Searches for new heavy resonances in final states with leptons, photons, and jets in CMS

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On behalf of the CMS Collaboration

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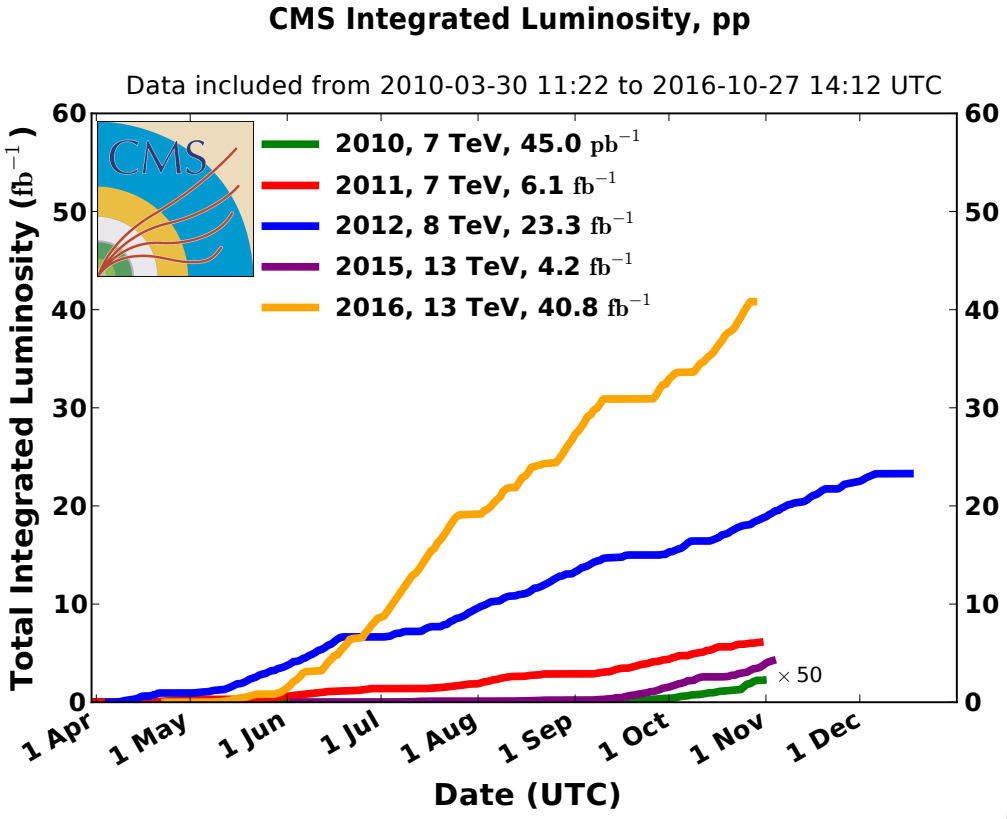
- Summary

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: 2016 data crucial for these searches
- A multitude of searches target anomalous production of resonant/ non-resonant di-leptons, di-jets and di-bosons 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)

LHC Performance

- About 40 fb^{-1} has been delivered by the LHC in 2016, exceeding the integrated luminosity accumulated in all years before 2016 and expectations.
- The CMS detectors has been working spectacularly with virtually no degradation in performance over the 3 years of Run 1 and 2 years of Run 2.



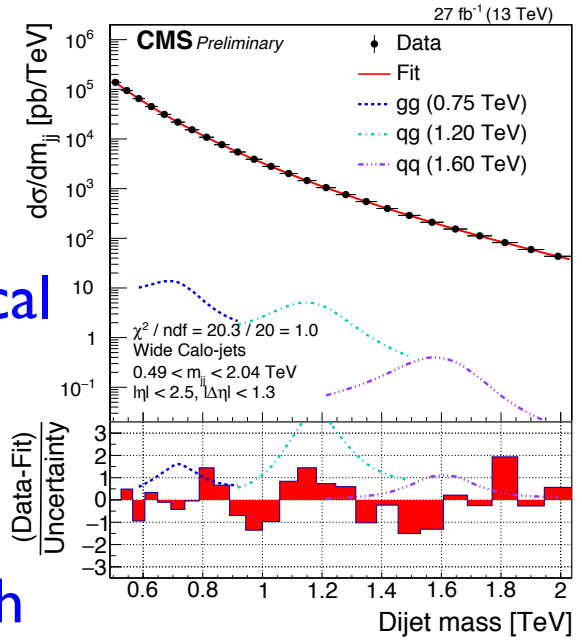
Extended Gauge Symmetries

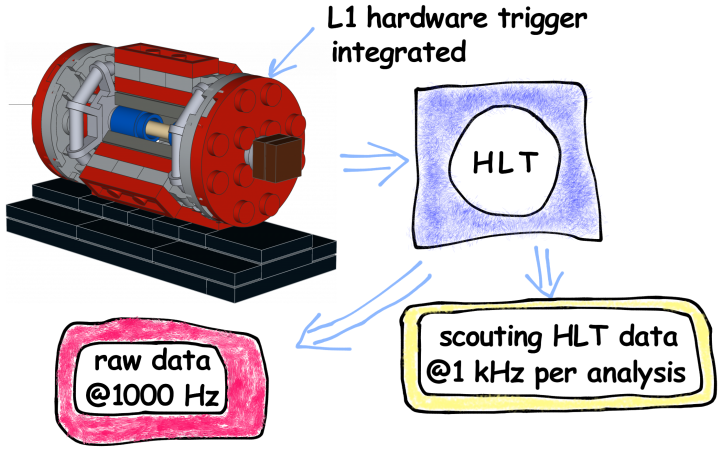
- New gauge bosons predicted by many extensions of the Standard Model with extended gauge symmetries
  - Sequential Standard Model Z_{SSM} with same coupling as in Standard Model
  - Z'_{ψ}, Z'_{χ}, Z'_{η} models from E6 and SO(10) GUT groups
  - Left-Right symmetry model (LRM) and Alternative LRM (ALRM)
  - The Kaluza-Klein model (KK) from Extra Dimensions
- No precise prediction for mass scale of gauge bosons
- Discrimination of different models requires measurement of
  - cross section, mass, width, angular distributions
- Backgrounds
  - relatively clean with good S/B
  - mostly tails of SM processes
- Experimental challenges
  - understanding detector resolution is key
  - 1.3% − 2.4% for electrons and 7% for muons at 1 TeV

Di-jet Resonances

CMS-PAS-EXO-16-056

- New particles coupling to quarks and gluons could be observed as resonances in the di-jet mass spectrum
- Search motivated by a wide range of hypothetical new particles
  - sensitive to quantum black holes, excited quarks, W'/Z', contact interactions
- Due to trigger thresholds, standard di-jet search at LHC explores higher masses (>1.5 TeV)
- Two ways to explore lower masses
  - Di-jet + ISR → use ISR jet to get above the trigger thresholds; jet substructure
  - Data-scouting (trigger-level) analysis based on low-threshold triggers writing only very limited information about the event





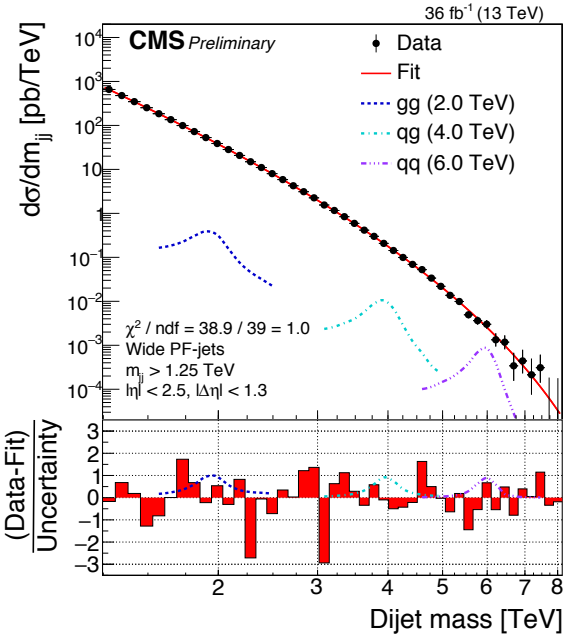
Di-jet Resonances

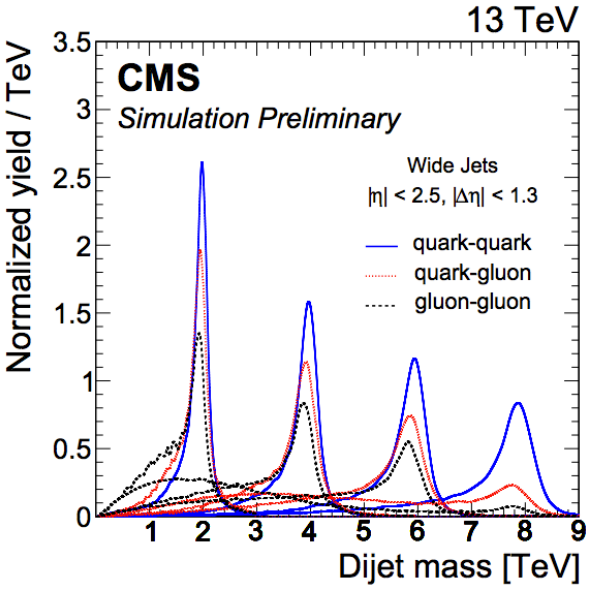
CMS-PAS-EXO-16-056

- Trigger requires scalar sum of the transverse momenta of the jets H_T > 900 GeV
  - Trigger fully efficient at m_{jj} > 1.25 TeV
- Fit smoothly falling di-jet background (full mass range) with:

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

- Search for bumps in di-jet mass spectrum
  - compare binned m_{jj} data to the fitted background estimate
- Finals states with gluons have more FSR and wider resonances → Limit depends on final state
  - Different signal shapes for qq, qg, gg final states



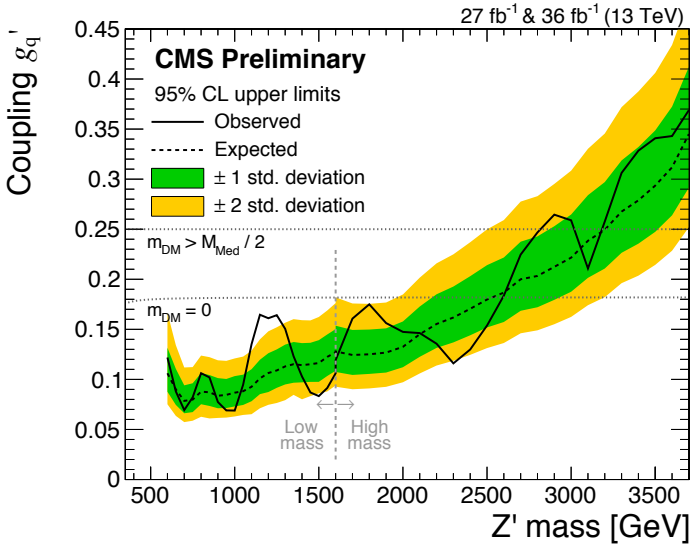


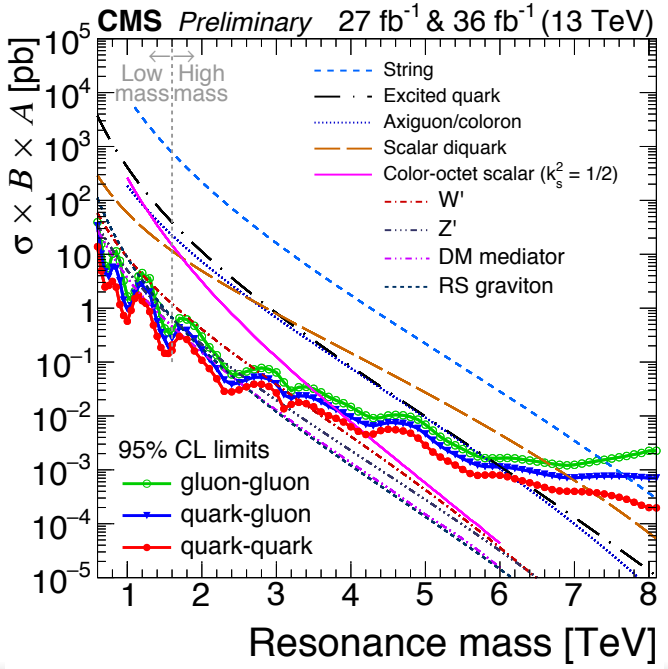
Di-jet Resonances

CMS-PAS-EXO-16-056

- Global significance is computed with pseudo experiments
- Upper limits on nine benchmark models
- No significant excess observed

Model	Final State	Observed (expected) mass limit [TeV] 36 fb^{-1} 13 TeV	12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.7 (7.7)	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	7.2 (7.4)	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$q\bar{q}$	6.1 (6.0)	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	6.0 (5.8)	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4 (3.6)	3.0 (3.3)	—	—
W'	$q\bar{q}$	3.3 (3.6)	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
Z'	$q\bar{q}$	2.7 (2.9)	2.1 (2.3)	—	1.7 (1.8)
RS Graviton ($k/M_{PL} = 0.1$)	$q\bar{q}$, gg	1.7 (2.1)	1.9 (1.8)	—	1.6 (1.3)
DM Mediator ($m_{DM} = 1$ GeV)	$q\bar{q}$	2.6 (2.5)	2.0 (2.0)	—	—

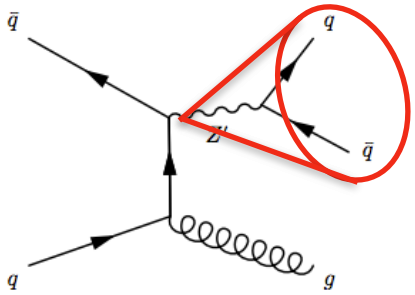


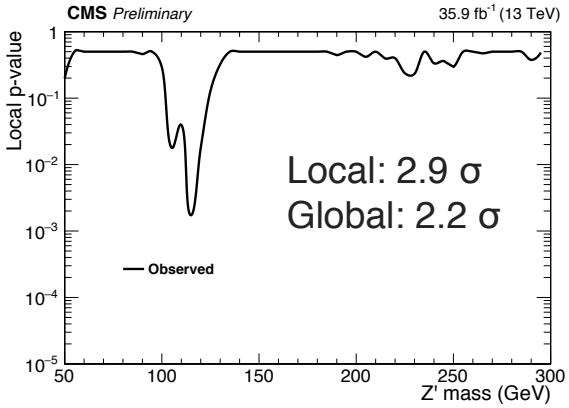


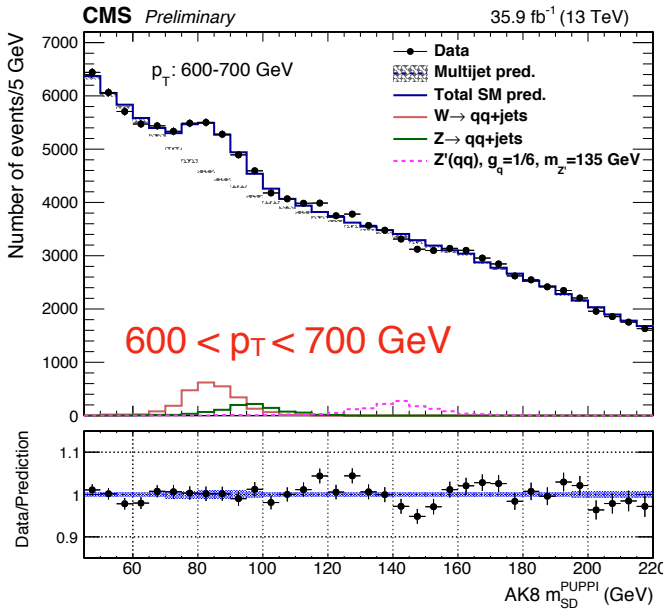
Di-jet + ISR

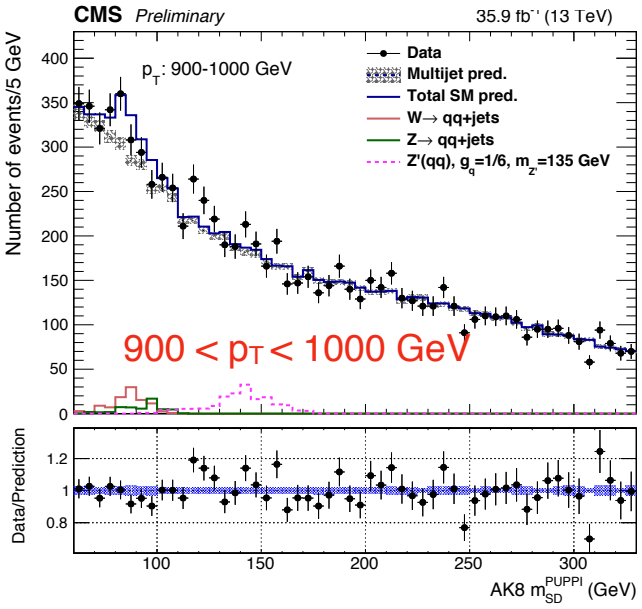
CMS-PAS-EXO-17-001

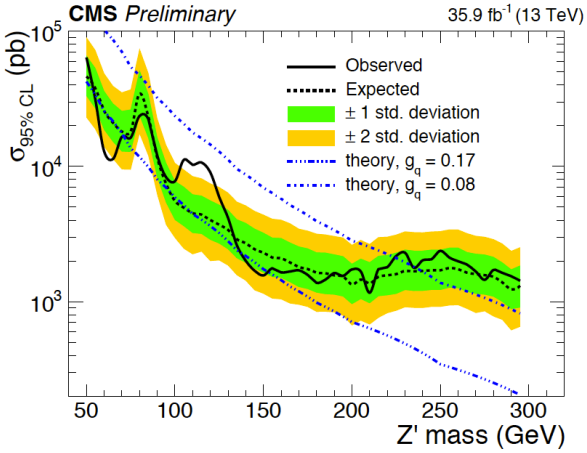
- Exploring low mass with di-jets
- Boosted regime: New particles not produced at rest
- Data-driven background estimation using control regions
- Merged di-jet + ISR jet
- Mild excess ~115 GeV







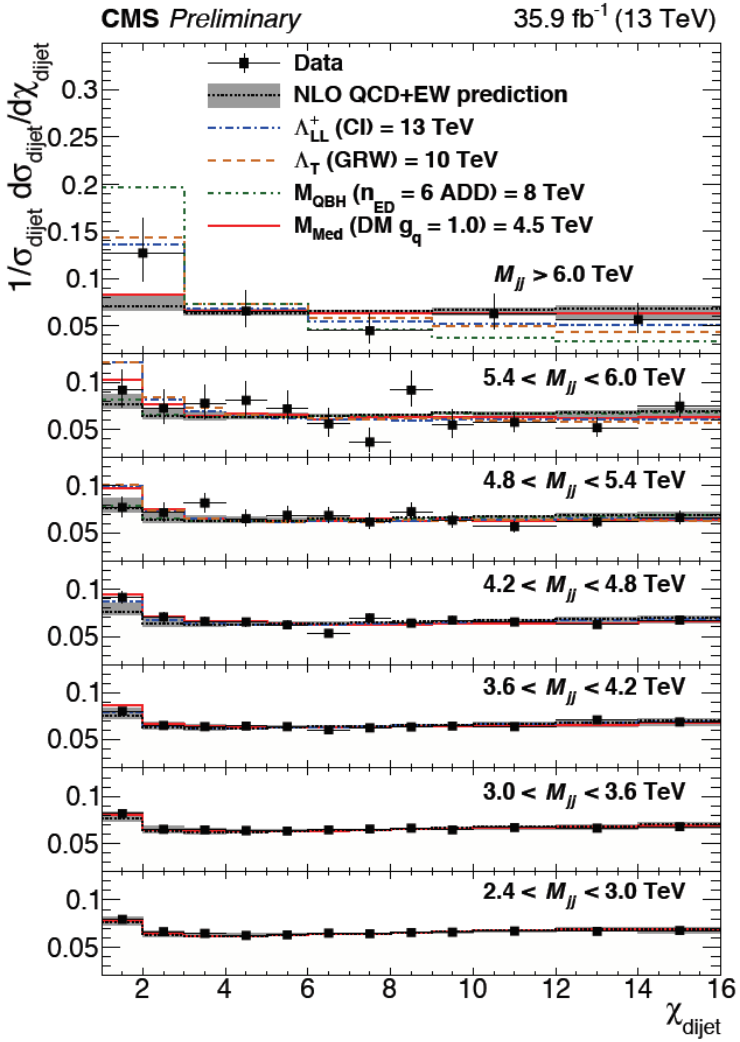


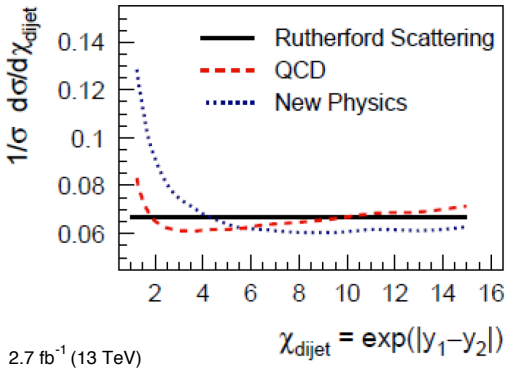


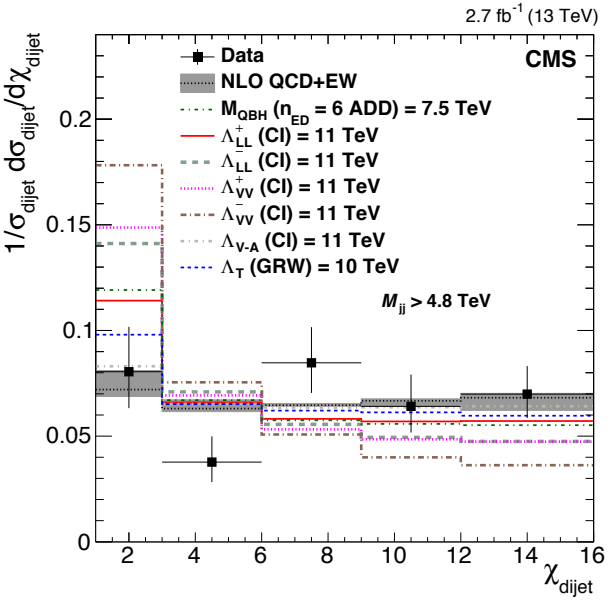
Di-jet Angular Analysis

CMS arXiv:1703.09986

- Use variable $\chi = e^{2|y^*|} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$







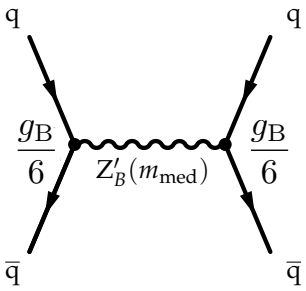
- ADD: $M_{Pl} > 7.9 - 11.2$ TeV
- Compositeness: $\Lambda > 11.5 - 14$ TeV
- $M_{QBH} > 5.3 - 7.8$ TeV

Coupling Limits

B. Dobrescu, F. Yu
arXiv:1306.2629

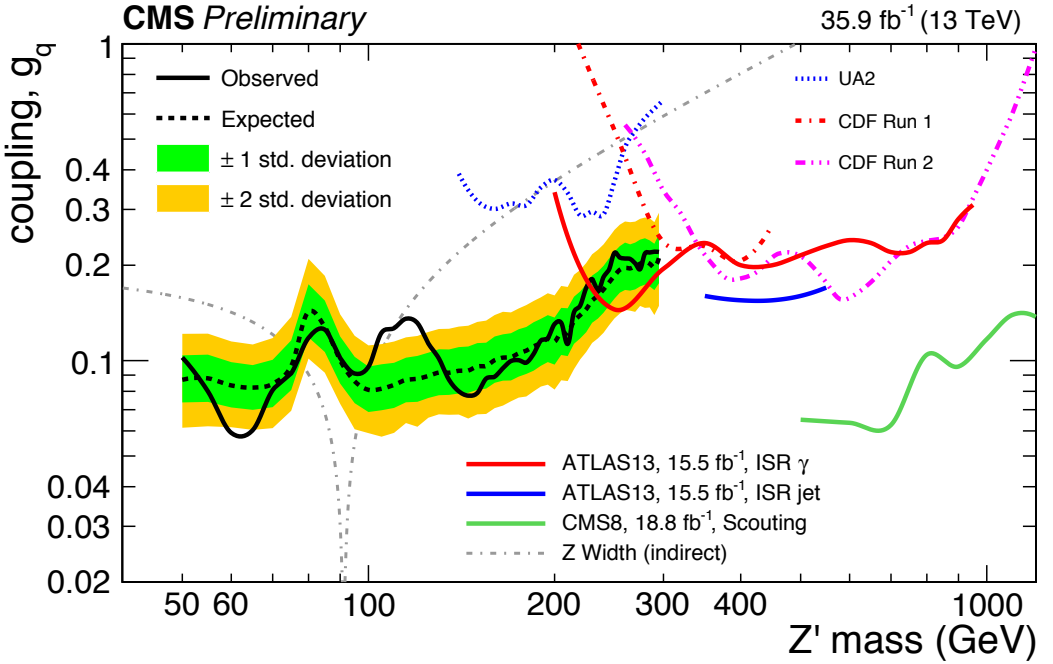
- Universal quark coupling to leptophobic Z'_B: $g_q = g_B/6$

$$\mathcal{L} \propto \frac{g_B}{6} Z'_{B\mu} \bar{q} \gamma^\mu q$$



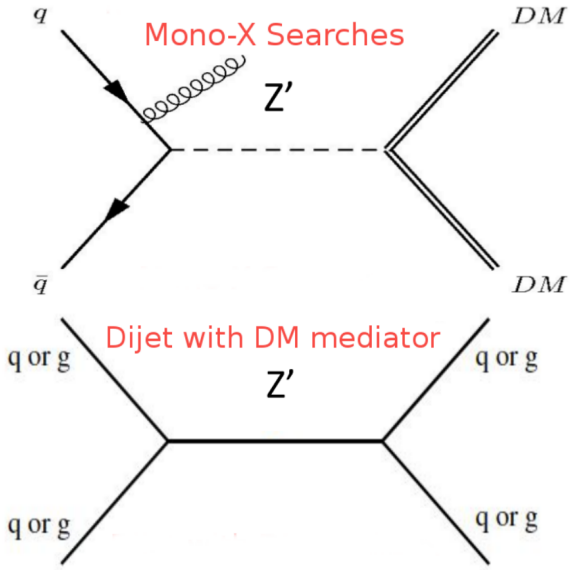
- Limits on the coupling g_q from various searches:
  - Probed masses down to 50 GeV
  - Provided stringent limits in 50-200 GeV
  - Di-jet + ISR photon/jet provided strong constraint above 200 GeV

CMS-PAS-EXO-17-001



Dark Matter Interpretation

- Results from di-jet bump search, di-jet angular search, di-jet boosted search can be interpreted for Dark Matter search
- DM mediator can decay to di-jets or dark matter pairs
- Set limits on the DM mediator in the plane (Mediator mass, DM mass or quark coupling)



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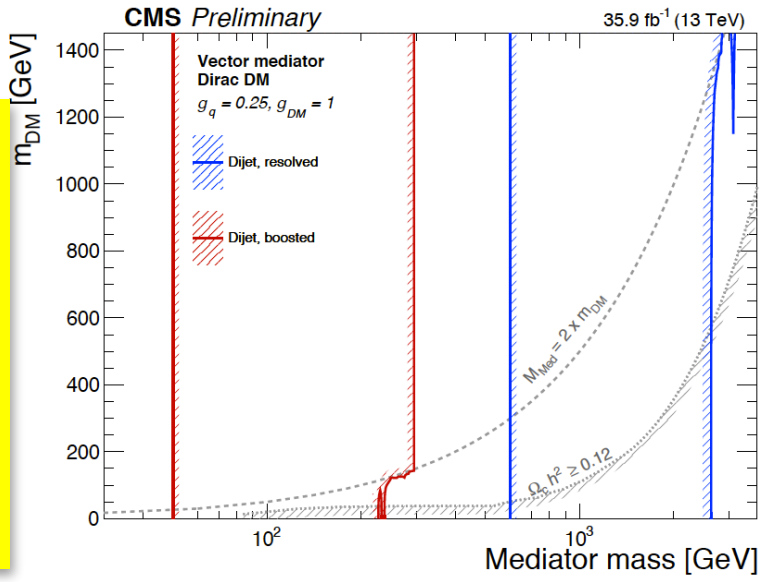
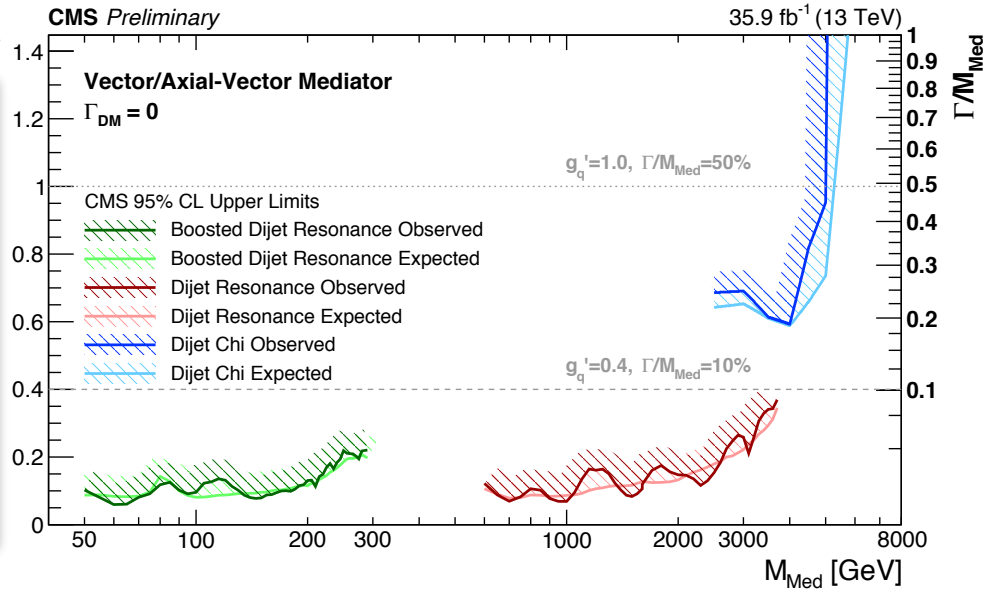


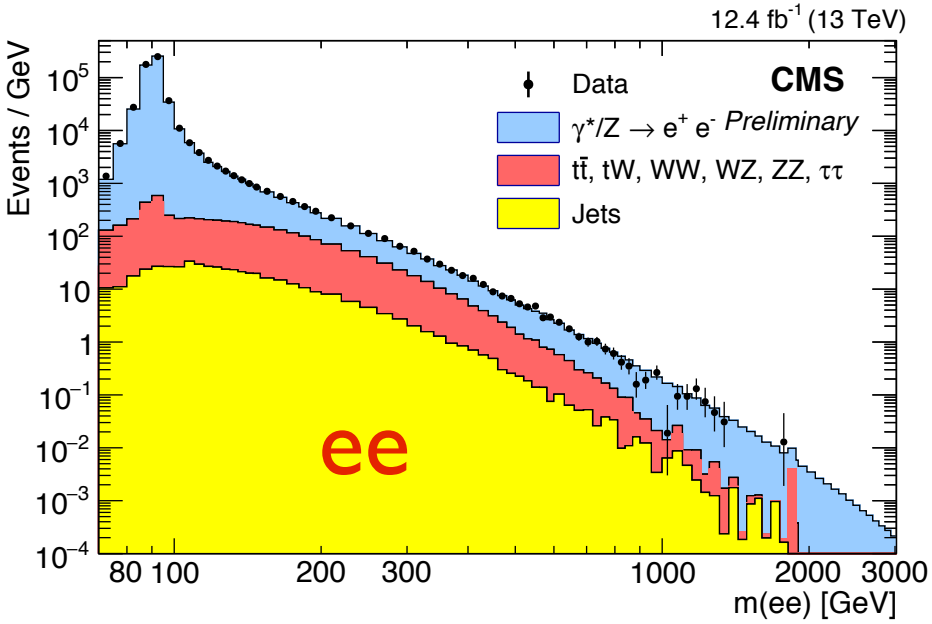
CMS-PAS-EXO-16-046

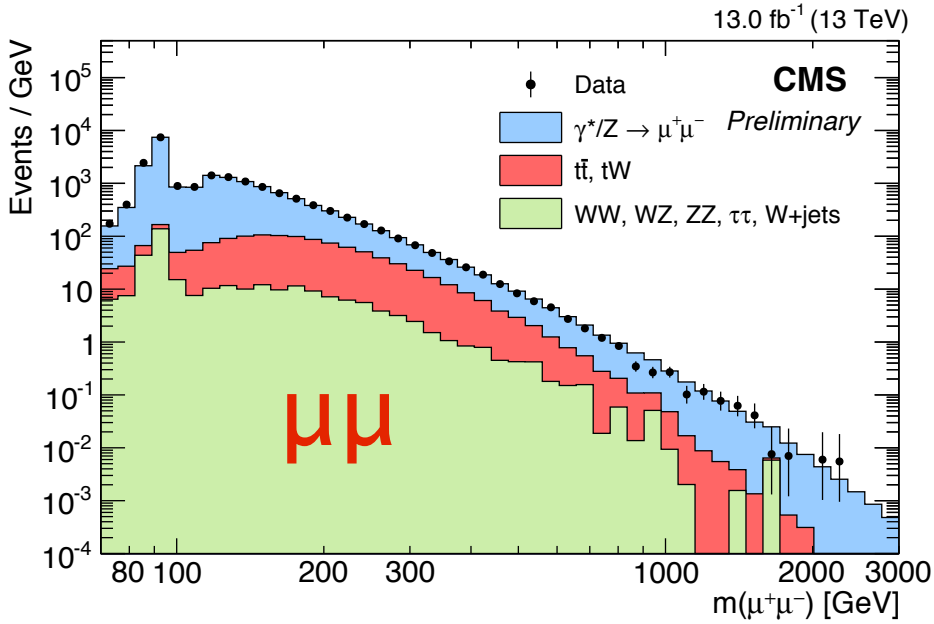


$Z' \rightarrow \ell^+\ell^-$

CMS-PAS-EXO-16-031

- Search for narrow resonances in $m_{\ell\ell}$ distributions above SM background
- Main background: Drell-Yan
- The amount of jet background is estimated from data
- Exclusion limits are set on the ratio $\sigma(Z')/\sigma(Z)$ using an unbinned maximum likelihood fit to the data

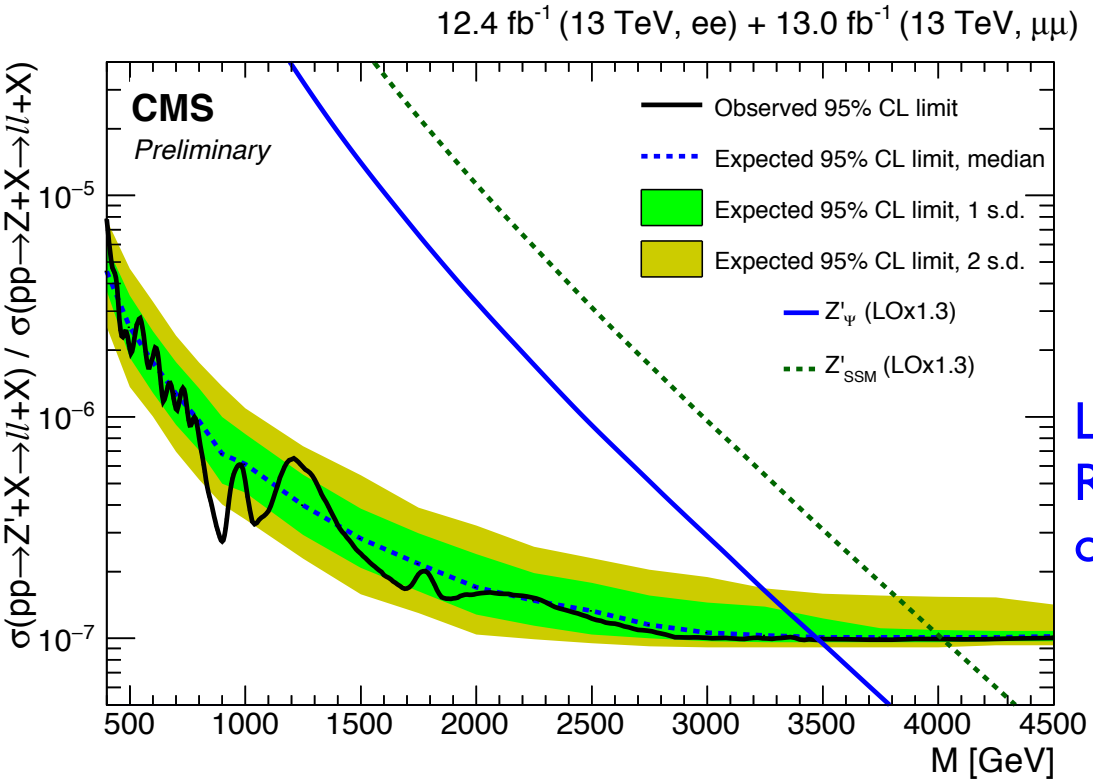




$Z' \rightarrow \ell^+\ell^-$

CMS-PAS-EXO-16-031

- The statistical analysis from the electron channel and muon channel are combined in order to place stronger limits on the lower bounds of the Z' mass
- Limits on sequential Z' : 4 − 4.5 TeV

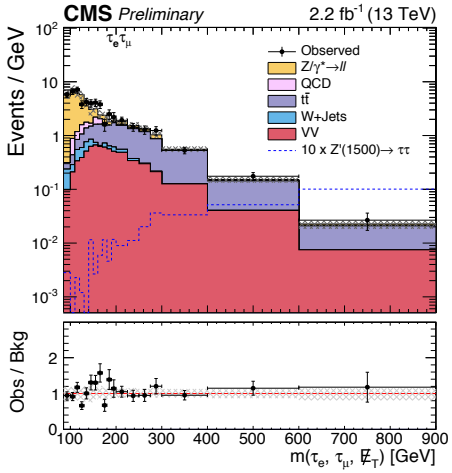


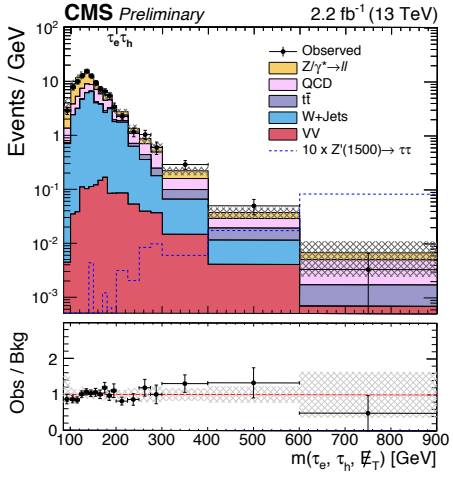
Limits weaken above 3.5 TeV: Rapidly falling signal x-sections and off-shell low mass signal tail.

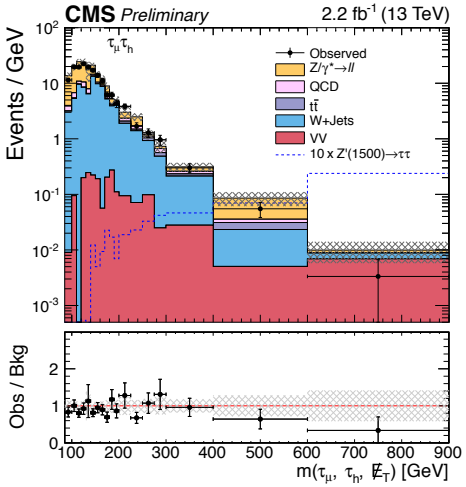
$Z' \rightarrow \tau\tau$

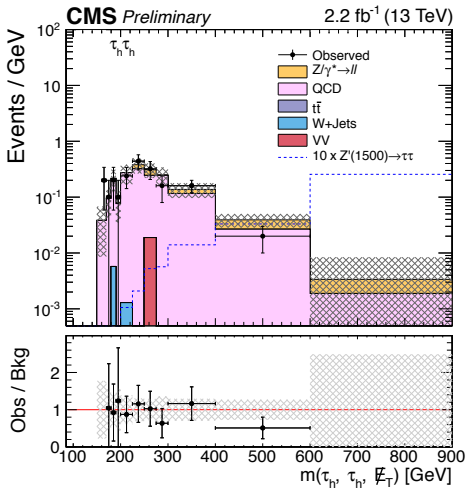
CMS JHEP 02 (2017) 048

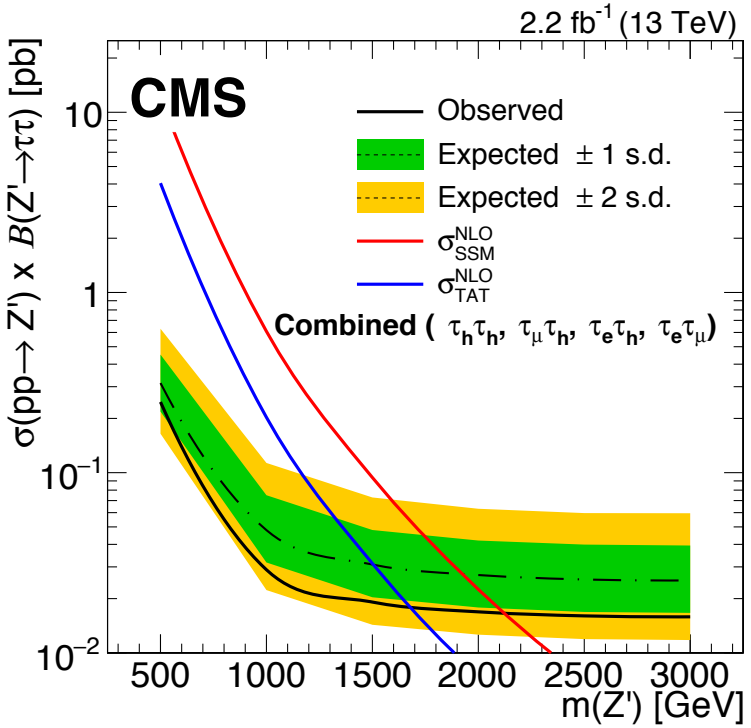
- Search for a Z' also performed in decay to $\tau\tau$
- Especially motivated by models preferring Z' couplings to the third generation
- Consider both hadronic and leptonic τ decays











- Lower mass limit for a SSM Z': 2.1 TeV
- As the Z' production is dominated by light quark annihilation, the overall exclusion limit is weaker: 1.7 TeV

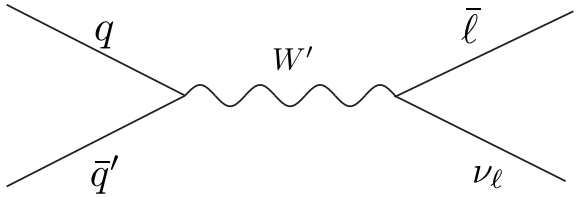
W'→μ/e+ν

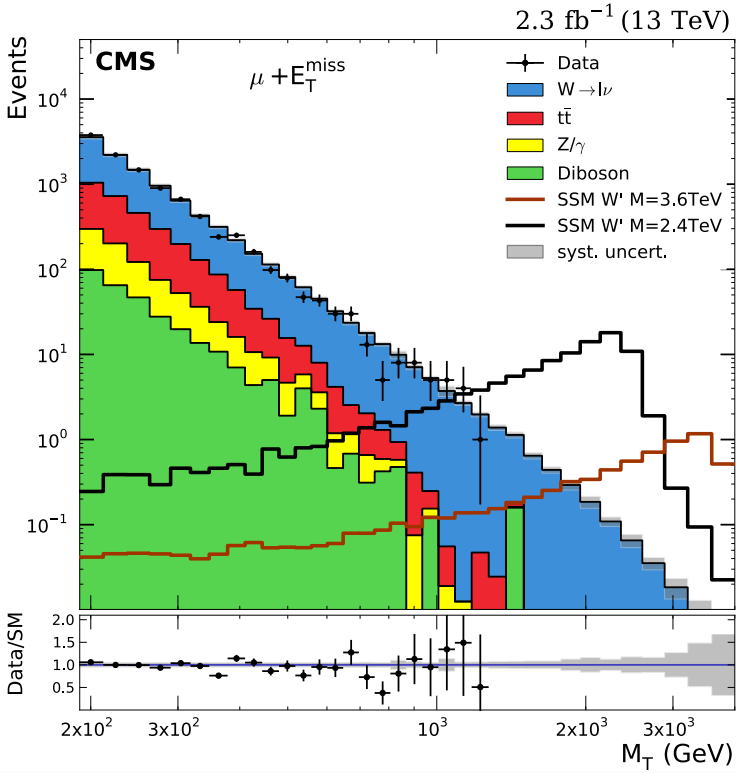
Phys. Lett. B 770 (2017) 278
arXiv:1612.09274

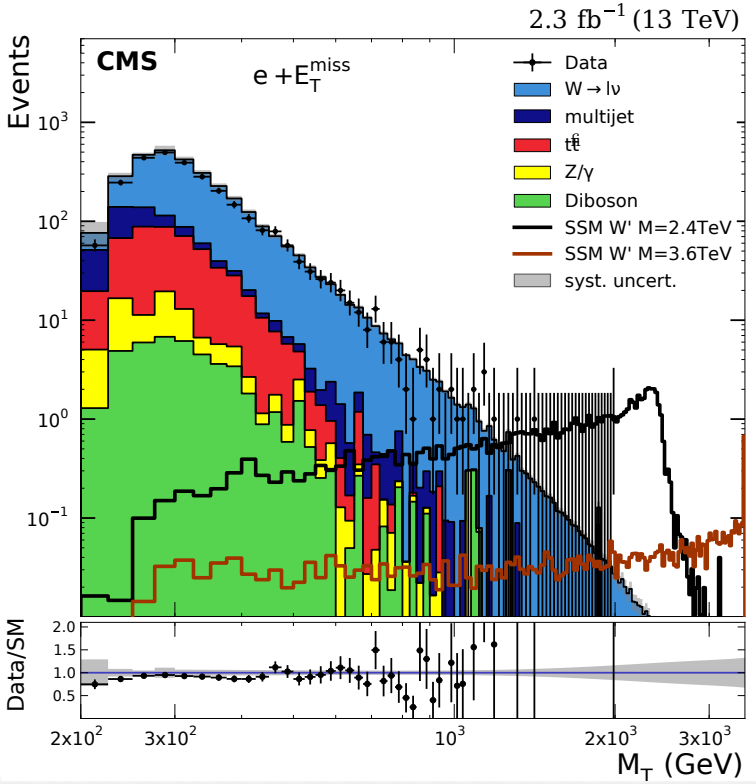
- Look for heavy W-like Jacobian peak in transverse mass

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

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



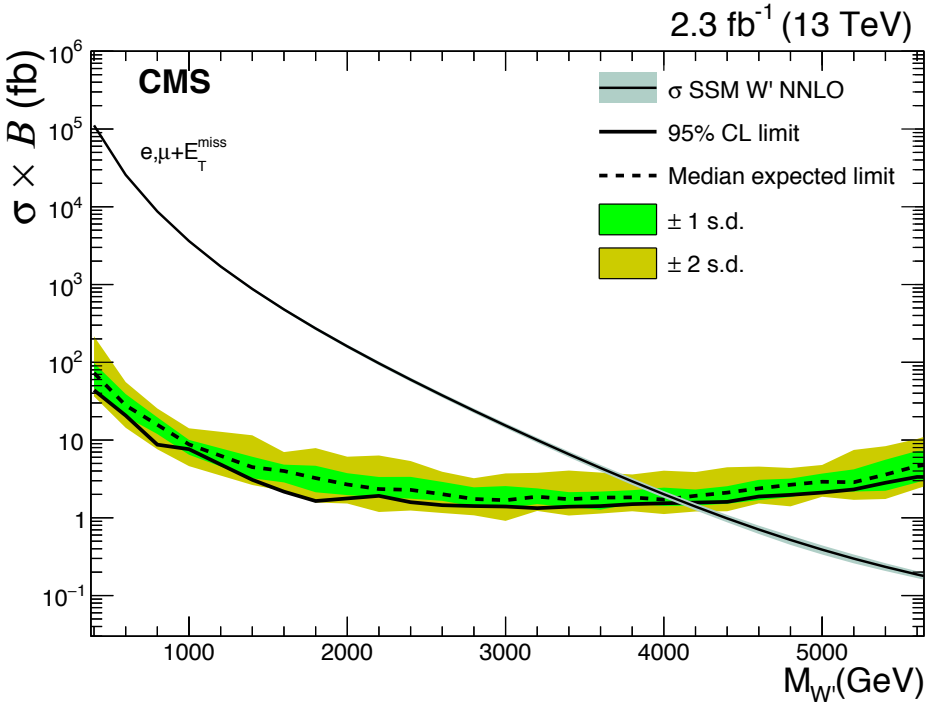


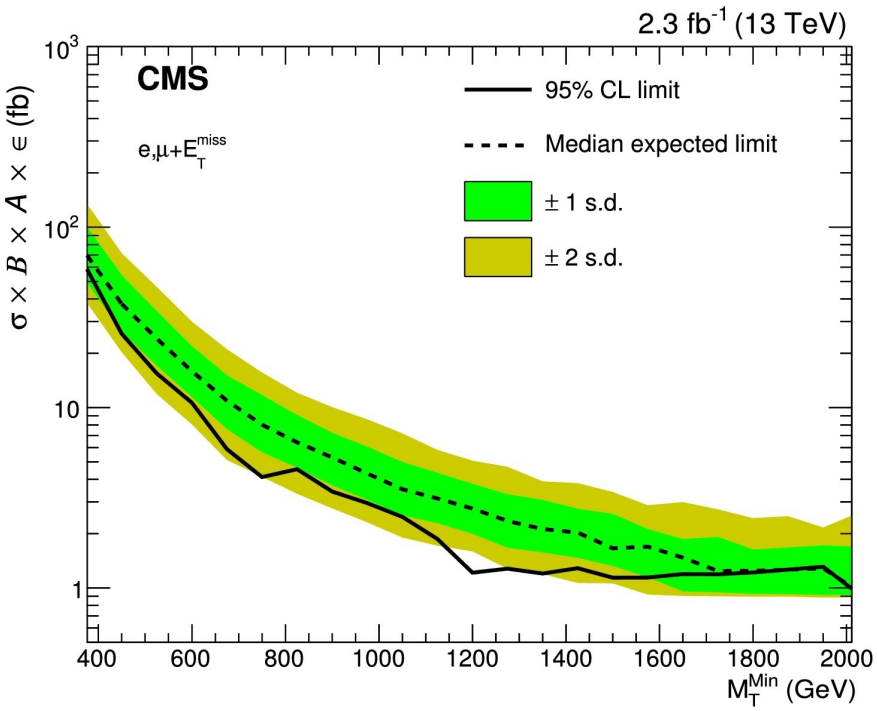


W'→μ/e+ν

Phys. Lett. B 770 (2017) 278
arXiv:1612.09274

- 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 4 - 5 TeV

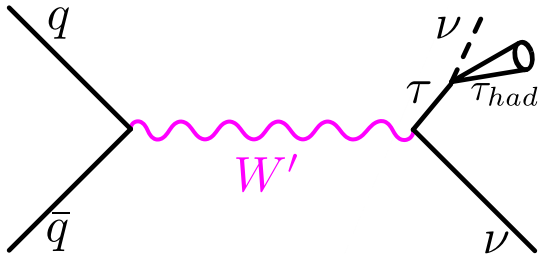


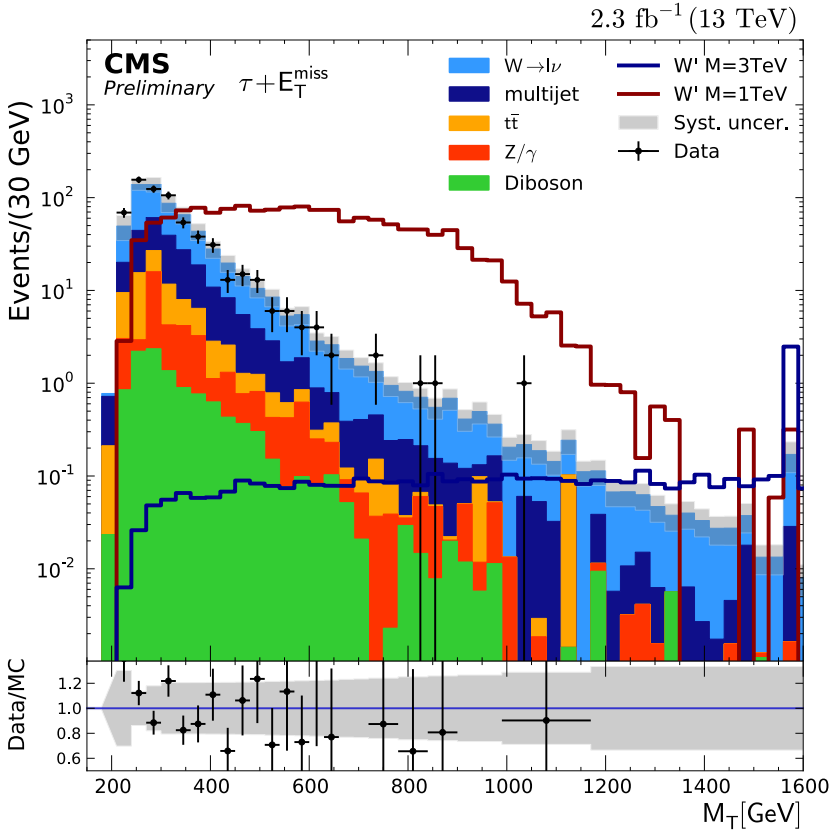


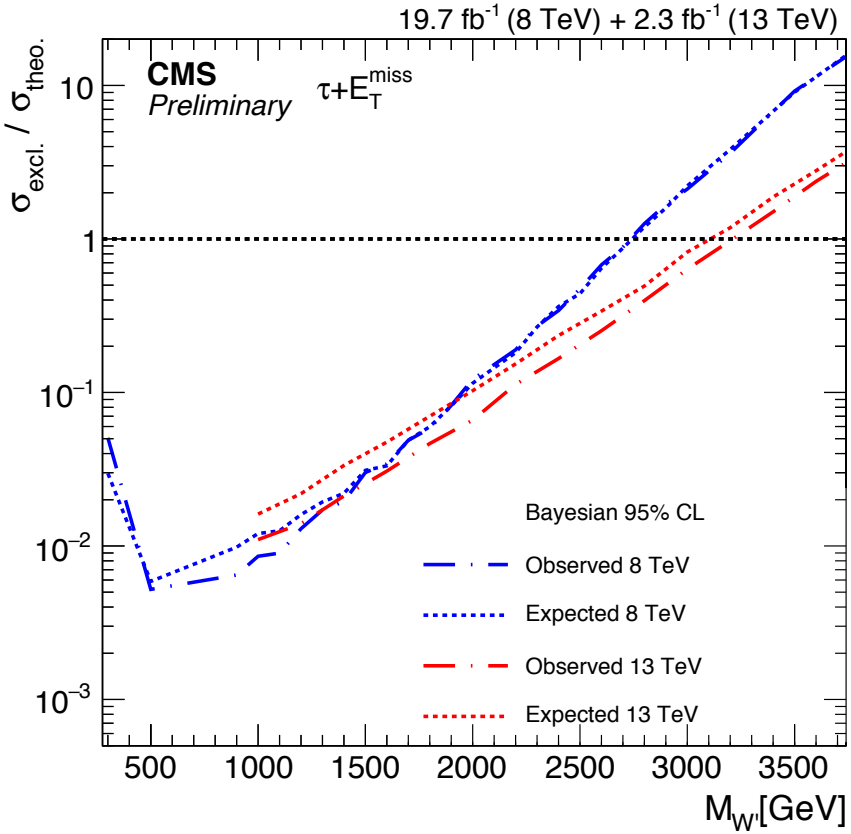
W'→τν

CMS-PAS-EXO-16-006

- Motivated by models preferring W' couplings to the third generation
- Limits sets on SSM benchmark model
  - limits on sequential W' reach 3.3 TeV



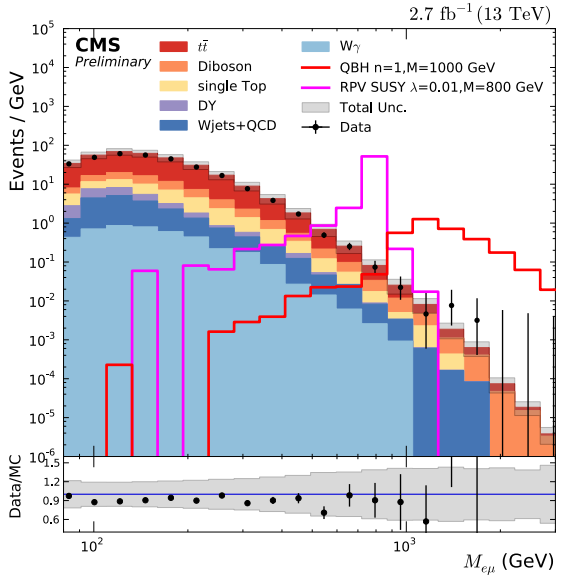


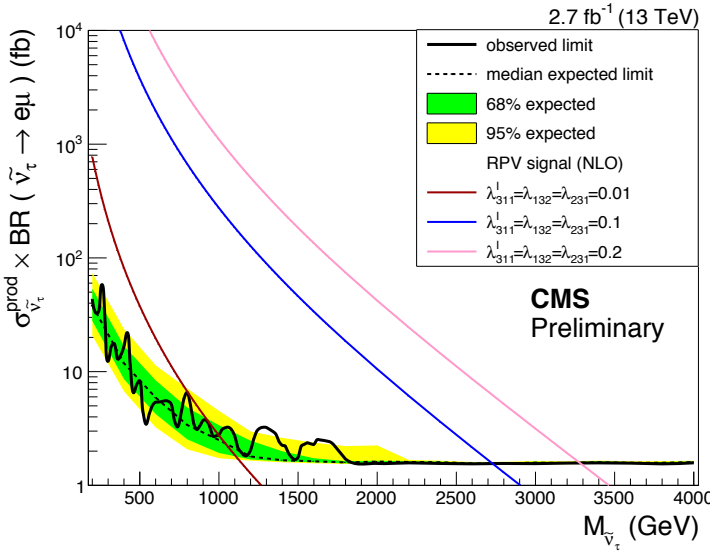


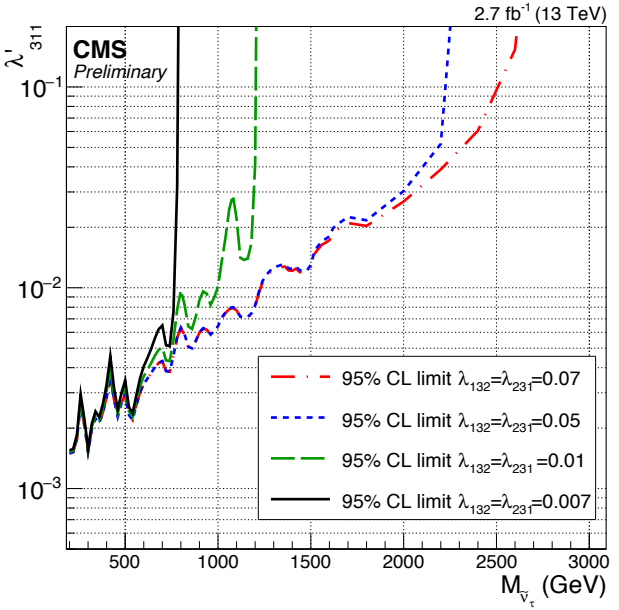
X→μe

CMS-PAS-EXO-16-001

- Searching for heavy resonances decaying into eμ using 2.7 fb^{-1} (2016)
- Lepton Flavour Violation may occur in models including τ sneutrino production in R-parity violating (RPV) supersymmetry (SUSY)RPV. SUSY also naturally generates non-zero neutrino masses.
- m(X) > 1.0, 2.7, 3.3 TeV for RPV couplings $\lambda_{132}=\lambda_{231}=\lambda'_{311}=0.01, 0.1, 0.2$
- In narrow width approximation the σ×BR scales with the RPV coupling.

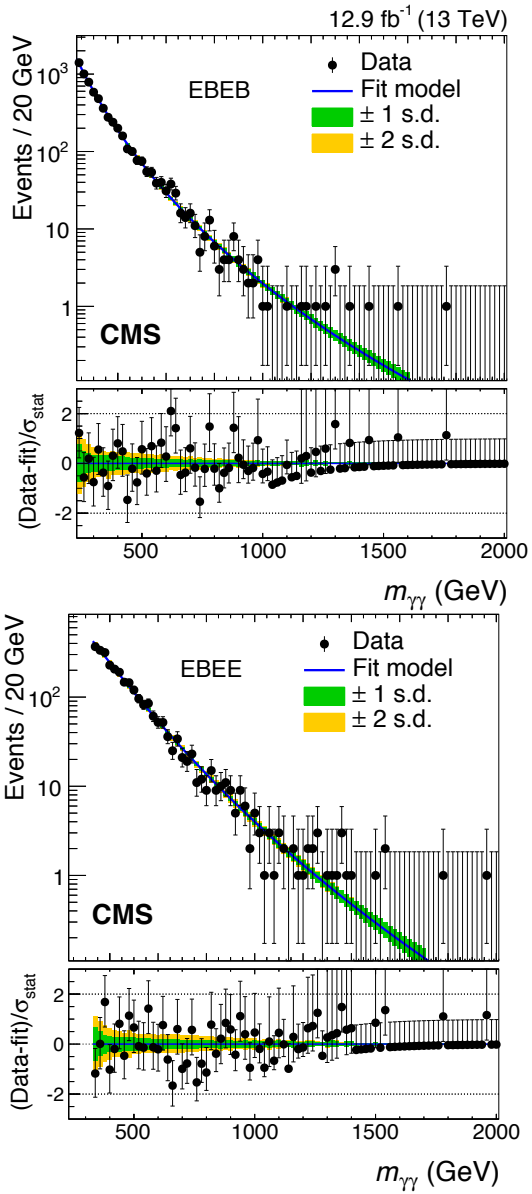






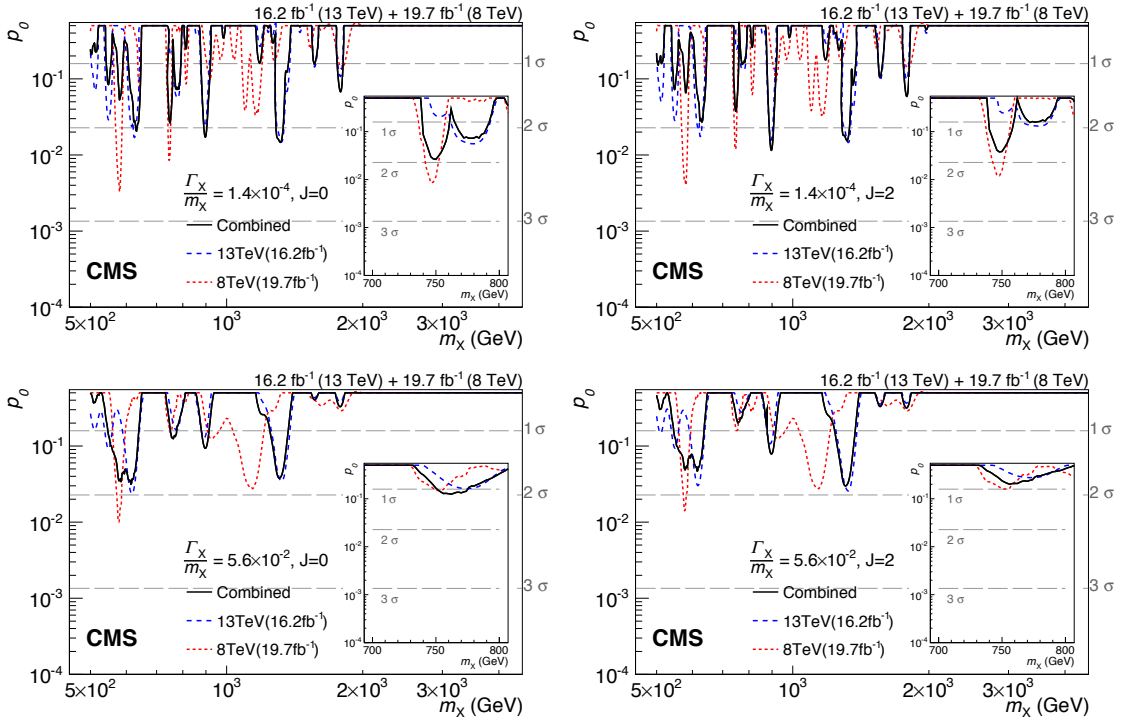
Di-photon Searches CMS-PAS-EXO-16-027

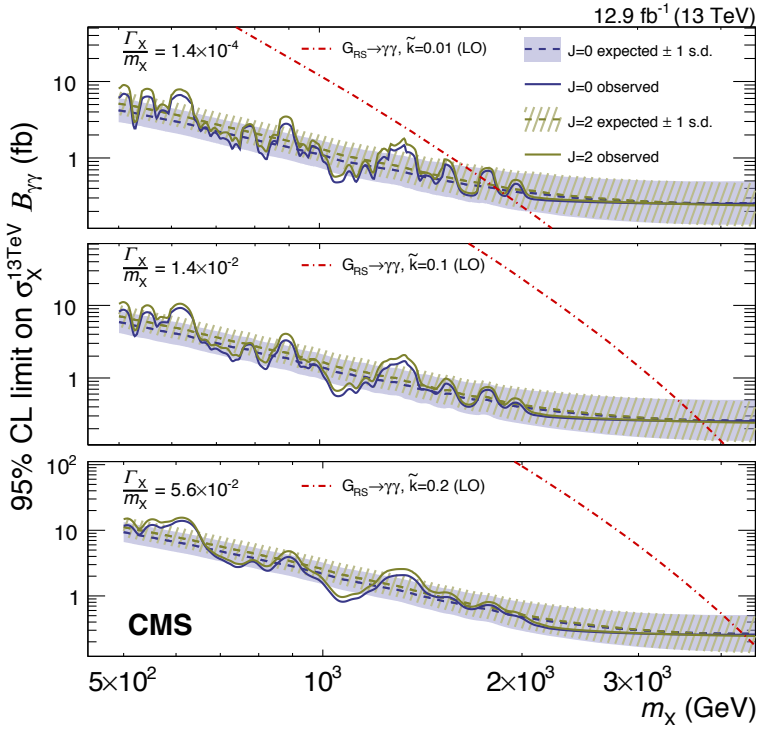
- Search for resonant production of photon pairs using12.9 fb^{-1} (2016) + 3.3 fb^{-1} (2015) + 19.7 fb^{-1} (Run I).
- A very clean state without additional activity in the direction of the two photons.
- Three values of the relative width Γ_X/m_X are used as benchmarks: 1.4×10^{-4}, 1.4×10^{-2}, and 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 Searches CMS-PAS-EXO-16-027

- 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)>3.85 (4.45) TeV for $\tilde{k}$=0.1 (0.2)
  - m(RSG)>1.95 except for 1.75 < m(RSG) < 1.85 for $\tilde{k}$=0.01





Summary

- Extensive search program for heavy resonances decaying to leptons, photons, and jets at CMS
  - So far no significant hint for the existence of new physics, despite some excitement last year
  - 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
- Searches for heavy resonances will continue to explore uncharted territories
  - More 13 TeV results still to come
  - Stay tuned!