Selected results of searches for new physics from the CMS experiment

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Motivations

Search strategies

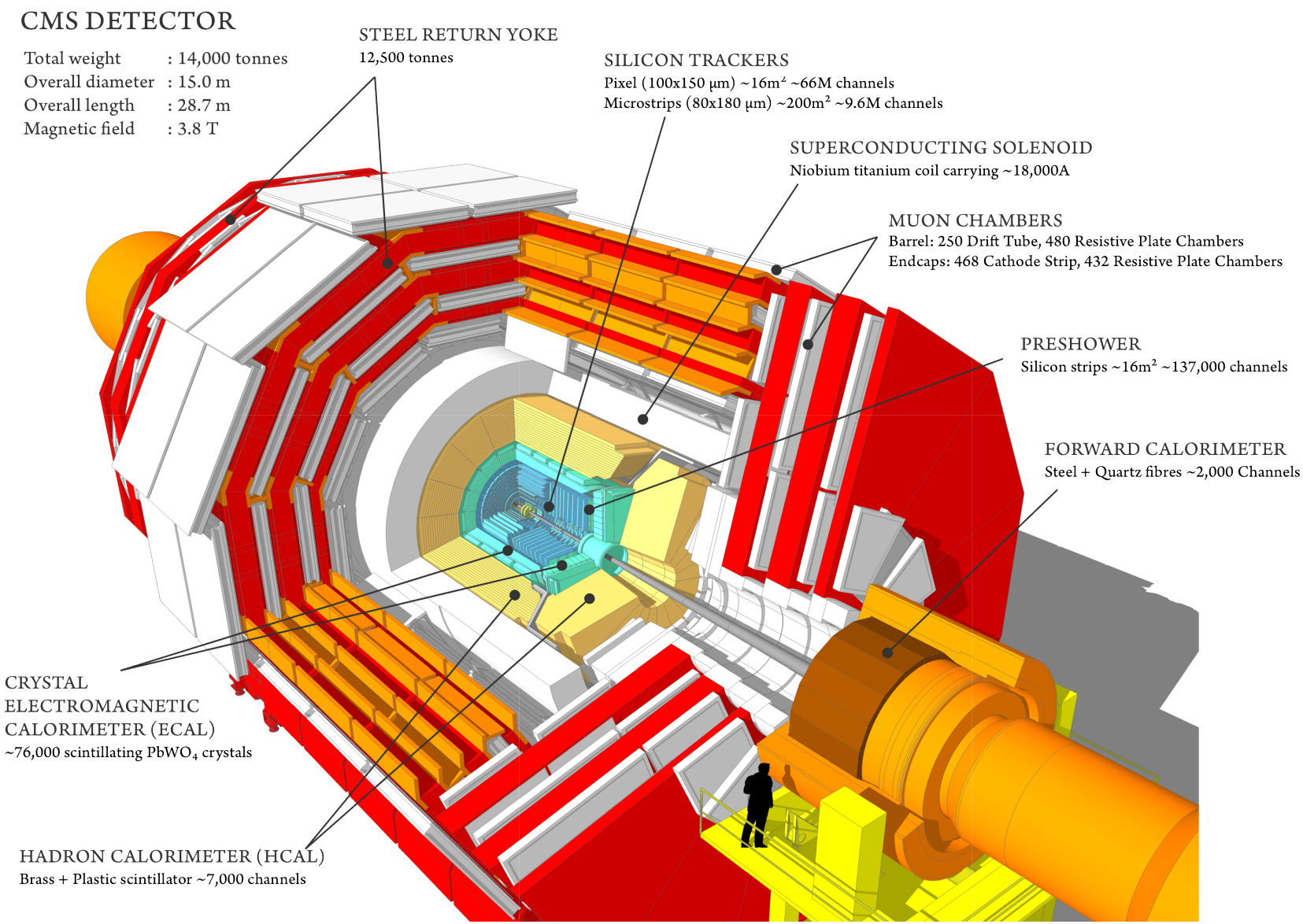
- Many handles to search for evidence of new phenomena
  - Multi-lepton final states
  - Lepton flavour violation
  - Exploit Higgs
  - Di-jet events

Physics models

- Heavy resonances
- Quantum black holes
- Extra dimensions
- Non-resonant effects
- Excited quarks
- ...

Highlighted analyses

- Try to highlight a subset of the many analyses being pursued at CMS
- Focus on some of the more recent results


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

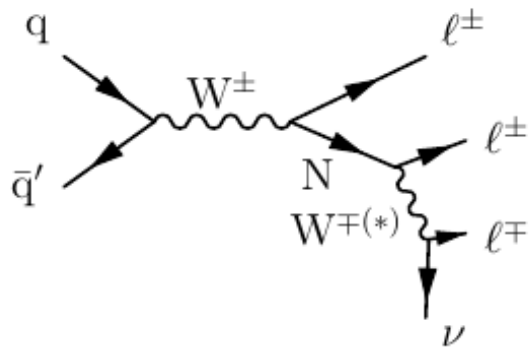
Heavy neutral leptons

Motivation and strategy

- Majorana neutrinos mixing with SM neutrinos

νMSM

- Incorporates the “seesaw” mechanism
- Provides DM candidate as well as candidates for baryon asymmetry



CMS-EXO-17-012
1802.02965

Heavy neutral leptons

Motivation and strategy

- Majorana neutrinos mixing with SM neutrinos
- Experimental signature: $\ell\ell\ell\nu$

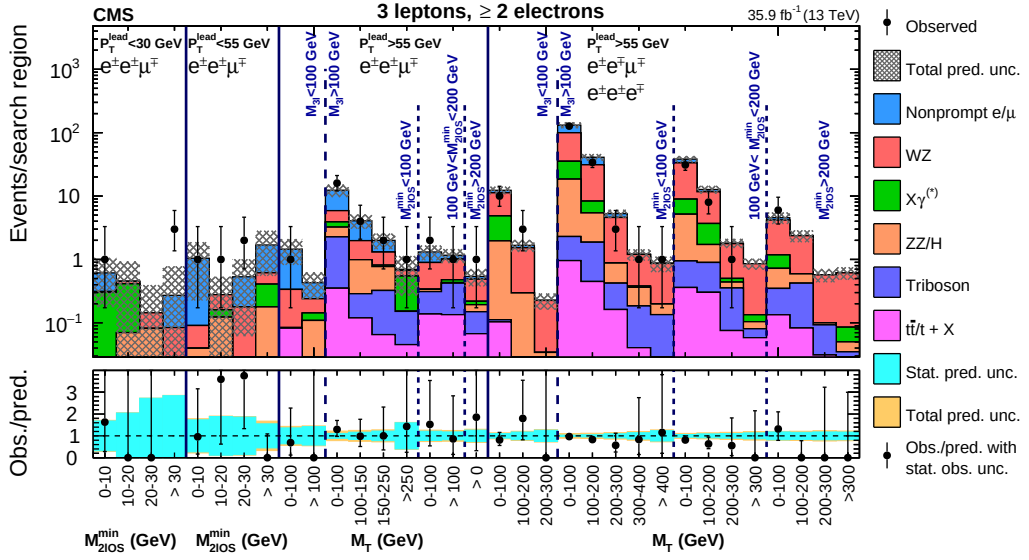
Selection and Background

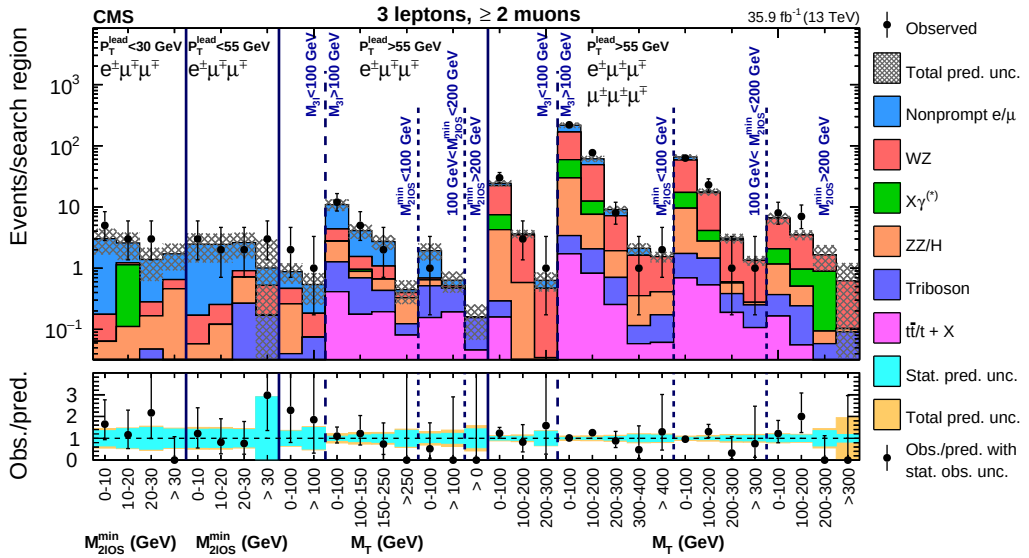
- Event selection
  - Three leptons – not same-sign
  - Divide search region to target low and high mass separately
- Background control
  - $t\bar{t}$: b jet veto
  - ZZ: Reject events with fourth identified lepton
  - WZ: Reject events with OSSF lepton pair in the Z mass window

Heavy neutral leptons

Motivation and strategy

- Majorana neutrinos mixing with SM neutrinos
- Experimental signature: $\ell\ell\ell\nu$
- Search variables: $M_{3\ell}$, $M_{2\ell OS}^{min}$, M_{T}, and $p_{\mathrm{T}}^{\mathrm{miss}}$





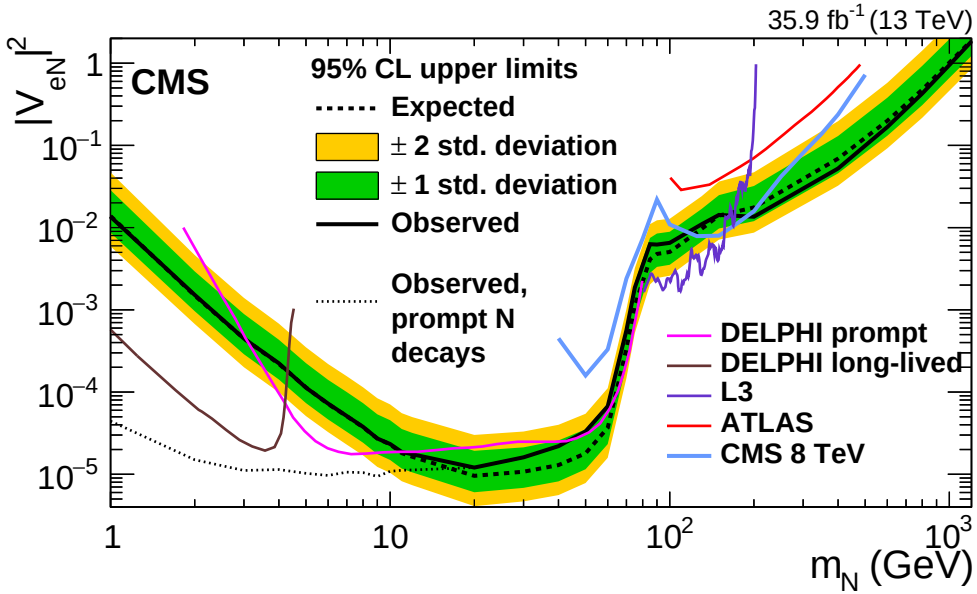
Heavy neutral leptons

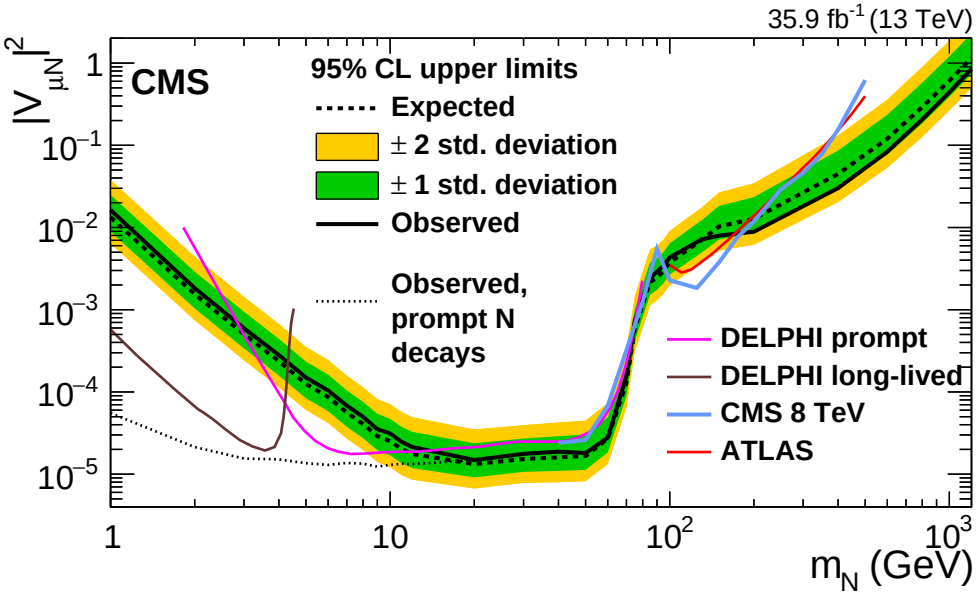
Motivation and strategy

- Majorana neutrinos mixing with SM neutrinos
- Experimental signature: $\ell\ell\ell\nu$
- Search variables: $M_{3\ell}$, $M_{2\ell OS}^{min}$, M_{T}, and $p_{\mathrm{T}}^{\mathrm{miss}}$

Results

- Limits set on the mixing parameters $|V_{eN}|^2$ and $|V_{\mu N}|^2$
  - 1.5×10^{-5}—1.8
  - 1 GeV $< m_N <$ 1.2 TeV
  - N.B.: $\tau_N \propto 1/m_N^5 |V_{\ell N}|^2$, affects limit in the low mass region



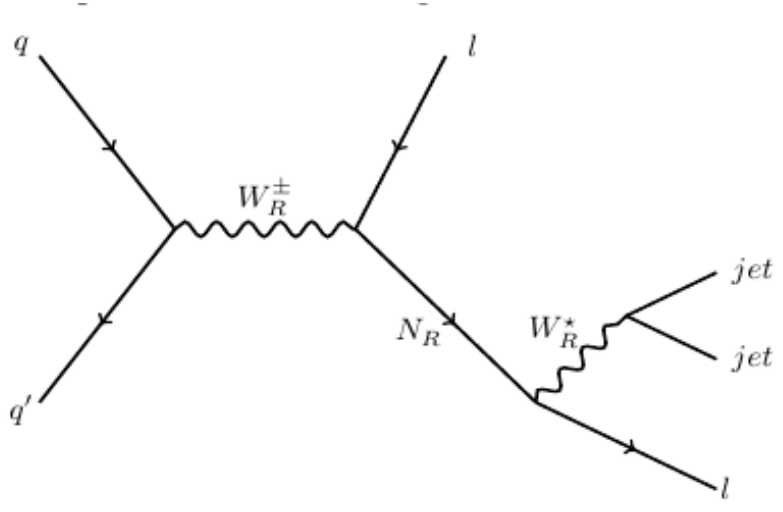


Heavy right-handed SM partners

Motivation and strategy

- Heavy W_R decaying to ℓN_R

- L–R symmetric scenarios in BSM models



CMS-PAS-EXO-17-011

Heavy right-handed SM partners

Motivation and strategy

- Heavy $\mathrm{W_R}$ decaying to ℓN_R
- Experimental signature: $\ell\ell jj$

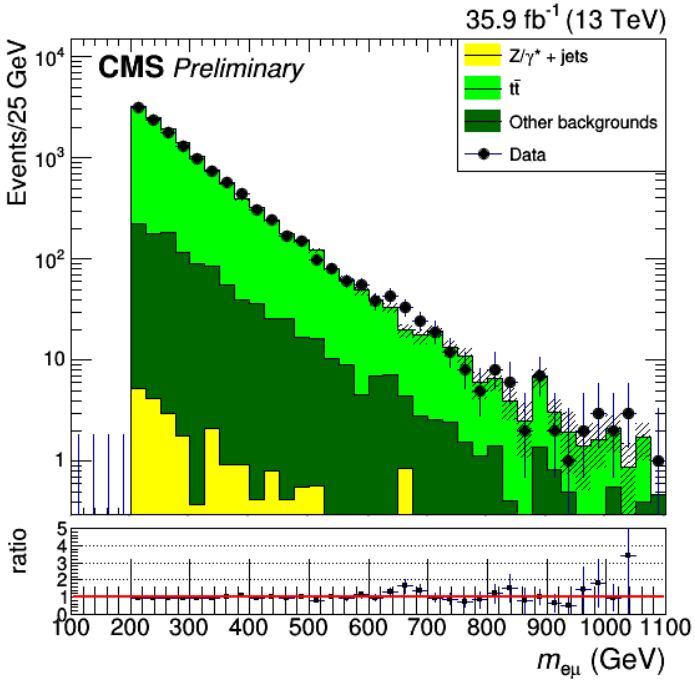
Selection and Background

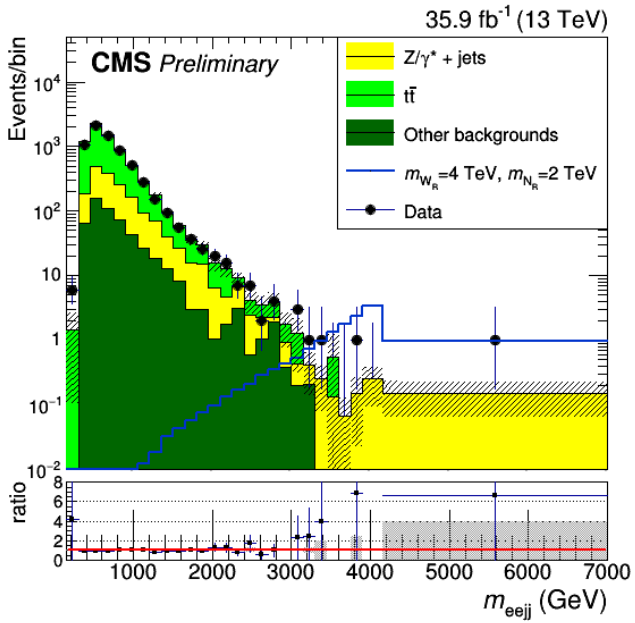
- Event selection
  - Same flavour lepton pairs and leading two jets in the event
  - Ensure separation ($\Delta R > 0.4$) between final state objects
- Background control
  - $\mathrm{t\bar{t}}$ +jets: utilize $e\mu$ control region to estimate contribution in signal region
  - DY+jets: $m_{\ell\ell} > 200$ GeV

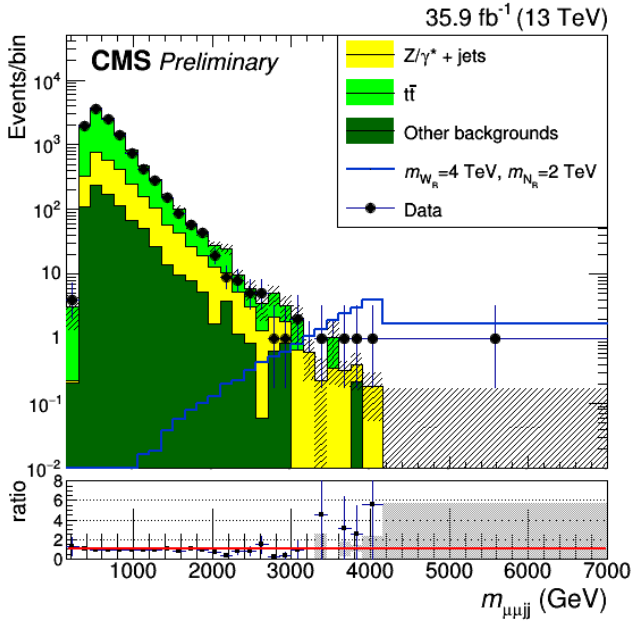
Heavy right-handed SM partners

Motivation and strategy

- Heavy W_R decaying to ℓN_R
- Experimental signature: $\ell\ell jj$
- Search variables: $m_{\ell\ell jj}$, $m_{\ell\ell}$







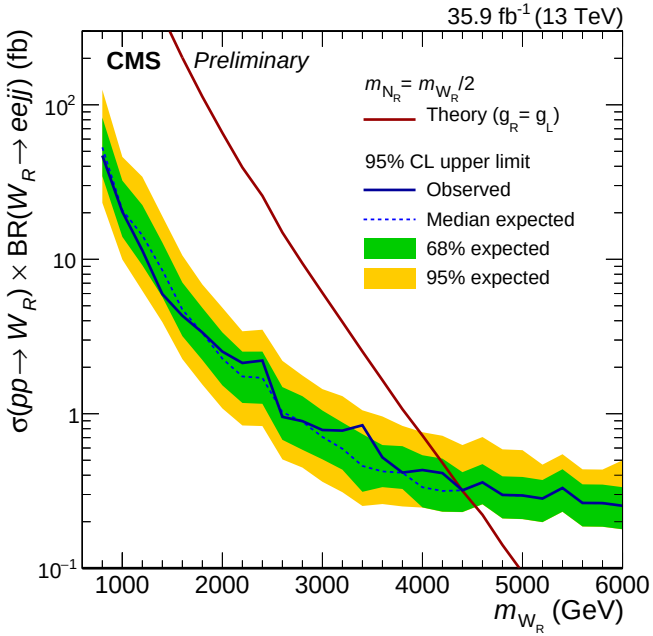
Heavy right-handed SM partners

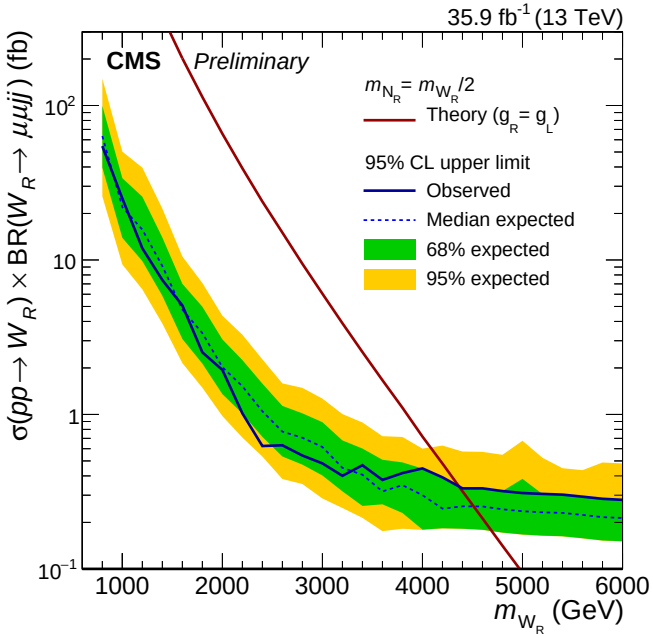
Motivation and strategy

- Heavy $\mathrm{W_R}$ decaying to ℓN_R
- Experimental signature: $\ell\ell jj$
- Search variables: $m_{\ell\ell jj}$, $m_{\ell\ell}$

Results

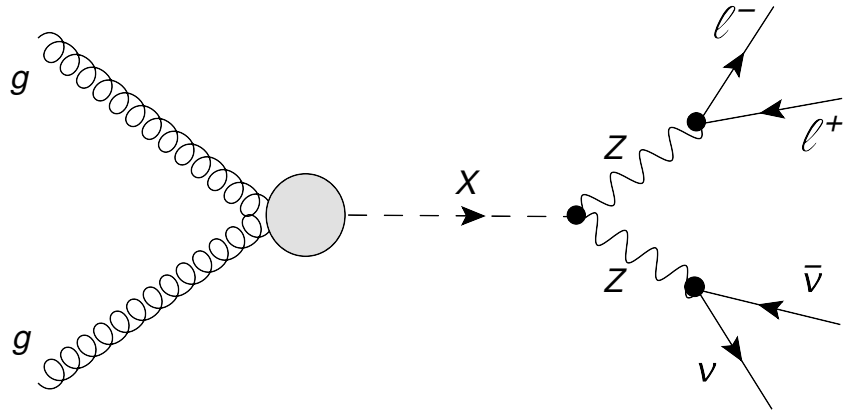
- Limits set on the mass of the heavy partners, assuming $m_{N_R} = \frac{1}{2} m_{\mathrm{W_R}}$
  - Exclude $m_{\mathrm{W_R}} < 4.4$ TeV





Motivation and strategy

- Composite Higgs, extra dimensions
- Experimental signature: $X \to ZZ$



CMS-B2G-16-023
1711.04370

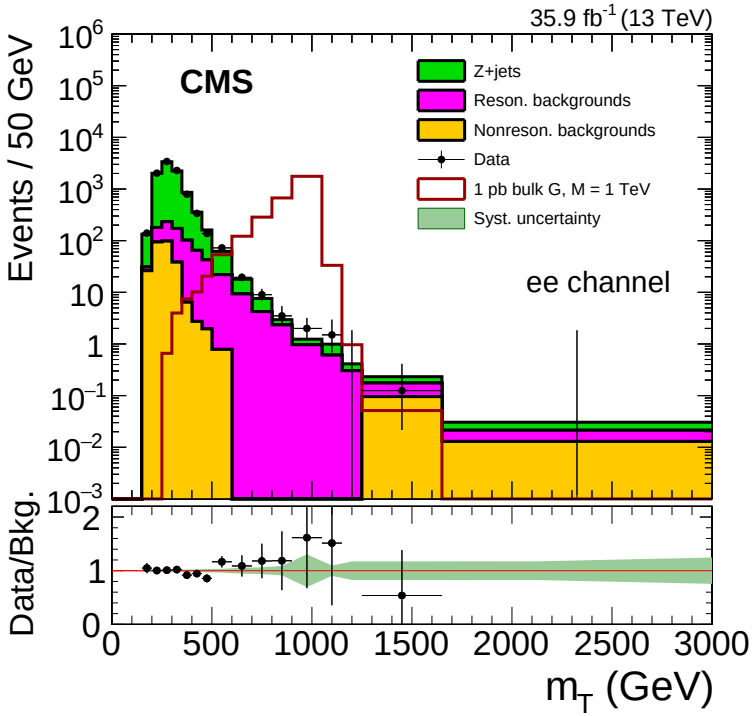
New di-boson resonances in the 2/2ν final state

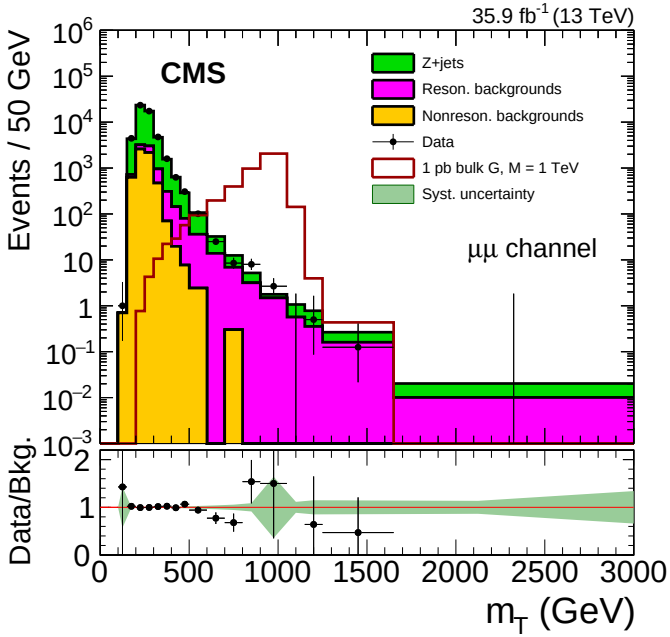
Motivation and strategy

- Composite Higgs, extra dimensions
- Experimental signature: $X \to ZZ$
- Search for a Jacobian Edge in the M_T spectrum

Selection and Background

- Event selection
  - Two opposite sign leptons with invariant mass in the Z mass window
- Background control
  - $p_T(Z) > 100$ GeV
  - $E_T^{miss} > 50$ GeV
  - $\Delta\Phi(Z, E_T^{miss}) > 0.5$





New di-boson resonances in the 2/2ν final state

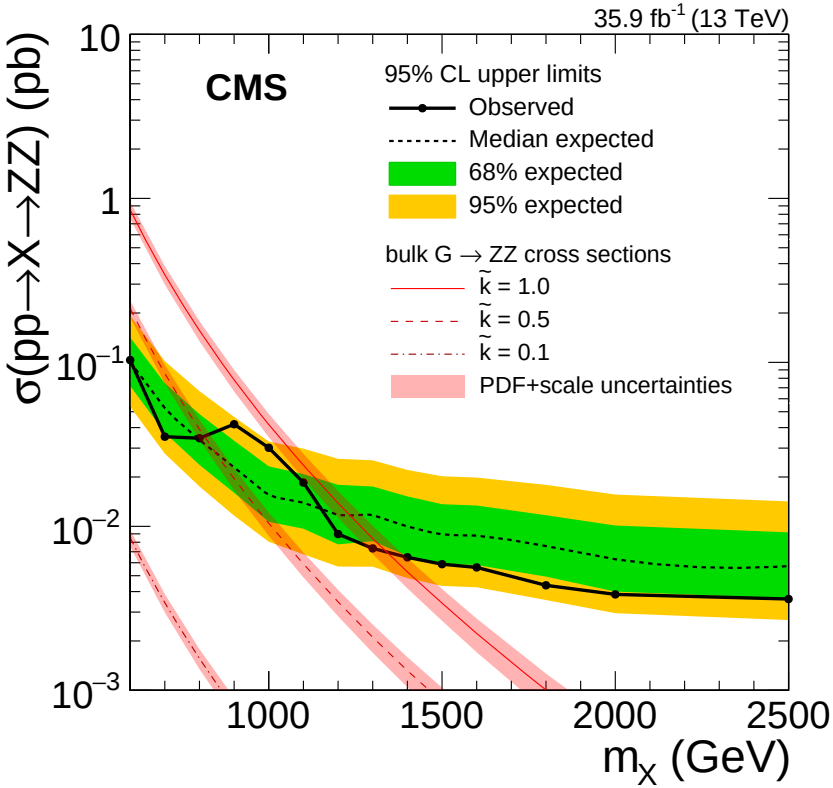
Motivation and strategy

- Composite Higgs, extra dimensions
- Experimental signature: $X \to ZZ$
- Search for a Jacobian Edge in the M_T spectrum

Bulk graviton (G_{bulk}) limit

- RS KK with SM flavour extensions
- Models with different expected curvature of the WED
  - $M_{G_{bulk}} < 1.2\,\text{TeV}(800\,\text{GeV})$ excluded for $\widetilde{k} = 1.0(0.5)$
  - Not sensitive to $\widetilde{k} = 0.1$ model

Limit



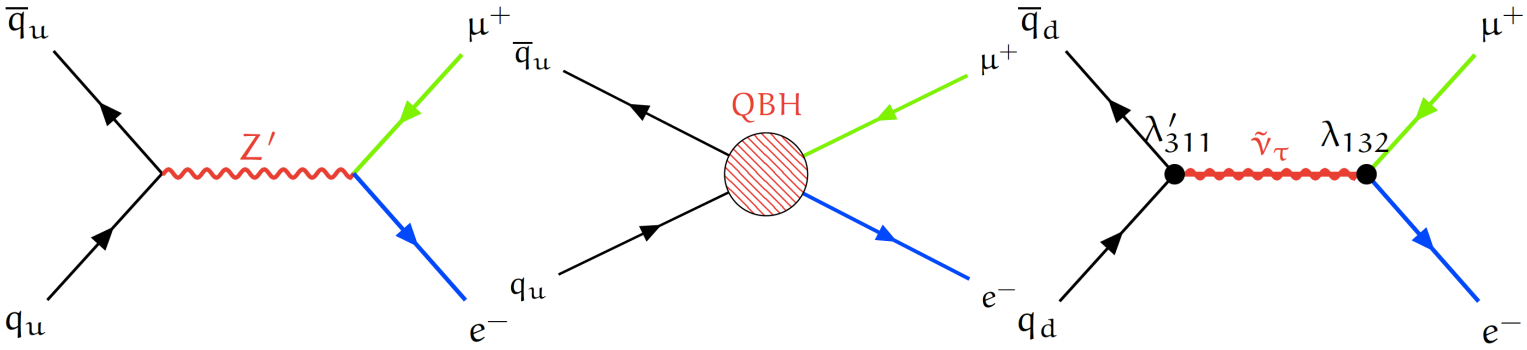
Lepton flavour violation

Motivation and strategy

- Predicted in several new physics models
- Model independent signature of $e\mu$

Motivation and strategy

- Quantum black holes
- R-parity violating SUSY
- Some Z′ models

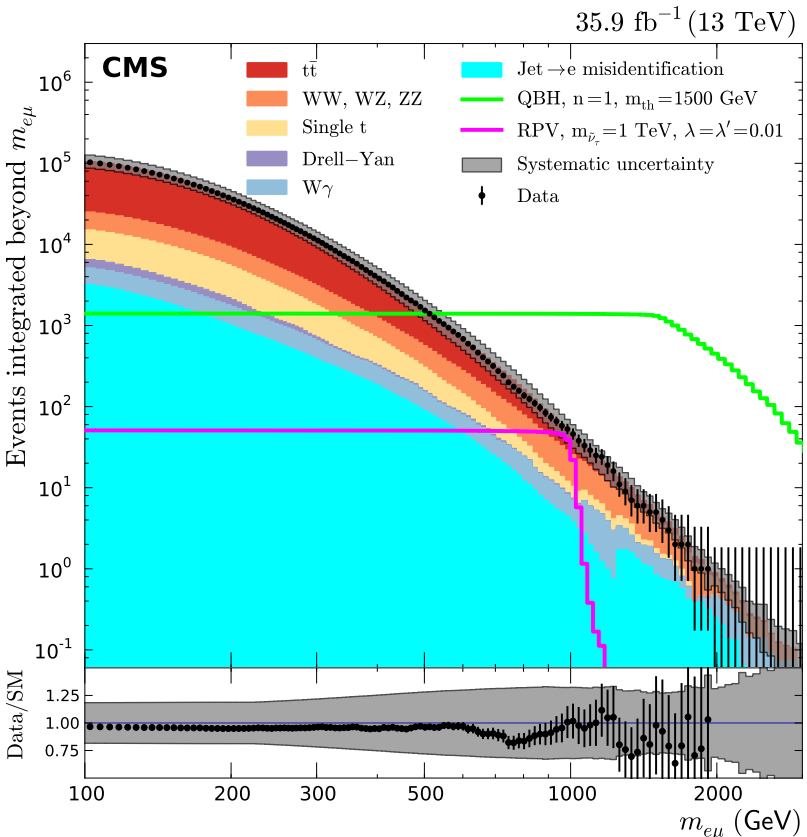


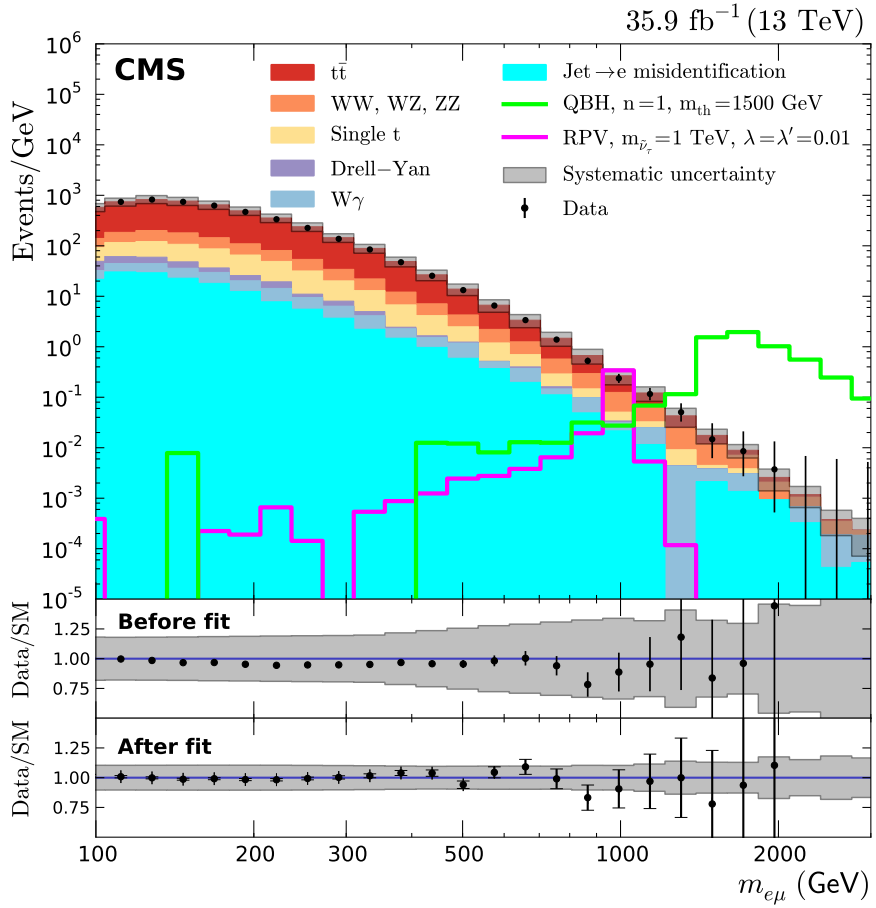
CMS-EXO-16-058
1802.01122

Lepton flavour violation

Motivation and strategy

- Predicted in several new physics models
- Model independent signature of $e\mu$

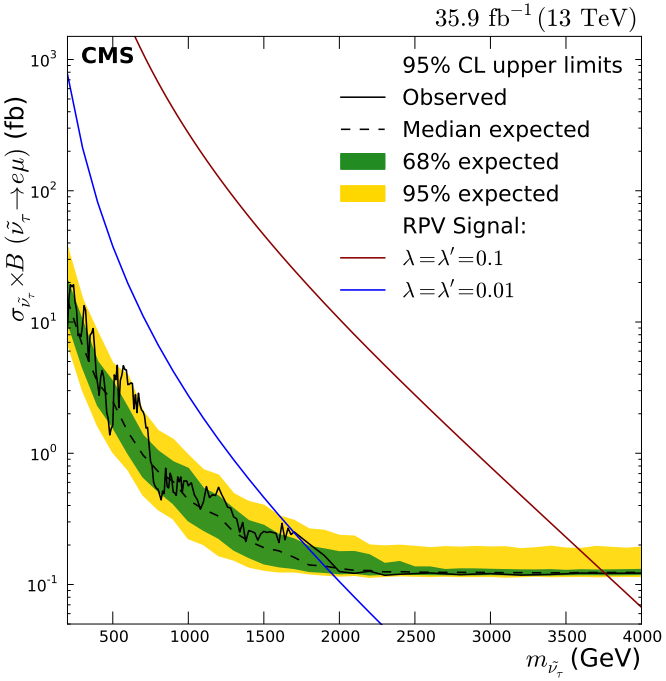




Lepton flavour violation

Results

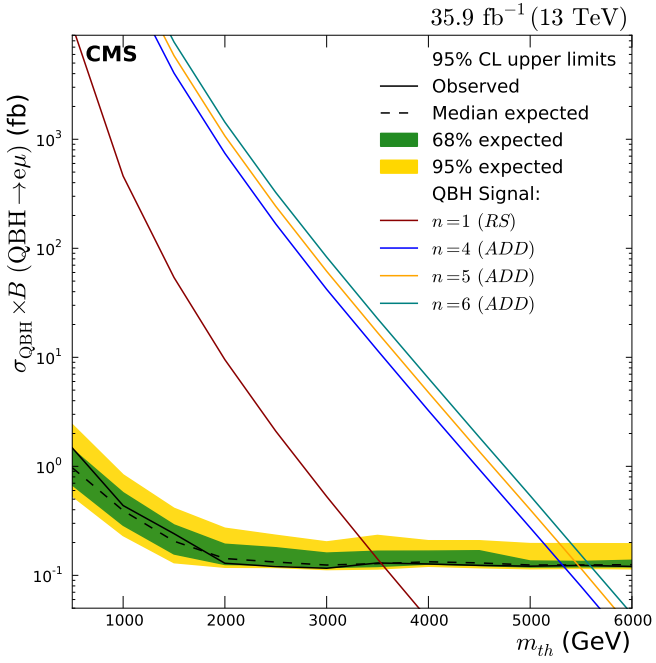
- RPV ($\widetilde{\nu}_\tau$) 1.7 and 3.8 TeV
  - $\lambda = \lambda_{132} = \lambda_{231}$
  - $\lambda' = \lambda'_{311}$

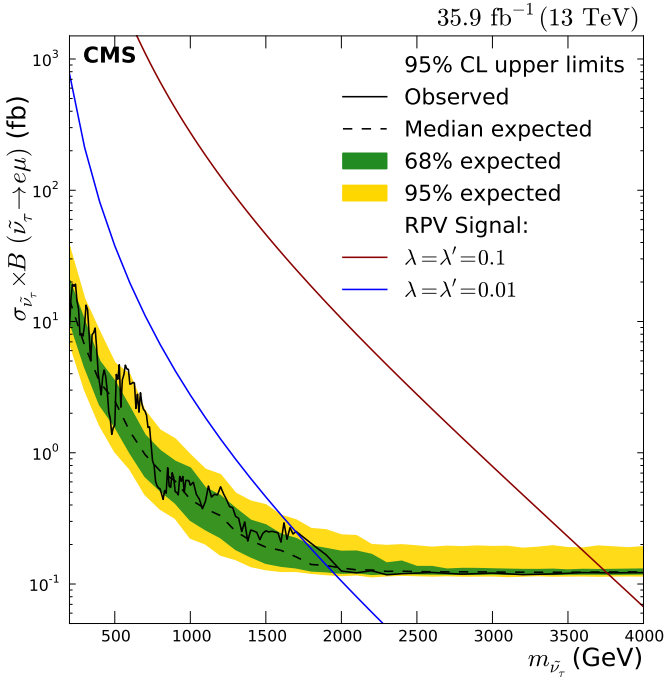


Lepton flavour violation

Results

- RPV ($\widetilde{\nu}_\tau$) 1.7 and 3.8 TeV
- QBH limits on production threshold
  RS: 3.6 TeV, ADD: 5.3, 5.5, 5.6 TeV

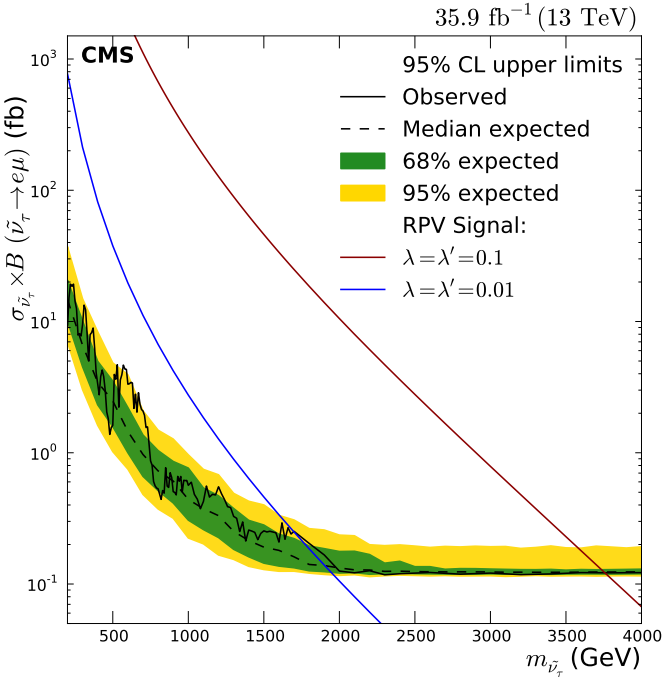


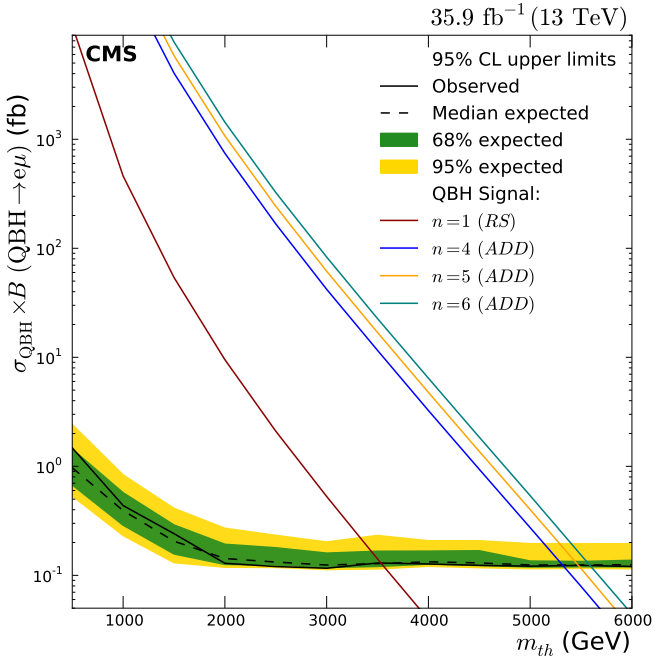


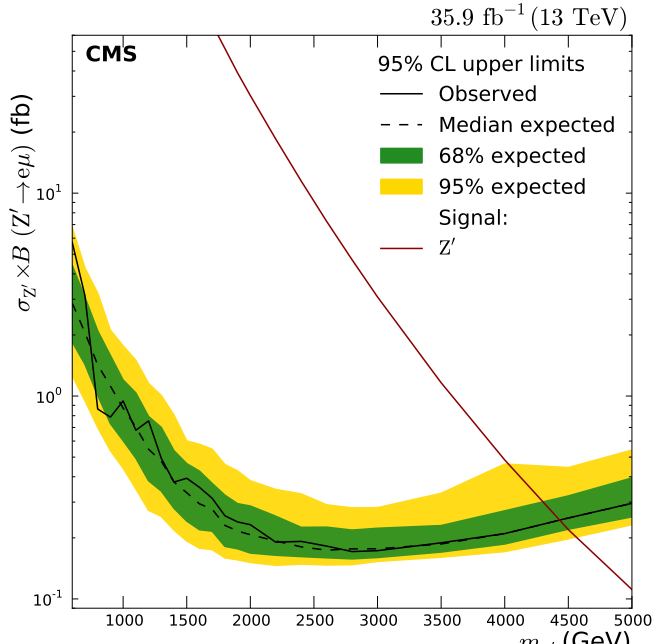
Lepton flavour violation

Results

- RPV ($\widetilde{\nu}_\tau$) 1.7 and 3.8 TeV
- QBH limits on production threshold
  RS: 3.6 TeV, ADD: 5.3, 5.5, 5.6 TeV
- Z′ (assuming BR of 10%) 4.4 TeV







New physics with dijet angular distributions

Motivation and search strategy

- Di-jet signature provides copious data at the LHC, and many new physics models provide di-jet signatures
- Angular distributions provide promising strategy to gain where invariant mass searches lacked sensitivity

- Quantum black holes
- Quark compositeness
- Extra dimensions
- Dark matter

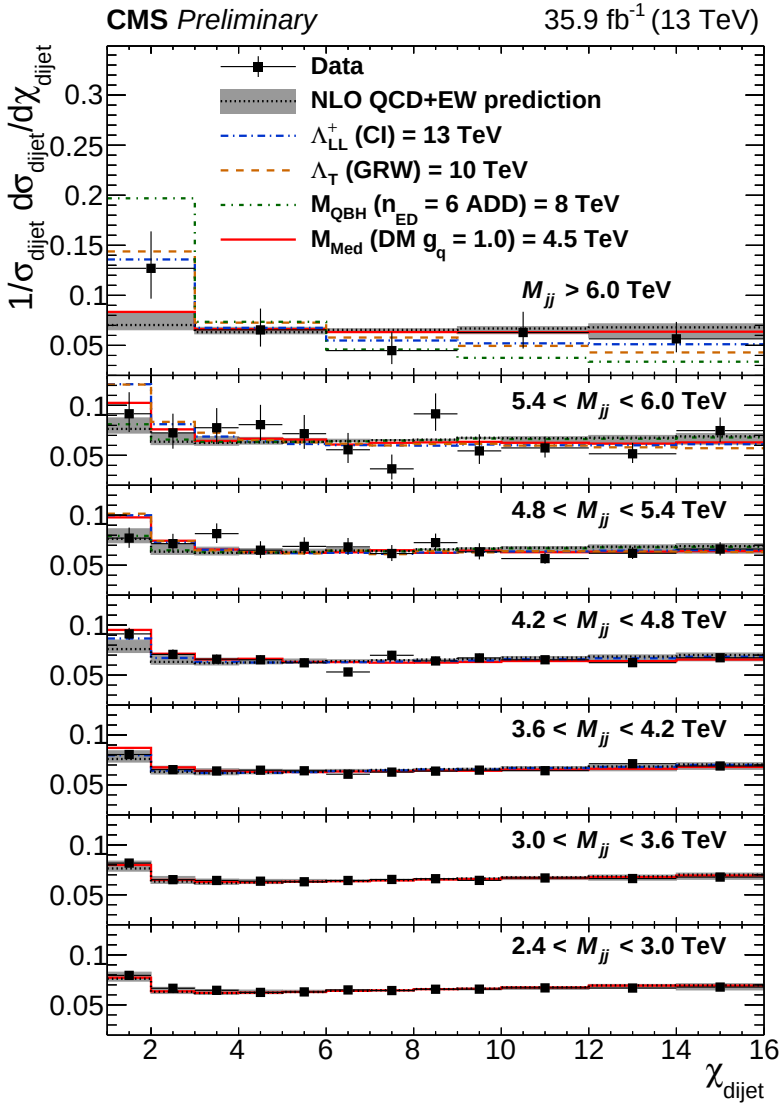
CMS-PAS-EXO-16-046

New physics with dijet angular distributions

Motivation and search strategy

- Di-jet signature provides copious data at the LHC, and many new physics models provide di-jet signatures
- Angular distributions provide promising strategy to gain where invariant mass searches lacked sensitivity
- Observables: $M_{jj}, \chi_{\text{dijet}}$

- $y^* = \frac{1}{2} ln(\frac{1+|cos(\theta^*)|}{1-|cos(\theta^*)|})$
- $\chi_{\text{dijet}} = e^{2y^*} \sim \frac{1+|cos(\theta^*)|}{1-|cos(\theta^*)|}$



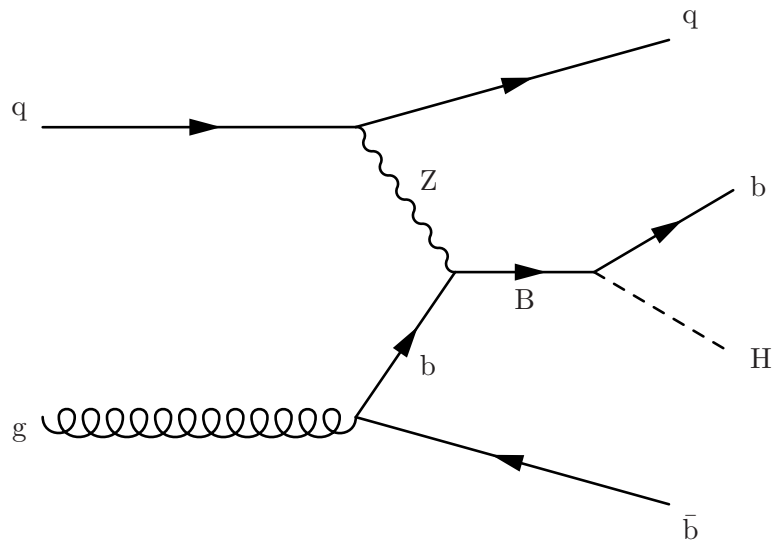
New physics with dijet angular distributions

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

Vector-like quarks: $B \to Hb$

Motivation and search strategy

- Several models predict the existence of vector-like quarks
- Experimental signature: boosted Higgs + forward jet



CMS-B2G-17-009
1802.01486

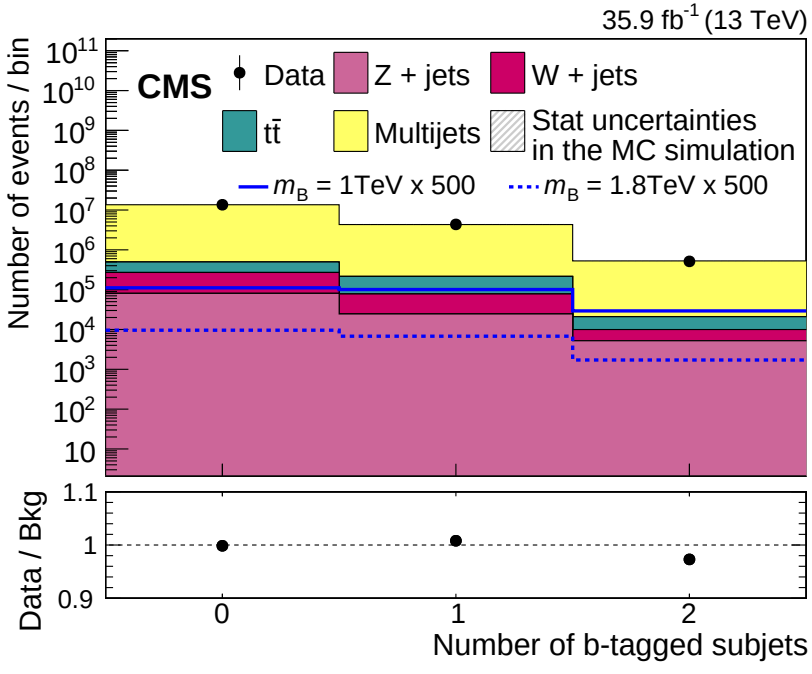
Vector-like quarks: $B \rightarrow Hb$

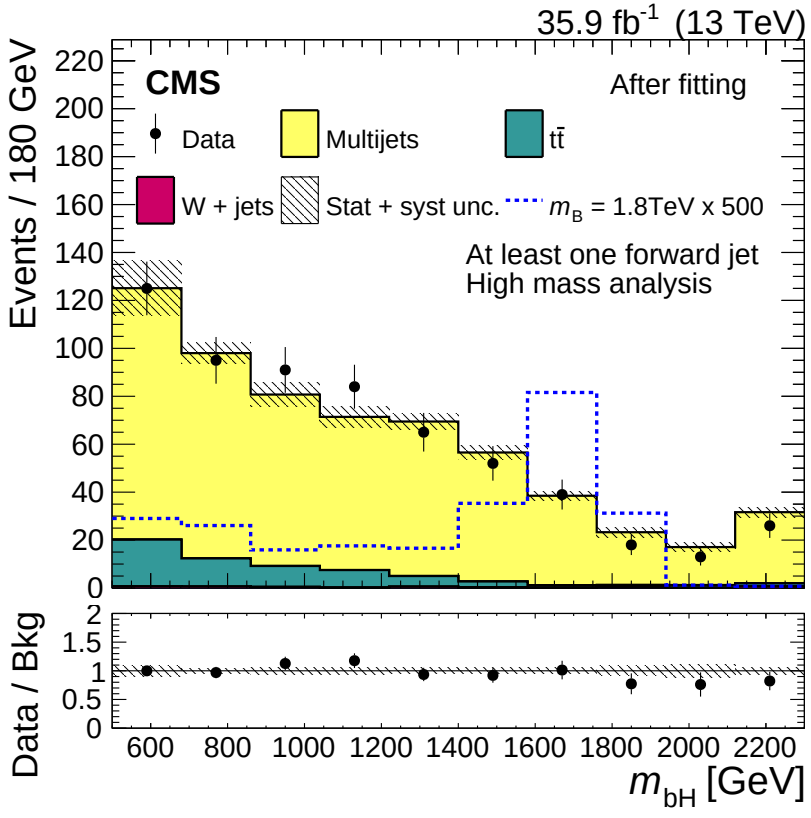
Motivation and search strategy

- Several models predict the existence of vector-like quarks
- Experimental signature: boosted Higgs + forward jet

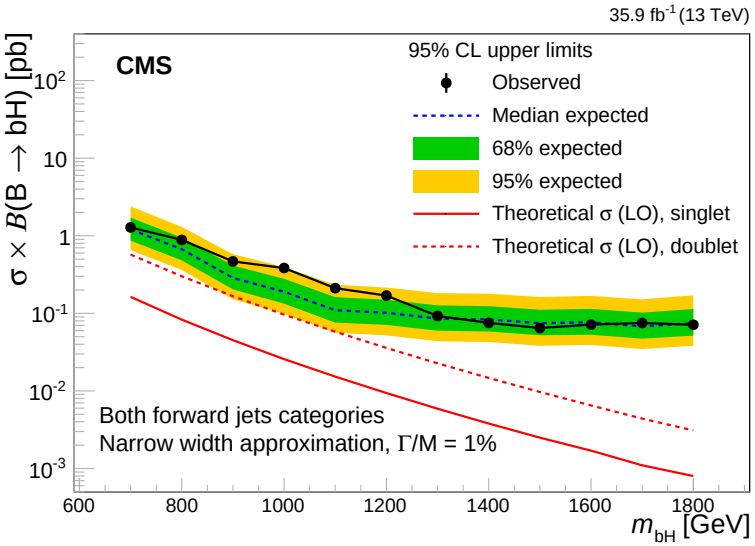
Event selection

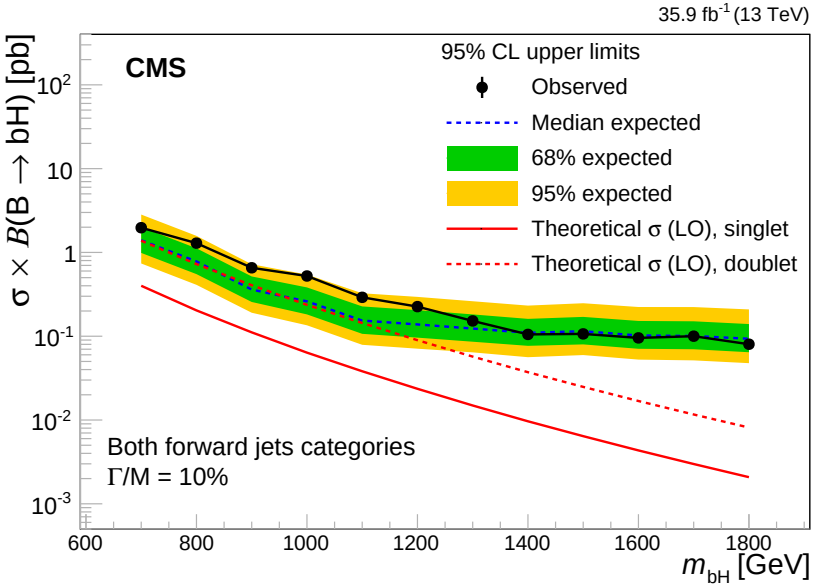
- Higgs-tagged jet
- Three additional jets (at least one b-tagged)

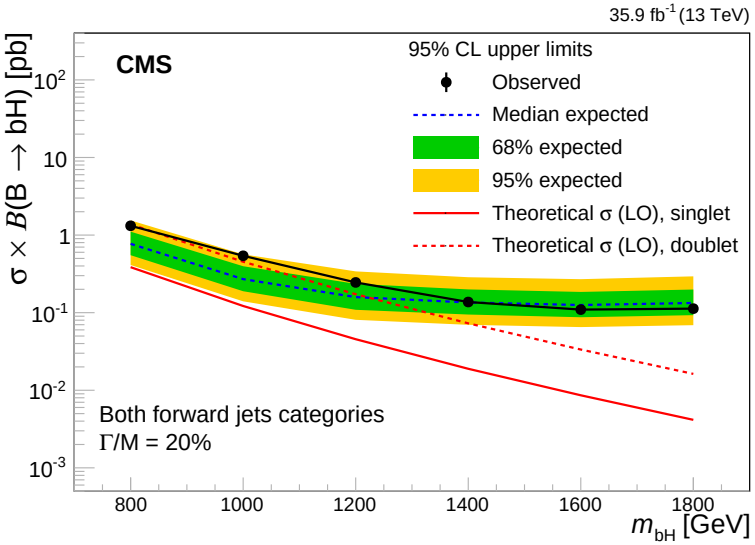


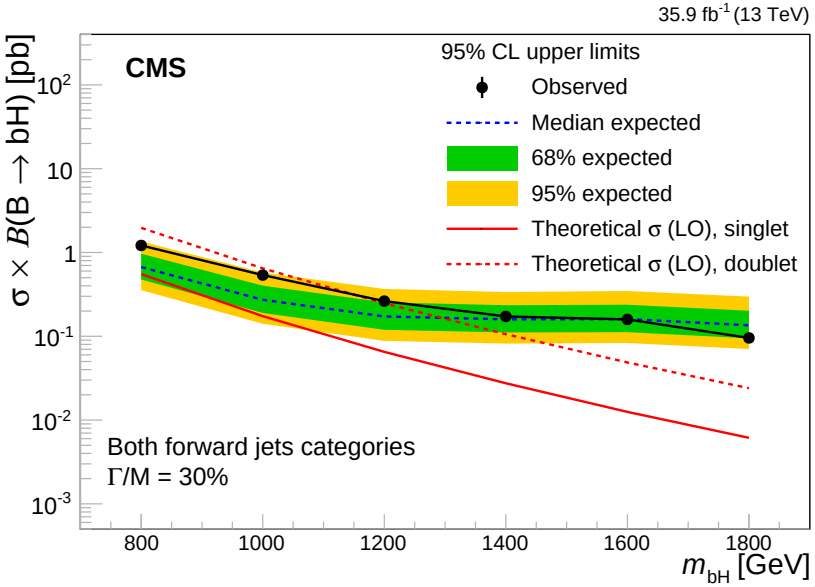


Vector-like quarks: $B \rightarrow Hb$









Third-generation scalar leptoquarks $LQ \to t\tau$

Motivation and strategy

- Leptoquarks appear in several BSM scenarios
- $LQ_3 \to \tau \mathrm{t}$
  - $\mathrm{t} \to \mathrm{bW}$
    - $\mathrm{W} \to \mathrm{qq}'$
    - $\mathrm{W} \to \ell\nu$

- Compositeness
- GUTs

CMS-PAS-B2G-16-028

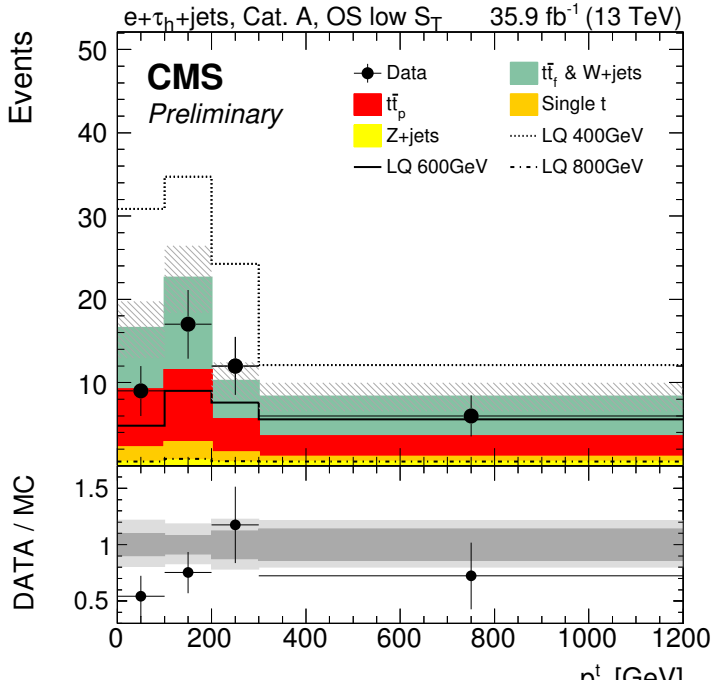
Third-generation scalar leptoquarks $LQ \to t\tau$

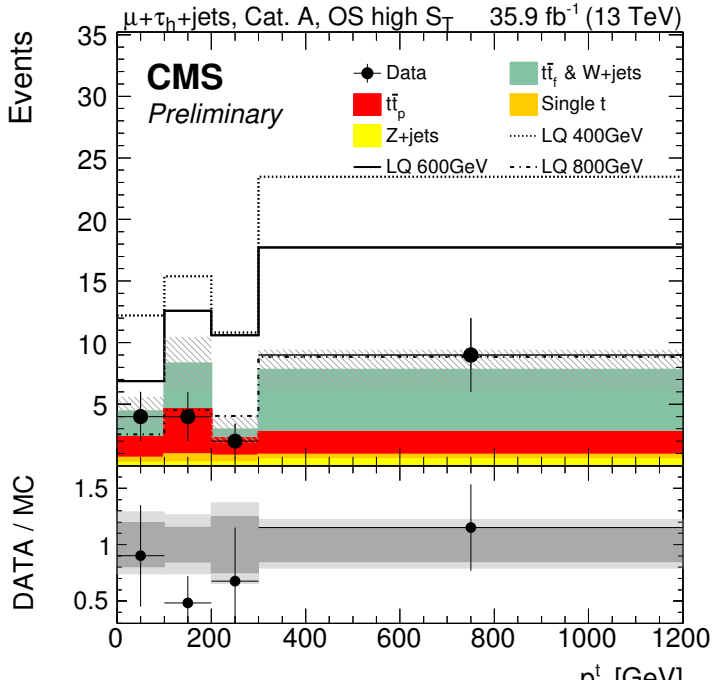
Motivation and strategy

- Leptoquarks appear in several BSM scenarios
- $LQ_3 \to \tau t$
  - $t \to bW$
    - $W \to qq'$
    - $W \to \ell\nu$
- Variable of interest p_T^{hadtop}

Event selection

- Select events with e or μ, one or two τ_h, and jets
  - Split into regions of S_T
  - Split into τ_h multiplicity categories
    - 1 τ_h same or opposite sign of accompanying lepton
    - 2 τ_h of opposite sign

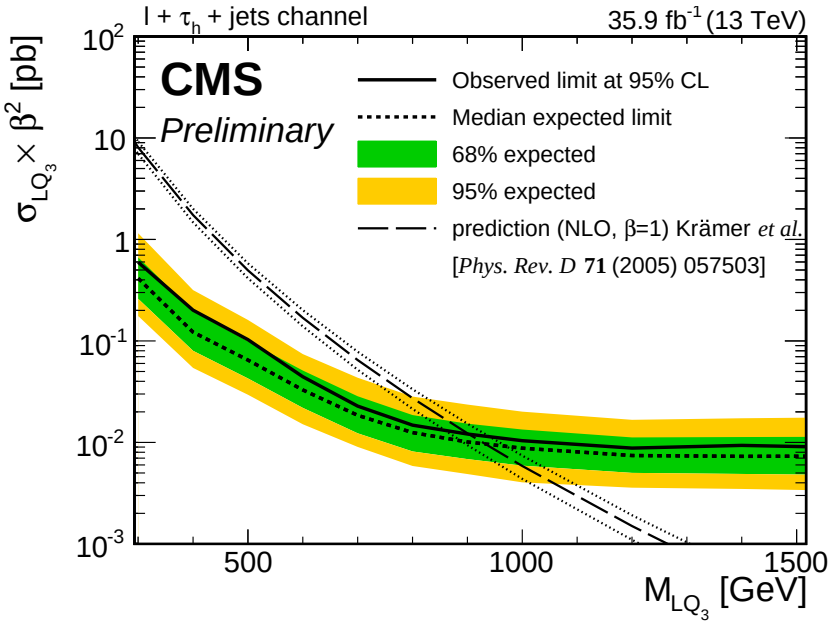




Third-generation scalar leptoquarks $LQ \to t\tau$

Motivation and strategy

- Leptoquarks appear in several BSM scenarios
- $LQ_3 \to \tau t$
  - $t \to bW$
    - $W \to qq'$
    - $W \to \ell\nu$
- Variable of interest p_T^{hadtop}



Results

- $M_{LQ_3} < 900\,\text{GeV}$ excluded ($\beta = 1$)

Summary and Conclusions

- The new physics program at CMS is very active and well varied
- Taking advantage of many different final state topologies to investigate many BSM scenarios
- Different strategies targeting the same final states add robustness to the results
- Limits on a wide variety of models are being set and extended

Summary and Conclusions

- The new physics program at CMS is very active and well varied
- Taking advantage of many different final state topologies to investigate many BSM scenarios
- Different strategies targeting the same final states add robustness to the results
- Limits on a wide variety of models are being set and extended

Thanks for your attention!

Questions?

Backup

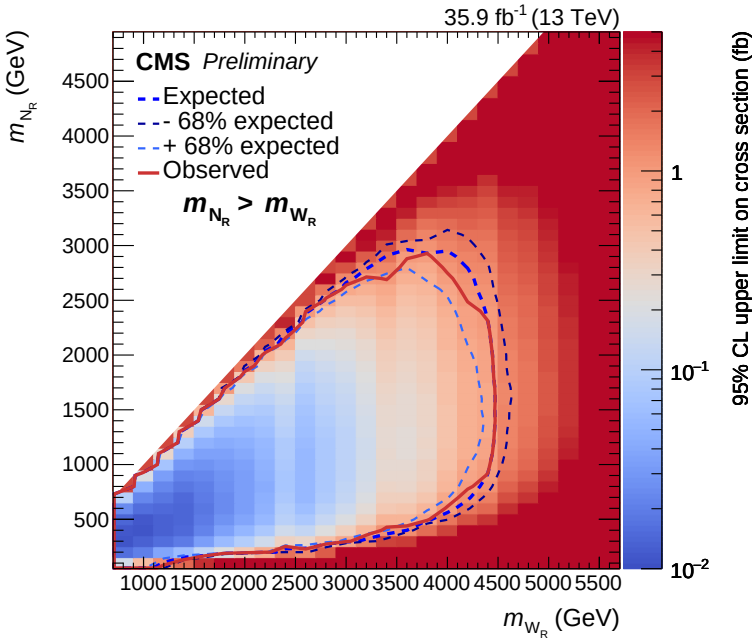
CMS Results Links

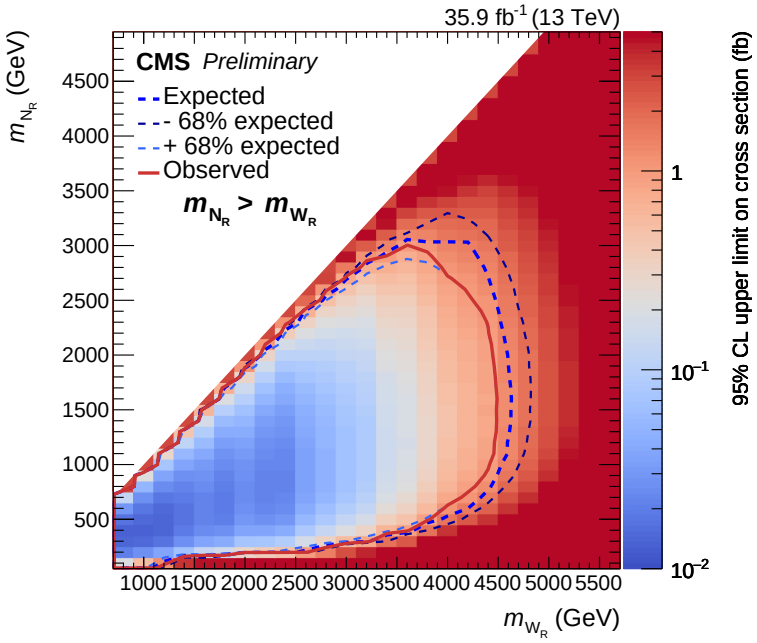
Further documentation

- CMS public publications page:
  `http://cms-results.web.cern.ch/cms-results/public-results/publications/Run2/index.html`
- CMS public results page:
  `http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/Run2/index.html`
- CMS Exotica publications page:
  `http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html`
- CMS Exotica public results page:
  `http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html`
- CMS Beyond 2 generations publications page:
  `http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html`
- CMS Beyond 2 generations public results page:
  `http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/index.html`

Heavy neutral leptons

Heavy right-handed partners





Heavy right-handed partners

Uncertainty	Signal (%)	Background (%)
Jet Energy Resolution	3.2 - 25.8	0.9 - 25.2
Jet Energy Scale	0.2 - 28.9	4.8 - 26.8
Electron Energy Resolution	3.7 - 4.8	2.7 - 4.5
Electron Energy Scale	3.7 - 6.4	4.9 - 5.9
Electron Reco/Trigger/ID	8.7 - 10.9	6.1 - 10.4
Muon Energy Resolution	4.7 - 10.1	6.9 - 12.2
Muon Energy Scale	4.7 - 10.2	6.2 - 11.9
Muon Trigger/ID/Iso	2.3 - 4.7	1.9 - 5.2

Uncertainty	Magnitude (%)
$t\bar{t}$ extrapolation ee/eμ SF	16.9 (stat.+syst.)
$t\bar{t}$ extrapolation $\mu\mu$/eμ SF	20.1 (stat.+syst.)
DY ee PDF	15 – 70 (syst.)
DY ee renormalization/factorization	5 – 40 (syst.)
DY $\mu\mu$ PDF	10 – 70 (syst.)
DY $\mu\mu$ renormalization/factorization	10 – 50 (syst.)
Luminosity	2.5 (stat.+syst.)

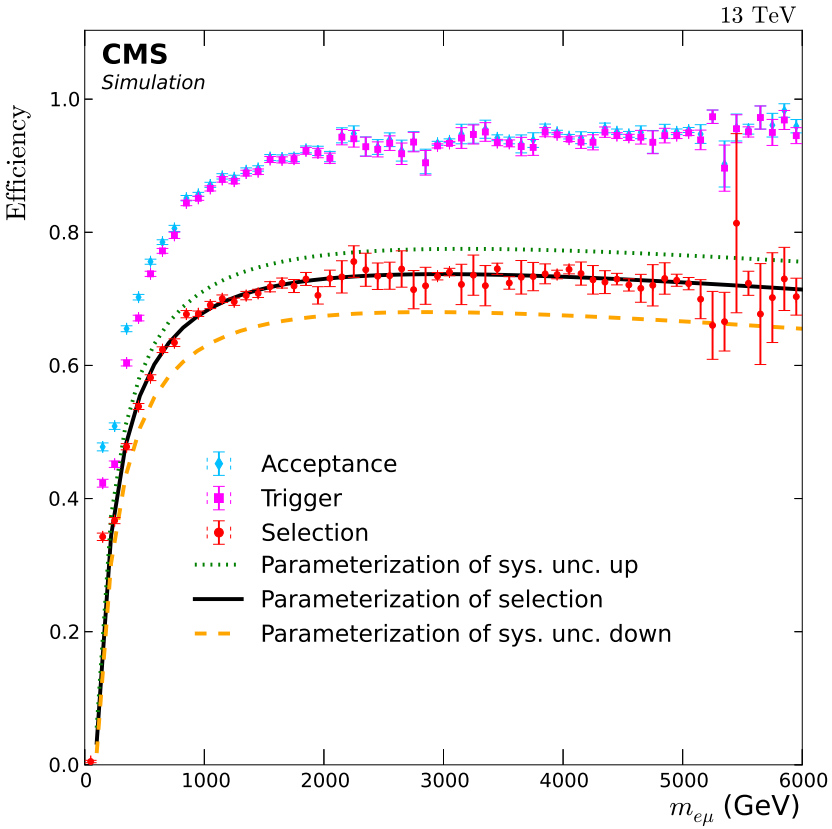
New physics with dijet angular variables

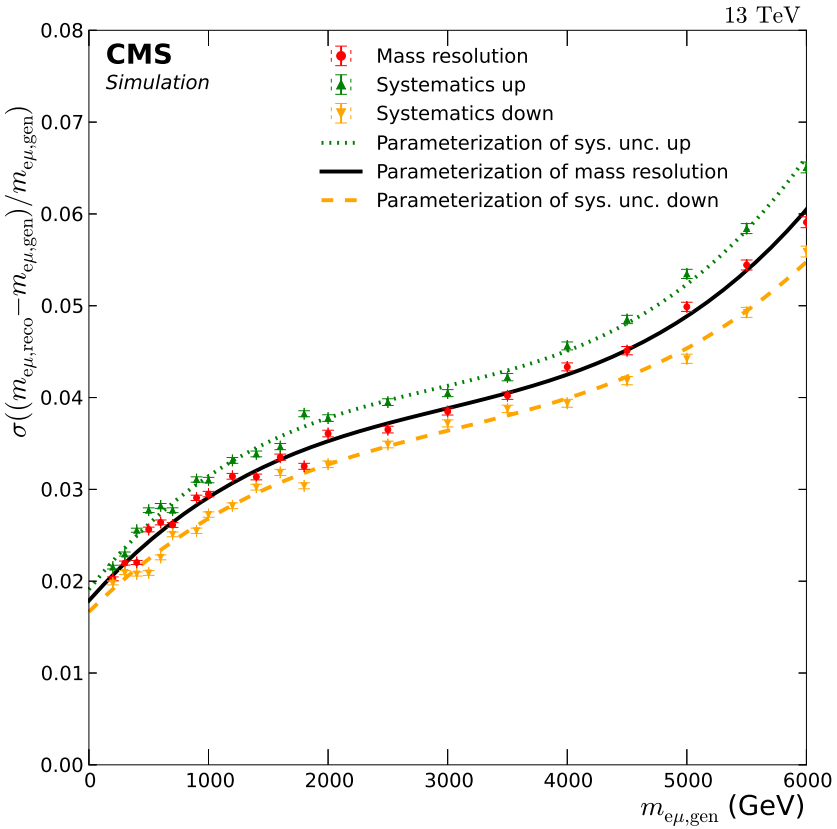
Source of uncertainty	$2.4 < M_{jj} < 3.0$ TeV	$M_{jj} > 6.0$ TeV
Statistical	0.7%	27%
Jet energy scale	3.6%	9.2%
Jet energy resolution (core)	1.0%	1.0%
Jet energy resolution (tails)	1.0%	1.5%
Unfolding, modelling	0.2%	1.5%
Unfolding, detector simulation	0.5%	1.0%
Pileup	<1%	<1%
Total experimental	4.1%	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%

New di-boson resonances in the 2/2ν final state

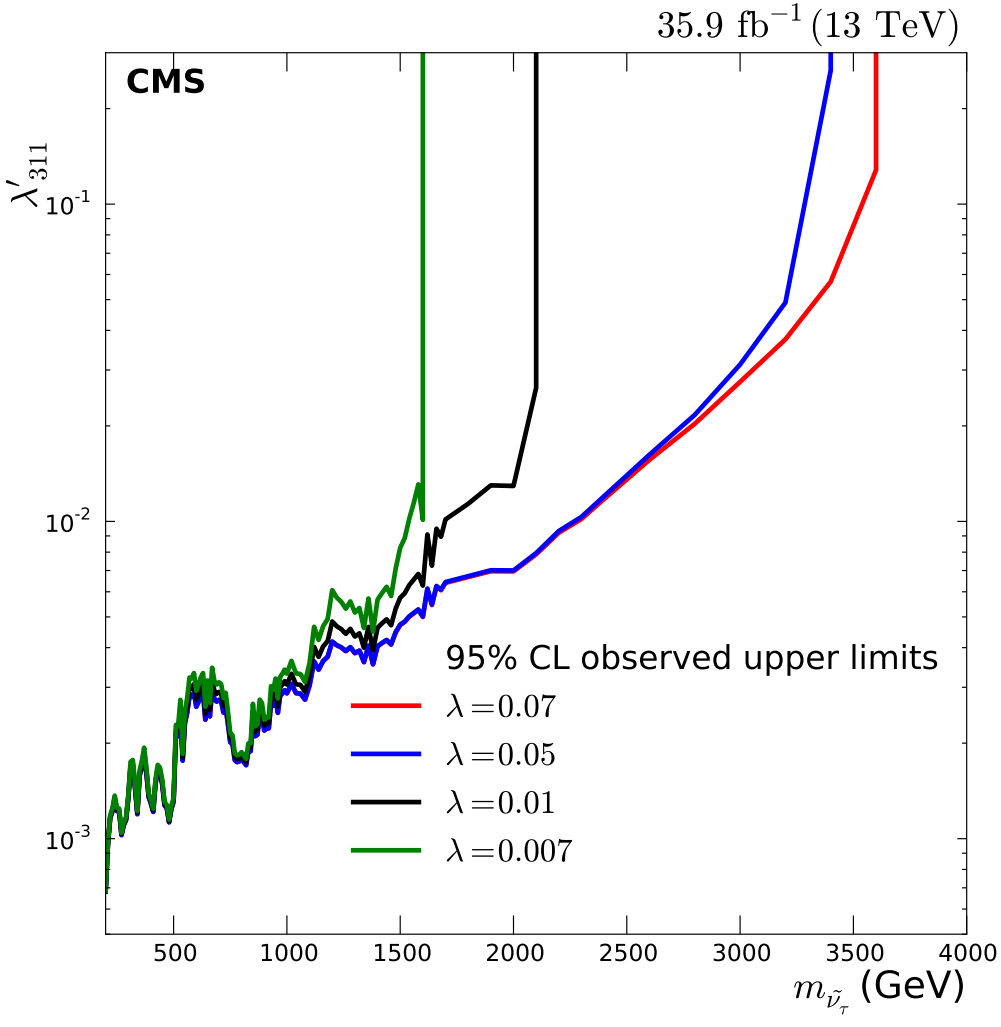
	Source	Signal (%)	Z+jets (%)	Resonant (%)	Nonresonant (%)
Electron channel	Integrated luminosity	2.5	2.5	2.5	2.5
	PDF: cross section	—	2.3	1.7	—
	Scale: cross section	—	3.5	3.0	—
	EW NLO correction	—	—	3.0	—
	PDF: acceptance	1.0	3.4	1.0	—
	Scale: acceptance	(—)	22.7	2.9	—
	Trigger/identification eff.	2.1	—	0.4	—
	p_TZ reweighting	—	6.8	—	—
	Nonresonant norm.	—	—	—	10.0
	p_T/energy scale	(—)	—	4.6	—
	Jet energy resolution	(—)	—	6.8	—
	Unclustered energy	(—)	—	5.5	—
	Hadronic recoil	—	3.4	—	—
Muon channel	PDF: acceptance	1.0	3.4	1.0	—
	Scale: acceptance	(—)	13.1	2.9	—
	Trigger/identification eff.	3.6	1.0	1.0	1.0
	p_TZ reweighting	—	3.2	—	—
	Nonresonant norm.	—	—	—	2.4
	p_T/energy scale	(—)	—	7.4	—
	Jet energy resolution	(—)	—	5.6	—
	Unclustered energy	(—)	—	6.3	—
	Hadronic recoil	—	2.0	—	—

Lepton flavour violation

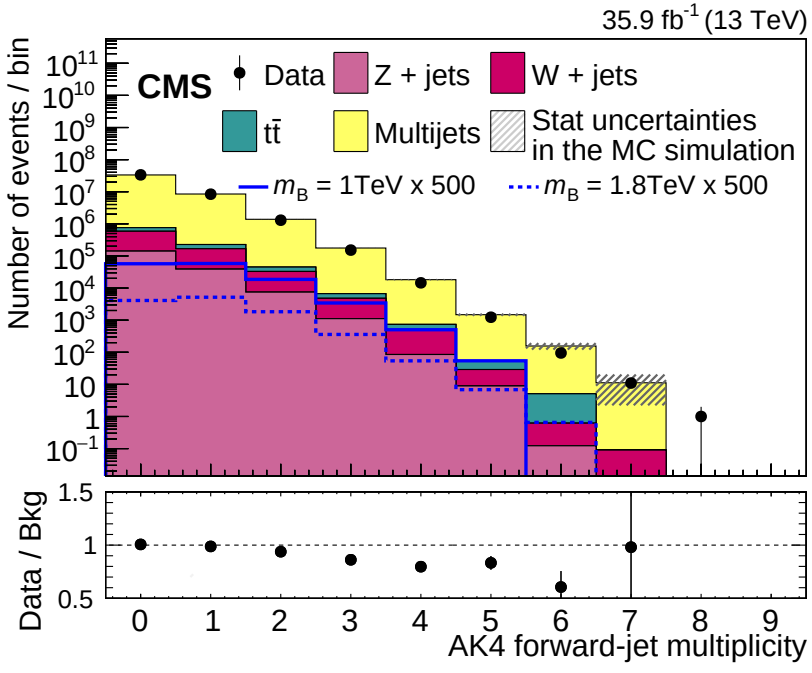


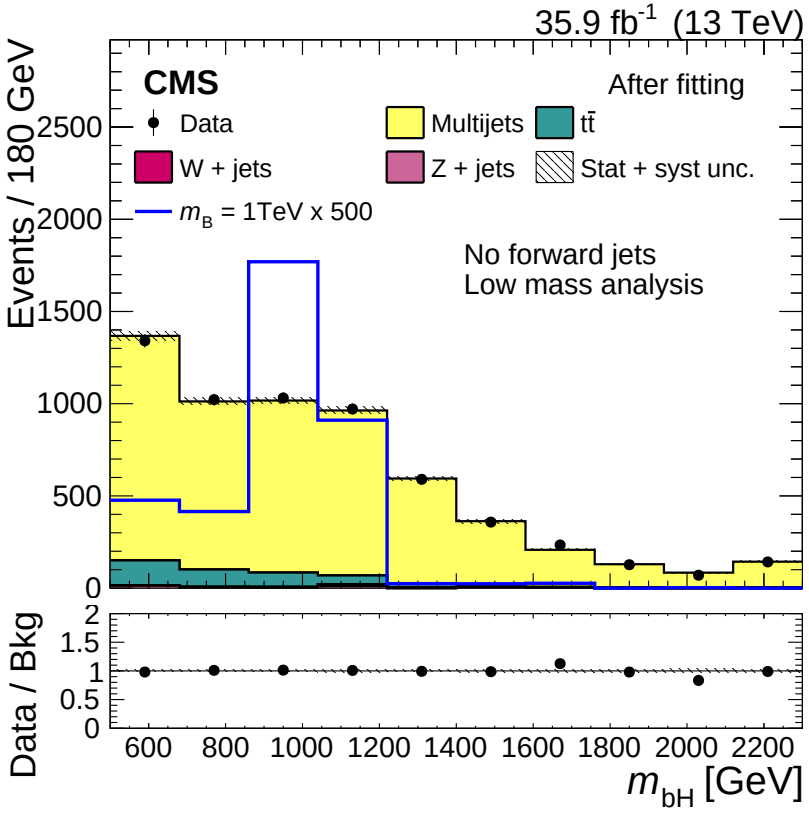


Lepton flavour violation



Vector-like quarks: $B \rightarrow Hb$





Third-generation scalar leptoquarks $LQ \to t\tau$