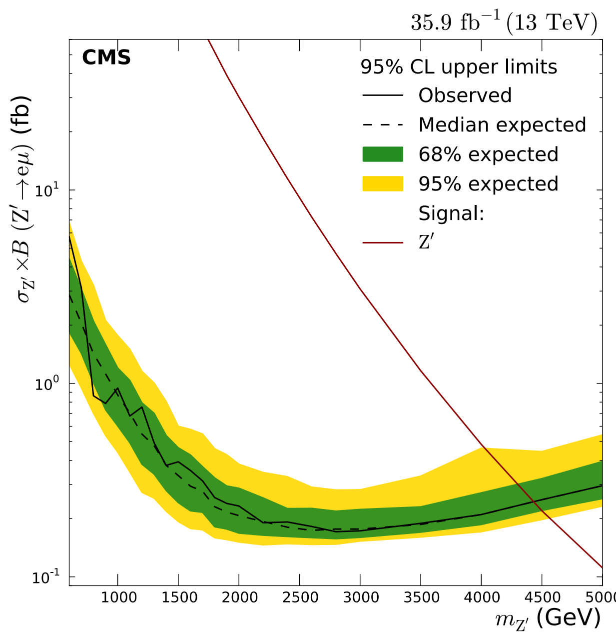
$X \to \mu e$

CMS-EXO-16-058



- Searching for heavy resonances decaying into eμ using 35.9 fb^{-1} (2016)
  - Model independent search
  - $p_T(e)>35$ GeV, $p_T(\mu)>53$ GeV, $p_T^{miss}>50$ GeV
- Heavy Z' gauge bosons with lepton-flavor violating transitions are excluded for masses up to 4.4 TeV
- m(X) > 1.7 TeV for RPV couplings $\lambda_{132}=\lambda_{231}=\lambda'_{311}=0.01$



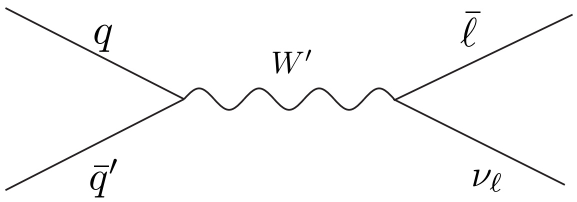


W’→μ/e+ν

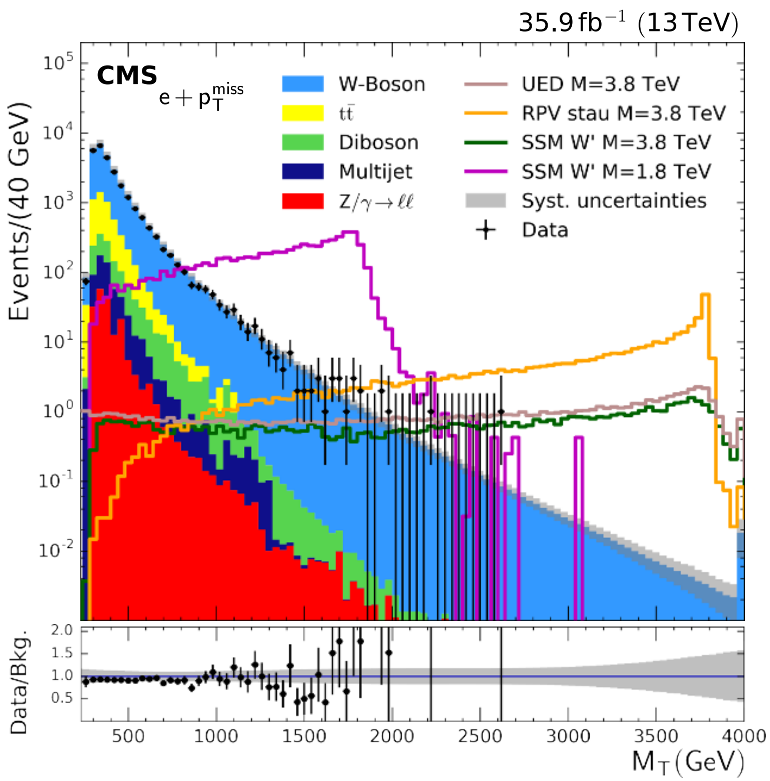
CMS-EXO-16-033

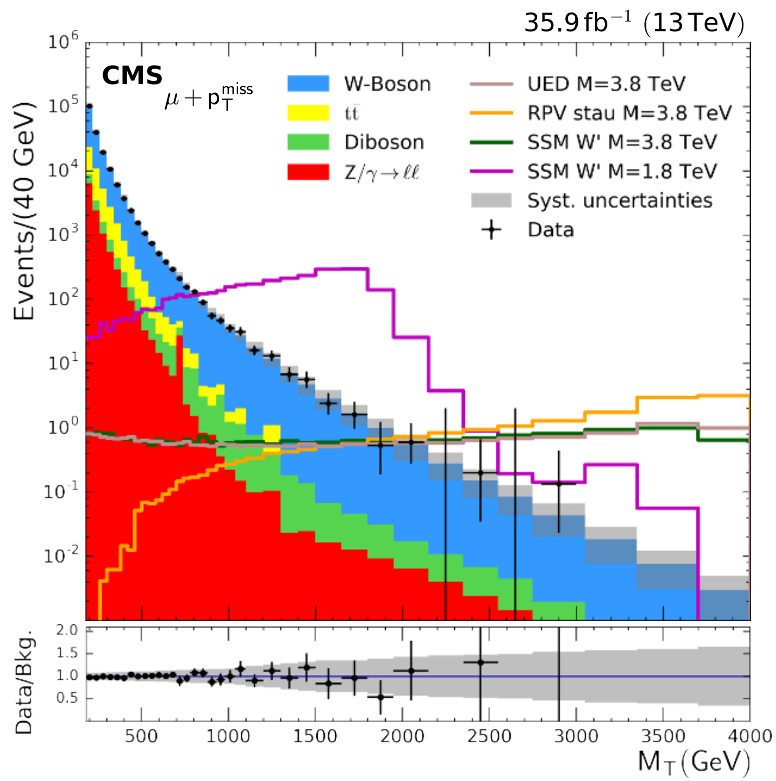
- Look for heavy W-like Jacobian peak in transverse mass

$$M_T = \sqrt{2p_T^l E_T^{miss}(1 - \cos[\Delta\phi(\vec{p}_T^{\,l}, \vec{p}_T^{\,miss})])}$$



- Dominant background: W production in standard model
- Take into account interference with SM

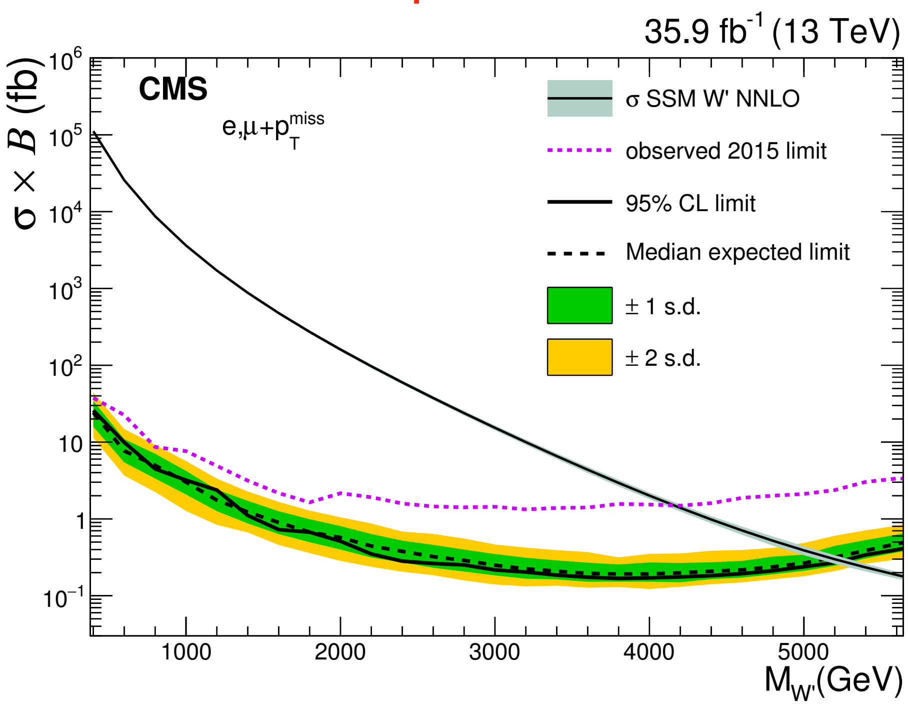


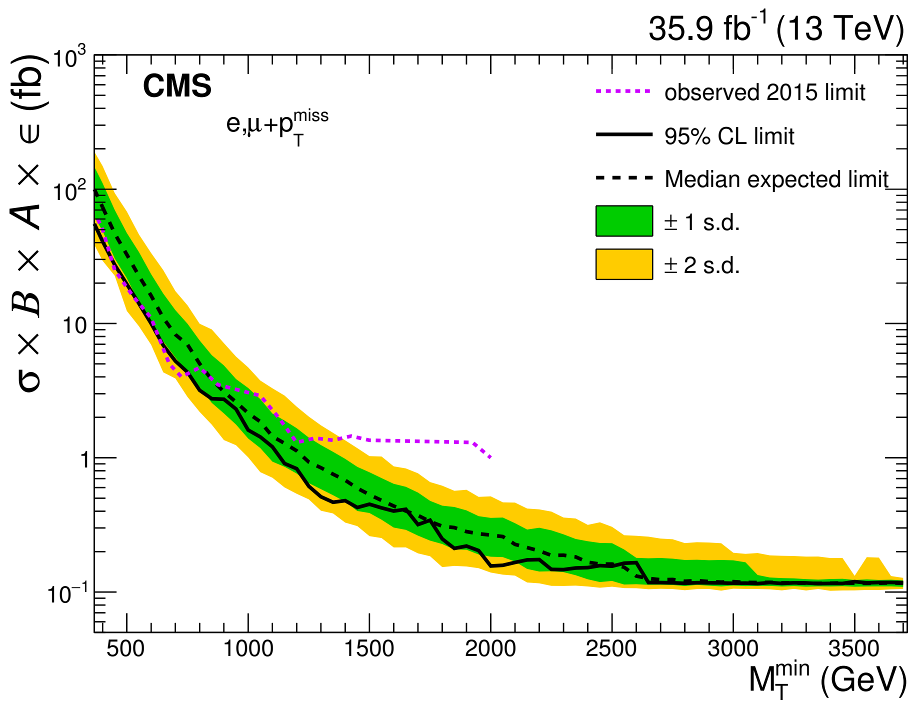


W'→μ/e+ν

CMS-EXO-16-033

- No significant excess → set exclusion limits
- Limits sets on SSM benchmark model with 8% BR into each lepton, no decays into W, H, Z bosons
- Combining both channels:
  - limits on sequential W' reach 5.2 TeV
  - model independent limits as function of minimum M_T for $X \to \ell\nu$

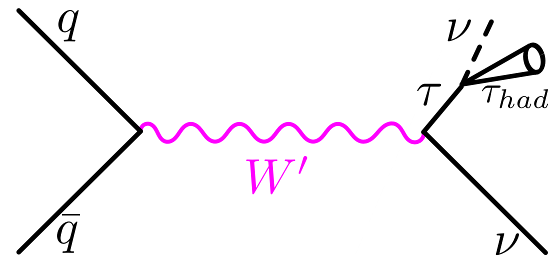




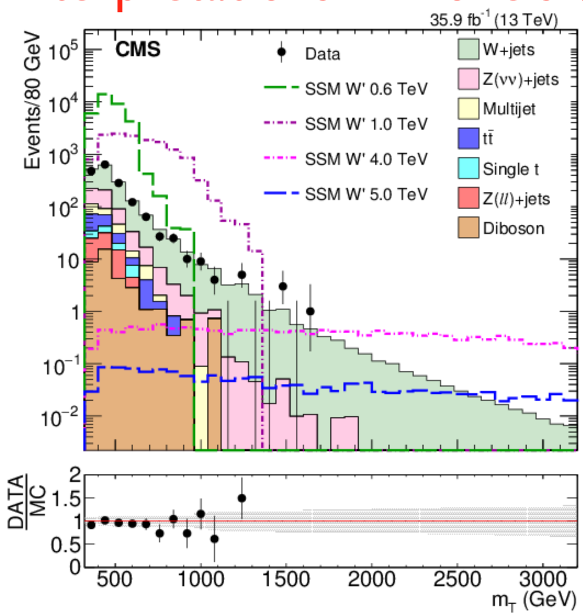
$W' \to \tau\nu$

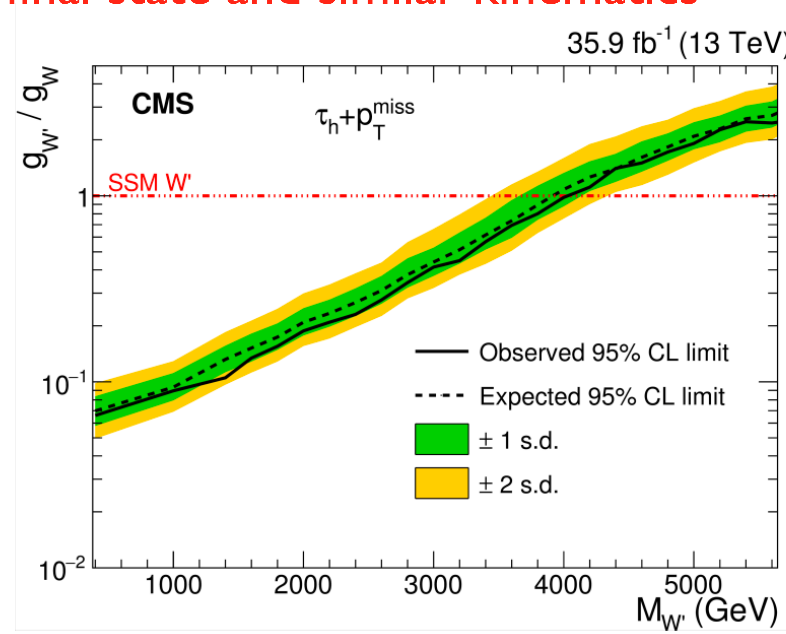
CMS-EXO-17-008

- Motivated by models preferring W' couplings to the third generation



- Limits sets on SSM benchmark model W'
  - $0.4 < M_{W'} < 4.0$ TeV at 95% confidence level
  - In addition, a model-independent limit is provided allowing other interpretations in models with the same final state and similar kinematics





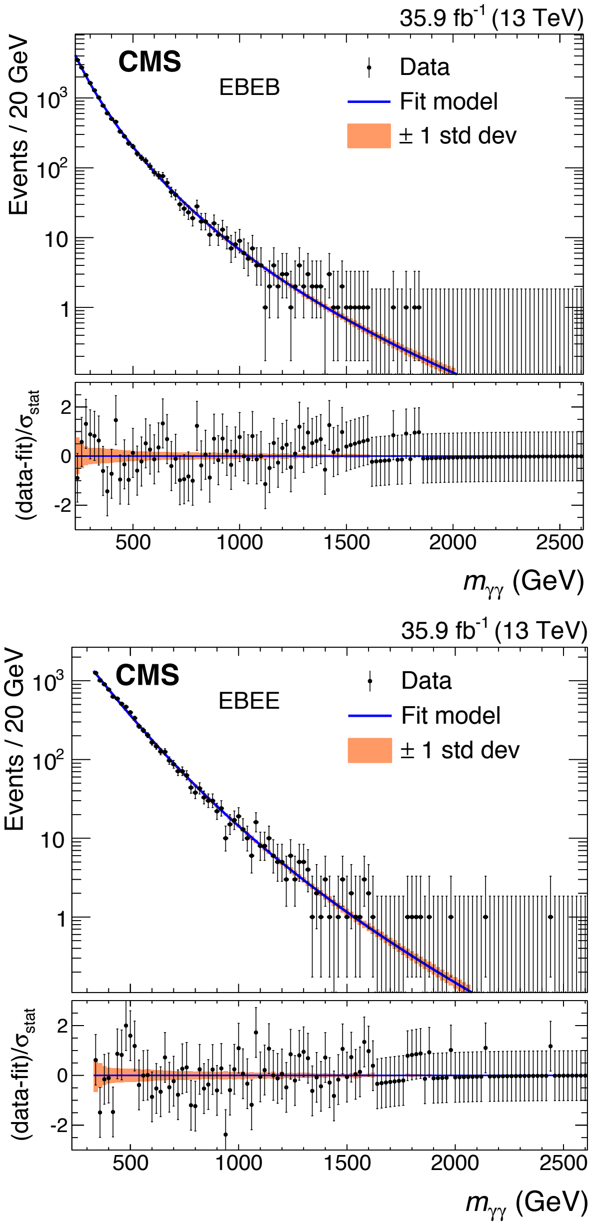
- For $M_{W'}$>180 GeV, $W' \to tb$ opens, affects $BR(W' \to \tau\nu)$=8.5% in SSM

$W' \to tb$ searches: Phys. Lett. B 788 (2019) 347 , Phys. Lett. B 777 (2017) 39

Di-Photon Search

CMS-EXO-17-017

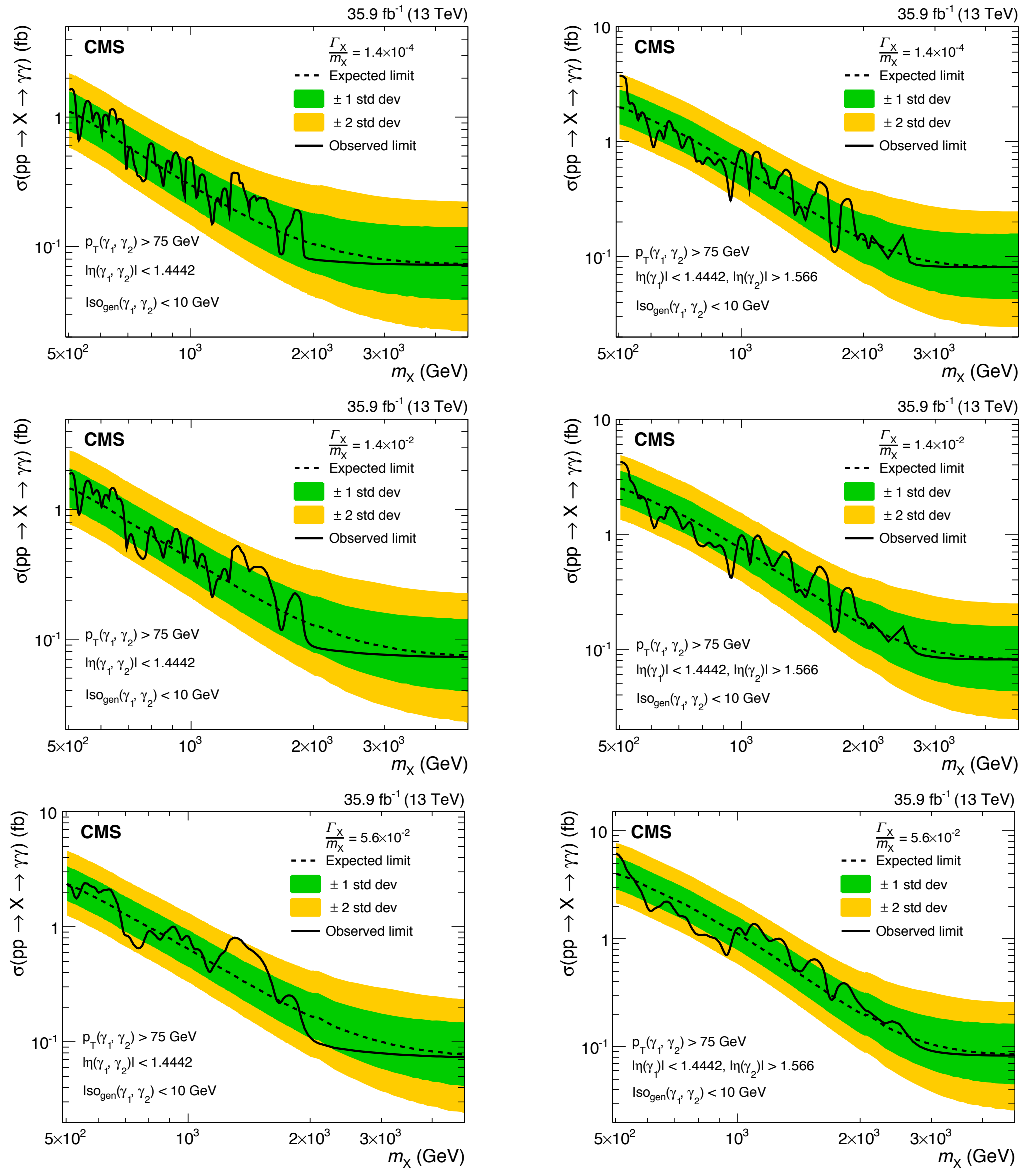
- Search for resonant production of photon pairs using 35.9 fb^{-1} (2016).
- A very clean state without additional activity in the direction of the two photons.
- Three values of the relative width Γ_X/m_X are used as benchmarks: 1.4×10^{-4}, 1.4×10^{-2}, and 5.6×10^{-2}; with $0.5<m_X<4.5$ TeV.
- Photons are required to have $p_T > 75$ GeV
- Events are categorized depending on the location of the two photons.
- A fit is performed to the invariant mass spectra to determine the compatibility of the data with the background-only and the signal+background hypotheses.



Di-Photon Search

CMS-EXO-17-017

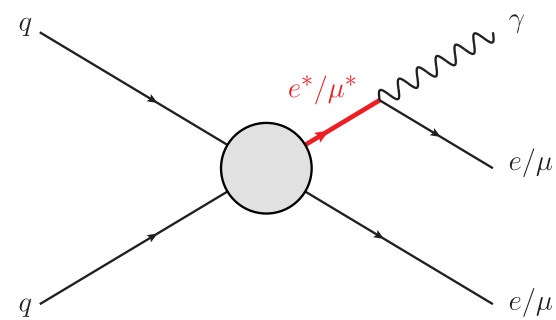
- Compatibility of the observation with the background-only hypothesis is evaluated by computing the background-only p-value.
- Lower limits on the mass of the RS graviton are set as:
  - m(RSG) > 2.3 TeV
    for $\tilde{k}$=0.01 $\Gamma_X/m_X = 1.4 \times 10^{-4}$
  - m(RSG) > 4.1 TeV $\tilde{k}$=0.1
    for $\tilde{k}$=0.1 $\Gamma_X/m_X = 1.4 \times 10^{-2}$
  - m(RSG)> 4.6 TeV $\tilde{k}$=0.2
    for $\tilde{k}$=0.2 $\Gamma_X/m_X = 5.6 \times 10^{-2}$
- Also, model independent limits on cross sections in the fiducial volume (p_T^γ>75 GeV) for resonant pp →γγ processes.

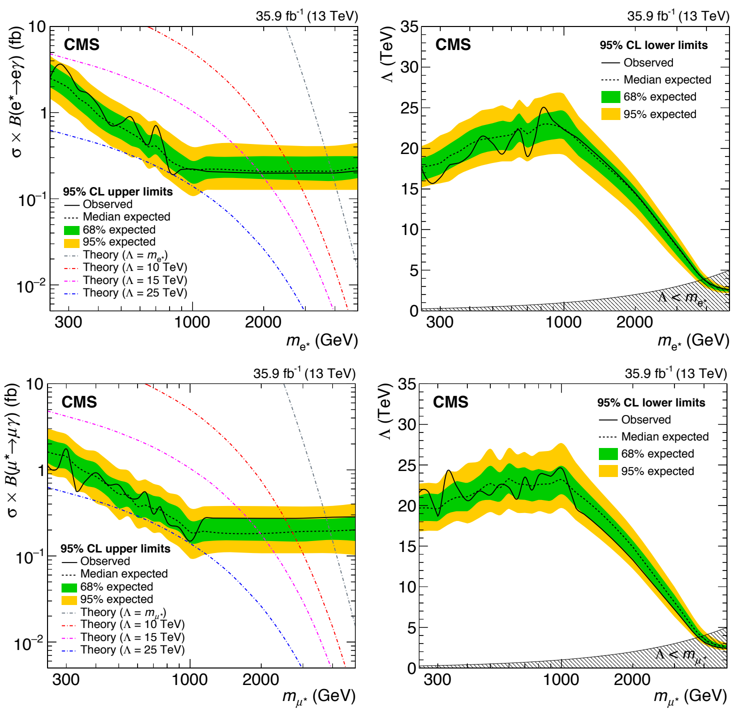


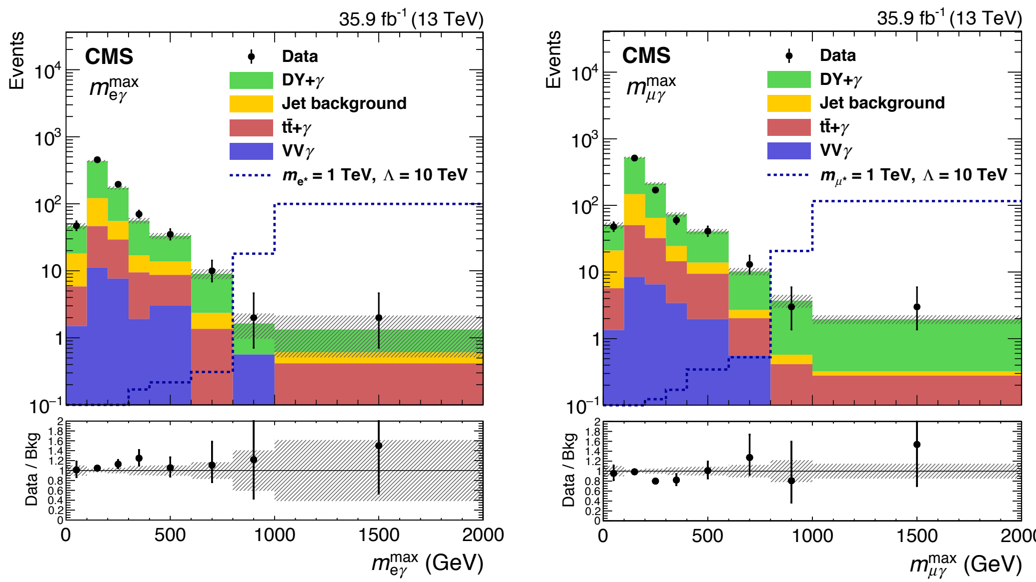
Excited Leptons

CMS-EXO-18-004

- Compositeness models predict excited leptons: e*(μ*)→eγ (μγ)
- Production through Contact Interactions (CI), decay via SM gauge interactions
- Final state: same-flavor lepton pair; low background but ambiguity in the e*/μ* reconstruction







Channel	Observed (expected) limit on m_{ℓ^*} for $m_{\ell^*} = \Lambda$, TeV	Observed (expected) limit on Λ for $m_{\ell^*} \approx 1$ TeV, TeV
$ee\gamma$	3.9 (3.8)	25 (23)
$\mu\mu\gamma$	3.8 (3.9)	25 (23)

Summary

- Extensive search program for heavy resonances at CMS
  - So far no significant hint for the existence of new physics.
  - Data at $\sqrt{s}$ = 13 TeV offers sensitivity to new resonances in the multi-TeV range.
  - Further progress will be slower as more and more data comes in, but the centre-of-mass energy stays the same.
  - Still a lot of information to be gained from last year's dataset and more results to come in the next months.

- Searches for BSM physics will continue to explore uncharted territories
  - Stay tuned!