Search for new phenomena in leptonic final states at CMS

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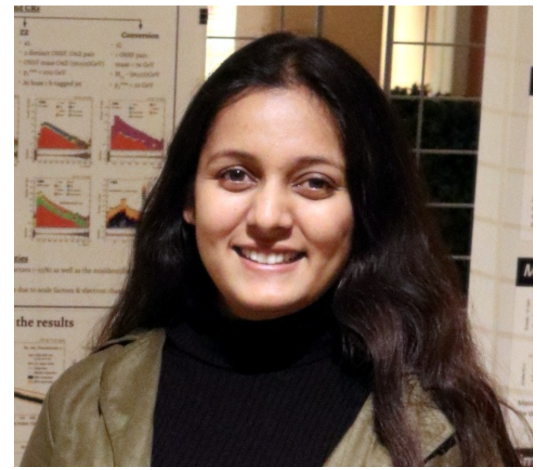

CMS

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CMS EXO Results with Leptons

- **Resonant signals**
  - A light scalar extension to SM (EXO-19-002)
  - $L_\mu - L_\tau$ local U(1) gauge invariant Z' (EXO-18-008)
  - Z' in SSM and superstring-inspired GUT model (EXO-19-019)
- **Non-resonant signals**
  - Type-III Seesaw (EXO-19-002)
  - Vector-like lepton doublet (EXO-18-005)
  - Excited leptons (EXO-18-013)
  - Right handed heavy neutrino in LRSM (EXO-17-016)
  - First and third generation leptoquark (EXO-17-009, EXO-17-016)
  - New charged vector gauge boson W' (EXO-17-008)

All CMS public results can be found here (EXO-XX-XXX).

Three or more Leptons

A LIGHT SCALAR EXTENSION TO SM

New Physics : Type-III Seesaw fermion triplet ($\Sigma^{\pm}$,Σ^{0}).

Light scalar boson (φ) produced in association with top quark pair.

Manifests as :

- Excess of events with large L_T or pT^{miss} for non-resonant heavy fermions.
- Localized excess in the dilepton mass spectra for the resonant φ boson.

Production & Decay :

For Type-III Seesaw, pp → $\Sigma^{\pm}\Sigma^{0}/\Sigma^{+}\Sigma^{-}$ (Σ→W/Z/h)

For scalar boson, pp → ttφ (φ→ ee/μμ)

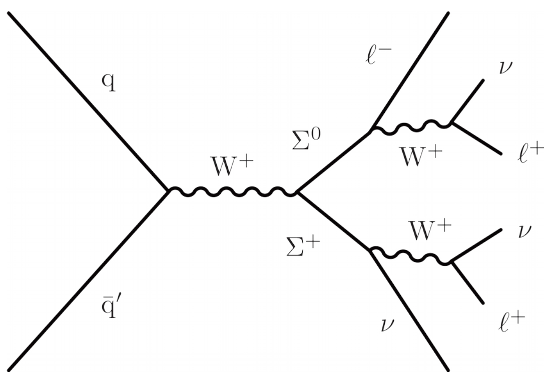
Final states :- ≥4L, 3L (L=e/μ)

Data analyzed : 137 fb^{-1} (2016+2017+2018)

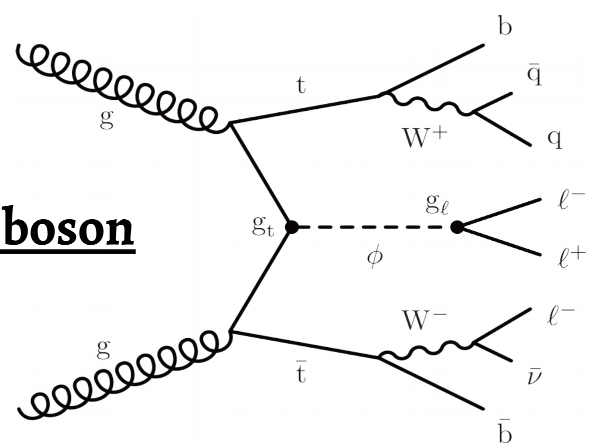
Major SM Backgrounds :

- Irreducible – WZ,ZZ,ttZ,ttW,VVV,Higgs
- Reducible – DY+jets, tt+jets,W+jets,WW+jets…

Type-III Seesaw



Light scalar boson



A LIGHT SCALAR EXTENSION TO SM

Analysis requirements :

Trigger : Combination of isolated single muon (pT>30 GeV) and single electron (pT>35 GeV).

Objects : PF objects with good identification criteria are used. Such as,

Muons	Electrons	AK4 Jets	pT^{miss} &
pT> 10 GeV, $\|\eta\|$<2.4	pT> 10 GeV, $\|\eta\|$<2.5	pT> 30 GeV, $\|\eta\|$<2.1	DeepCSV b-jets

Event selection :

- ≥4L events selected before =3L events.
- All leptons separated (ΔR=0.4) .
- Events with $M_{\ell\ell}$< 12 GeV are vetoed.
- Events consistent with FSR also rejected.
- Events classified using $N_{leptons}$, N_{OSSF} pairs and their mass.
- Control regions for major backgrounds.

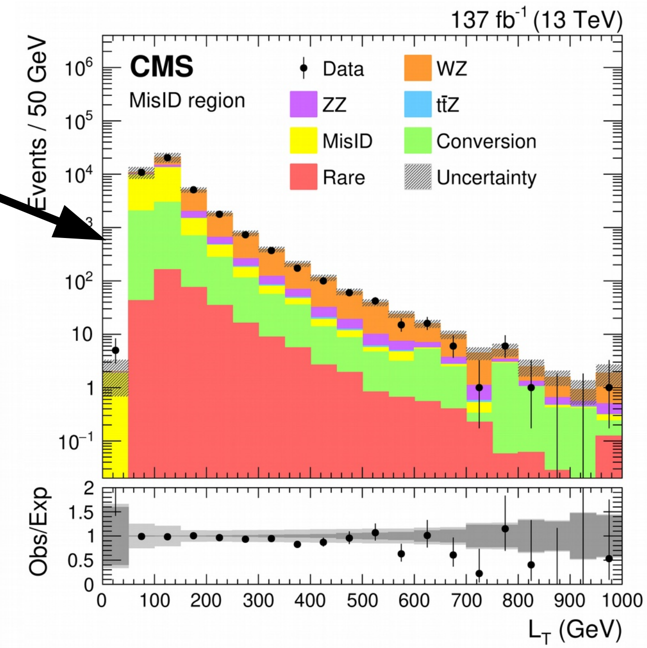
JHEP 03 (2020) 051

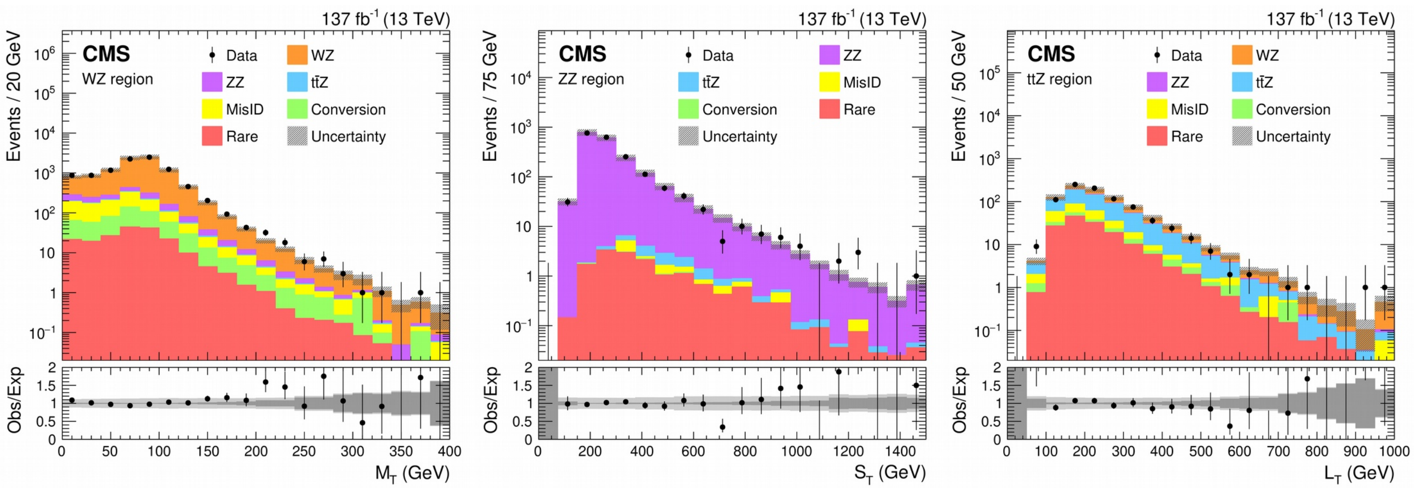
A light scalar extension to SM

Background techniques :

Reducible : Misidentified e/μ, estimated using data-driven 3D Matrix method.

- Universal prompt and fake rates for leptons.
- Rates measured in Z+jets events, parametrized by lepton pT, η and track multiplicity.
- Rates corrected using simulation for tt+jets effects.





Irreducible : Estimated using simulation normalized in dedicated CRs.

→ WZ : 3L, one Z-tag, 50<pT^{miss}<100GeV, no b-jet

→ ZZ : 4L, two Z-tags, pT^{miss}<100GeV

→ ttZ : 3L, one Z-tag, pT^{miss}<100GeV, S_T>350GeV, ≥1 b-jets

→ Conversion : 3L, 1 OSSF pair mass<76GeV, M_{3L} OnZ, pT^{miss}<50GeV

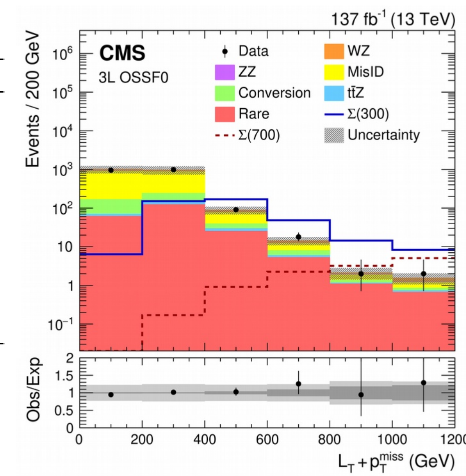
Z-tag = OSSF dilepton pair, mass within 15 GeV of Z boson mass (OnZ)

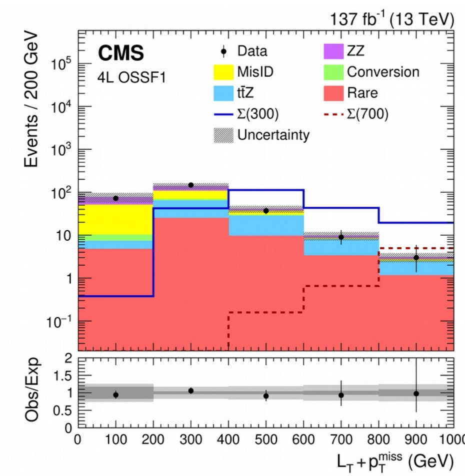
A light scalar extension to SM

Signal search strategy :

Type-III Seesaw : Counting experiment performed in 40 statistical independent bins.

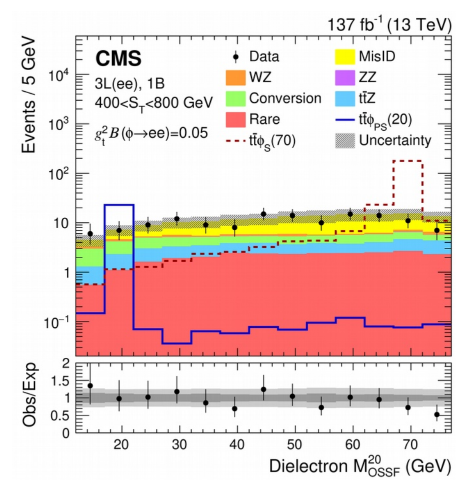
Label	N_{leptons}	N_{OSSF}	M_{OSSF} (GeV)	p_T^{miss} (GeV)	Variable and range (GeV)		Number of bins
3L below-Z	3	1	<76	—	$L_T + p_T^{\text{miss}}$	[0,1200]	6
3L on-Z	3	1	76–106	>100	M_T	[0,700]	7
3L above-Z	3	1	>106	—	$L_T + p_T^{\text{miss}}$	[0,1600]	8
3L OSSF0	3	0	—	—	$L_T + p_T^{\text{miss}}$	[0,1200]	6
4L OSSF0	≥4	0	—	—	$L_T + p_T^{\text{miss}}$	[0,600]	2
4L OSSF1	≥4	1	—	—	$L_T + p_T^{\text{miss}}$	[0,1000]	5
4L OSSF2	≥4	2	—	>100 if both pairs are on-Z	$L_T + p_T^{\text{miss}}$	[0,1200]	6

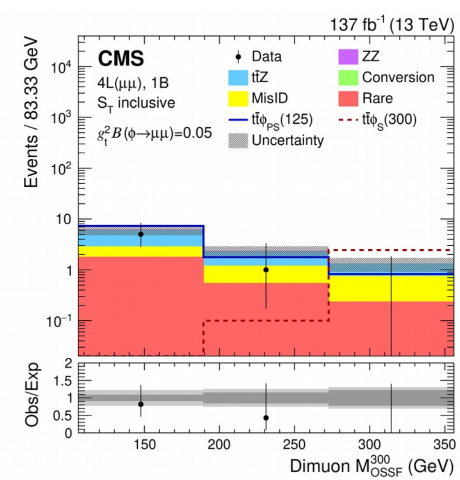




ttφ : Counting experiment performed in 70 (68) statistical independent low (high) dilepton mass search bins.

Label	N_{leptons}	N_{OSSF}	M_{OSSF}	N_b	Variable and range (GeV)		Number of bins		
						S_T (GeV)	0–400	400–800	>800
3L(ee/$\mu\mu$) 0B	3	1	off-Z	0	M_{OSSF}^{20}	[12,77]	13	13	5
					M_{OSSF}^{300}	[106,356]	10	10	10
3L(ee/$\mu\mu$) 1B	3	1	off-Z	≥1	M_{OSSF}^{20}	[12,77]	13	13	5
					M_{OSSF}^{300}	[106,356]	10	10	10
						S_T (GeV)	0–400	>400	
4L(ee/$\mu\mu$) 0B	≥4	≥1	off-Z	0	M_{OSSF}^{20}	[12,77]	3	2	
					M_{OSSF}^{300}	[106,356]	3	2	
						S_T inclusive			
4L(ee/$\mu\mu$) 1B	≥4	≥1	off-Z	≥1	M_{OSSF}^{20}	[12,77]	3		
					M_{OSSF}^{300}	[106,356]	3		

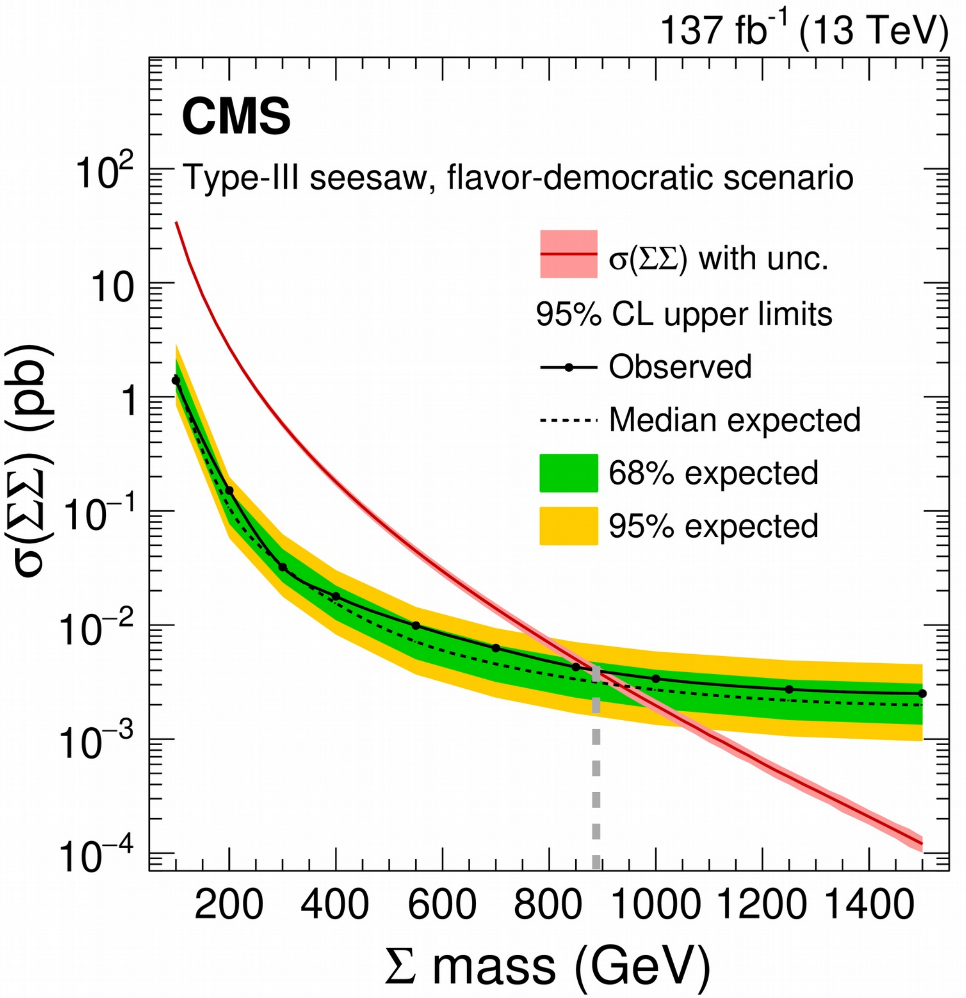




$M_{\text{OSSF}}^{20(300)}$ = attracter mass for light (heavy) φ.

A light scalar extension to SM

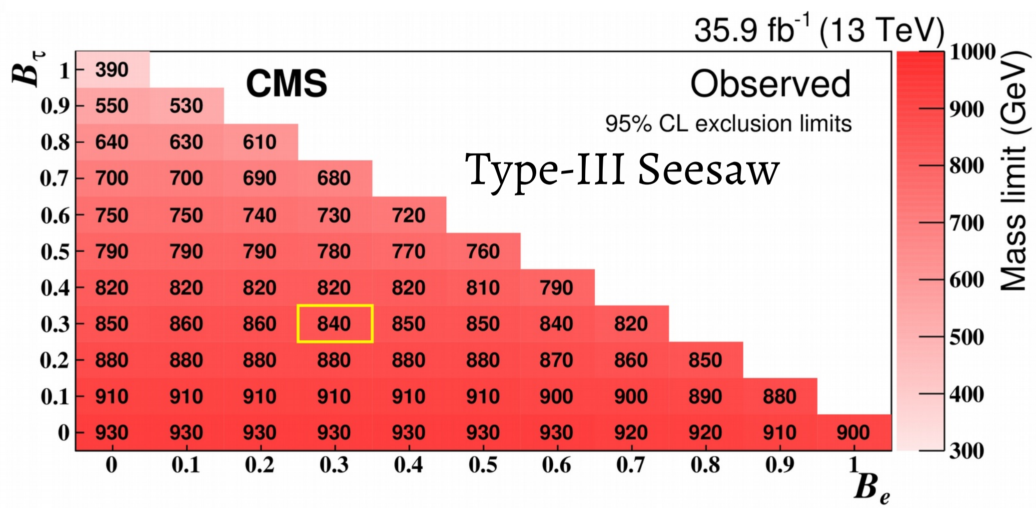
Results (1/2) :



Type-III seesaw heavy fermions are excluded at 95% CL with masses below 880 GeV, in the flavor-democratic scenario.

Limits in the different BR scenario

Phys. Rev. Lett. 119, 221802



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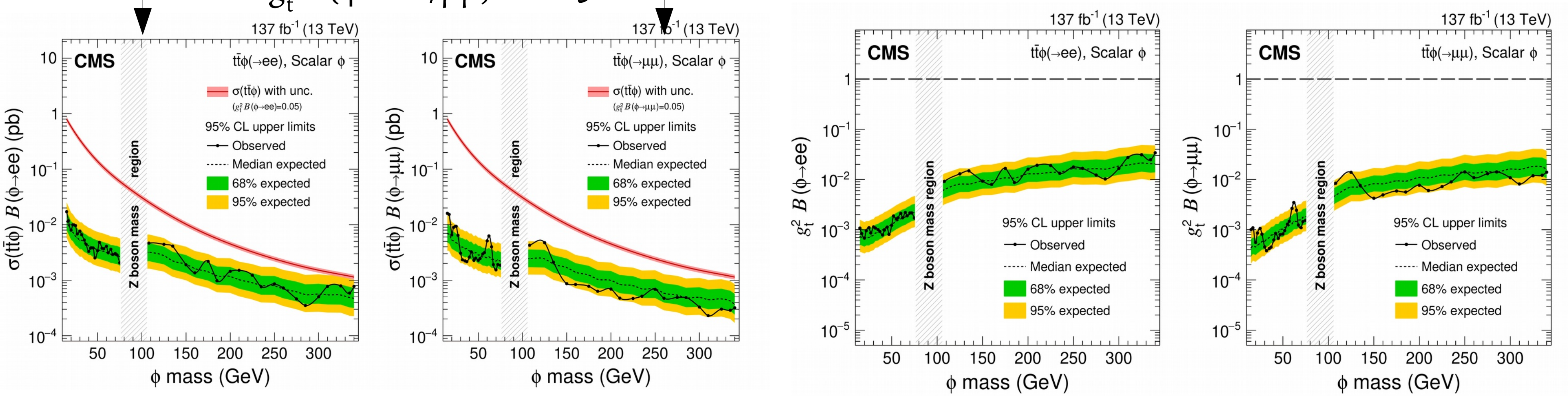
A light scalar extension to SM

Results (2/2) :

$g_t^2 B(\varphi \rightarrow ee/\mu\mu) = 0.05$



$\sigma_{tt\varphi}$ above 1–20 fb (0.3–5 fb) & $g_t^2 B(\varphi \rightarrow ee/\mu\mu)$ above 10^{-3} (10^{-4}) for φ mass in 15–75 GeV (108–340 GeV) are excluded at 95% CL.

Fiducial acceptance X event selection efficiency :-

Signal model	Product of acceptance and efficiency (%)														
Type-III seesaw (flavor-democratic scenario)															
Σ mass (GeV)	100	200	300	400	550	700	850	1000	1250	1500					
	0.32	1.82	2.63	3.02	3.29	3.34	3.29	3.21	2.99	2.82					
$t\bar{t}\phi$															
ϕ mass (GeV)	15	20	25	30	40	50	60	70	75	108	125	150	200	250	300
Scalar $\phi(\rightarrow ee)$	0.85	1.29	1.67	2.02	2.74	3.44	4.25	5.16	4.95	5.53	8.32	9.00	10.3	11.1	11.5
Scalar $\phi(\rightarrow \mu\mu)$	1.54	2.16	2.81	3.35	4.38	5.29	6.40	7.69	7.56	8.74	11.6	12.3	14.0	14.8	15.3
Pseudoscalar $\phi(\rightarrow ee)$	0.96	1.81	2.69	3.45	4.88	5.82	6.62	7.35	6.83	6.8	9.77	10.4	11.0	11.4	11.9
Pseudoscalar $\phi(\rightarrow \mu\mu)$	1.69	2.95	4.24	5.38	7.14	8.46	9.73	10.4	9.93	10.3	13.4	14.0	14.9	15.2	15.9

Phys. Rev. D 100, 052003

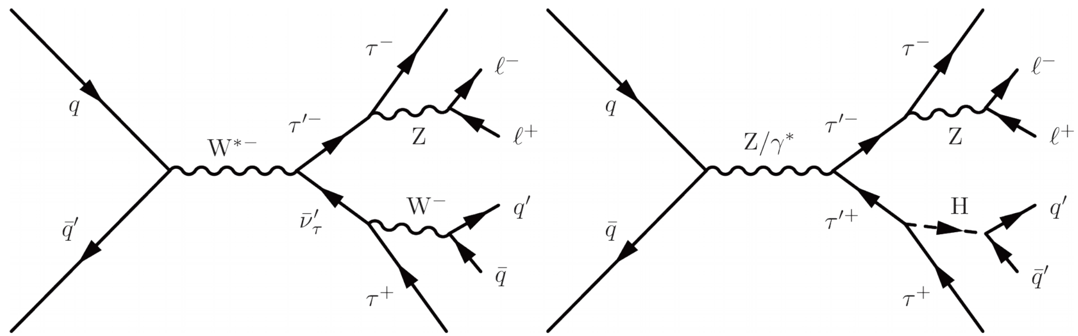
Vector-like Lepton Doublet

New Physics : Vector-like lepton (VLLs) doublet.

Manifests as : Excess of events with large L_T or pT^{miss}.

Production & Decay :

$pp \rightarrow \tau'\nu_\tau'/\tau'\tau'/\nu_\tau'\nu_\tau'$ ($\tau' \rightarrow Z\tau/h\tau$, $\nu_\tau' \rightarrow W\tau$)



Associated production — Pair production

Final states :- ***≥4L, 3L, 2L +≥1τ (L=e/μ)***

Data analyzed : 77 fb[-1] (2016+2017)

Major SM Backgrounds :

- Irreducible – WZ,ZZ,ttV,VVV,Higgs
- Reducible – DY+jets,tt+jets,W+jets,WW+jets...

Events selection flow :

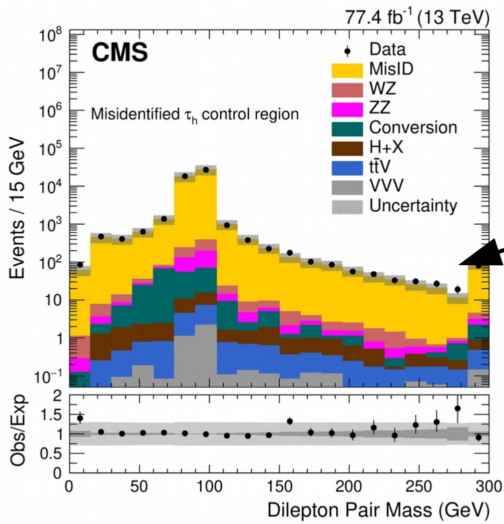
≥4L events → Exactly 3L events → 2L OS (SS) + ≥1τ events

Each channel is further subdivided into low & high pT^{miss} regions.

Phys. Rev. D 100, 052003

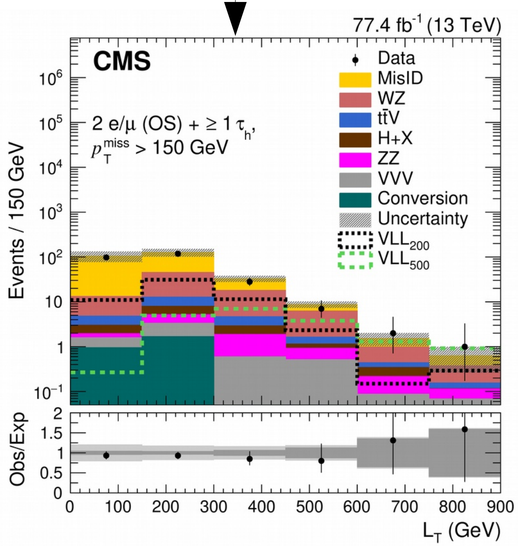
Vector-like Lepton Doublet

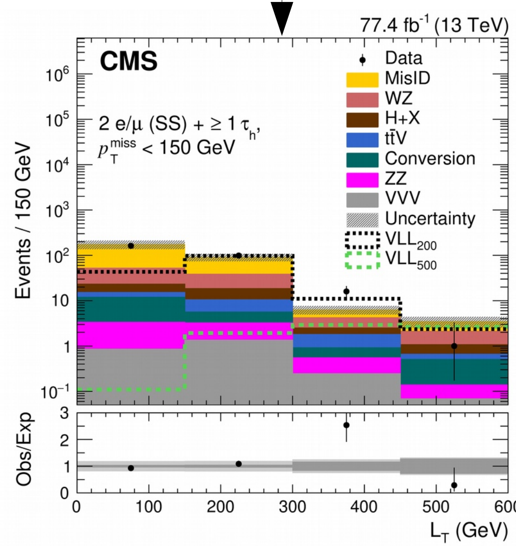
Results : No significant discrepancies between the background predictions and the observed data. Limits are set on the combined cross section of VLLs.

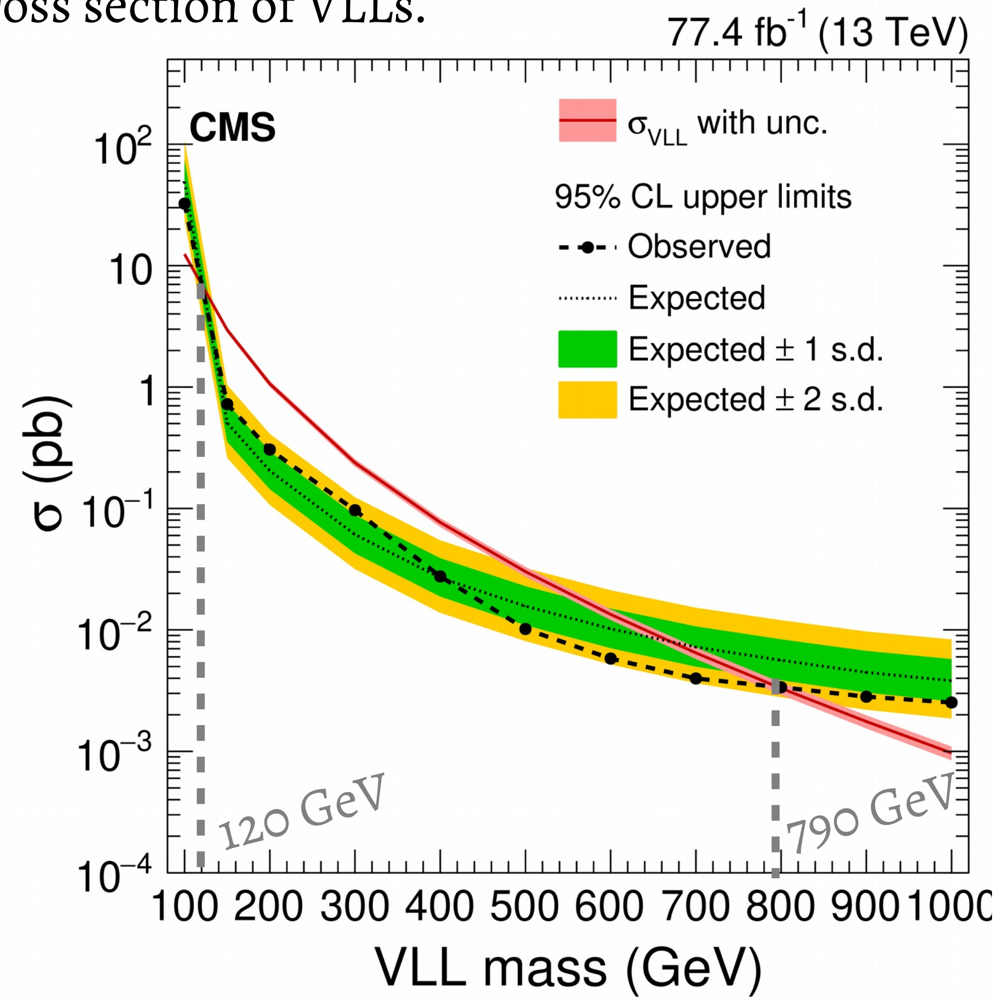


Using 3D Matrix method

Signal regions with taus







Excluded VLLs doublet in the range 120–790 GeV at 95% CL.

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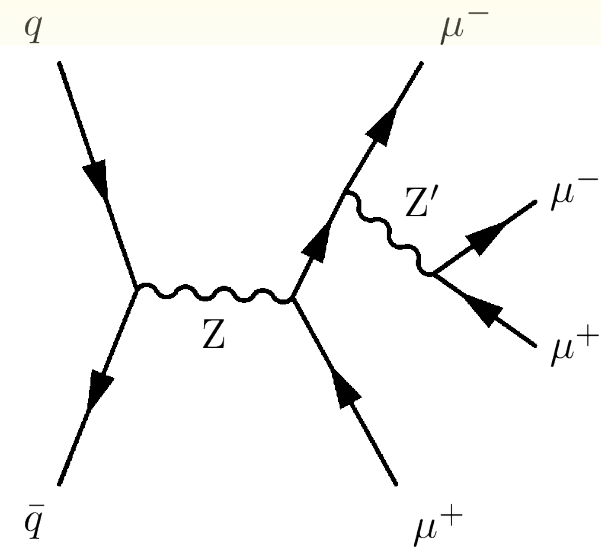
$L_\mu - L_\tau$ local U(1) Gauge invariant Z'

New Physics : Z'

$$\mathcal{L}_{Z'} = -gZ'_\mu \left(\bar{L}_2\gamma^\mu L_2 + \bar{l}_2\gamma^\mu l_2 - \bar{L}_3\gamma^\mu L_3 - \bar{l}_3\gamma^\mu l_3\right)$$



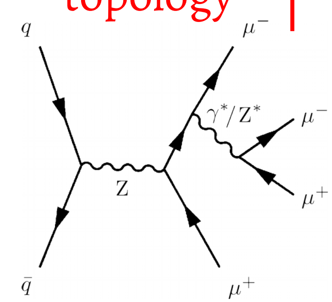
Manifests as : A narrow resonance, mass between 5 – 70GeV.

Production & Decay :

pp → Z → Z'μμ (Z' → 2μ)

Final state :- ***4μ***

Annihilation topology

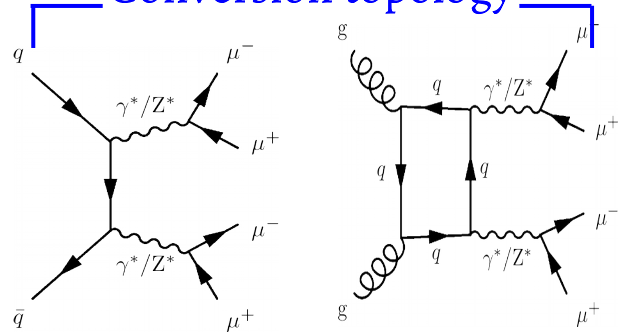


Data analyzed : 77 fb^{-1} (2016+2017)

Major SM Backgrounds :

- Dominant - Resonant Z→ 4μ from annihilation.
- Subdominant - Continuum qq→ 4μ and gg→ 4μ from conversion.

Conversion topology



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$L_\mu - L_\tau$ local U(1) Gauge invariant Z'

Analysis requirements :

Trigger : Isolated Single Muon (pT>27 GeV) / DiMuon (pT>17,8 GeV) / TriMuon (pT>12,10,5 GeV).

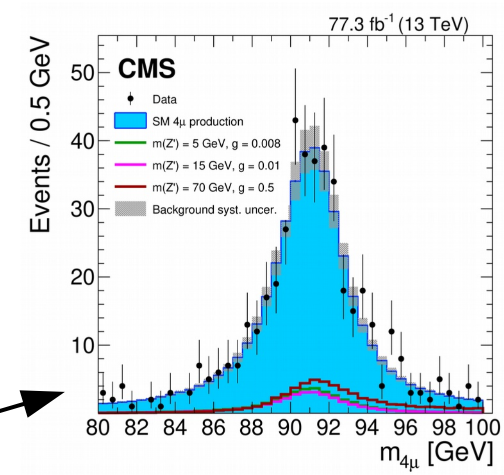
Object selection :

Prompt muons -

- pT>5GeV, $|\eta|$<2.4, isolated.
- 3D Impact parameter significance < 4.

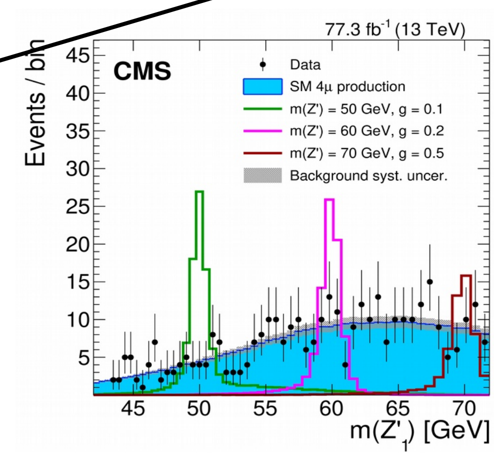
FSR Photons -

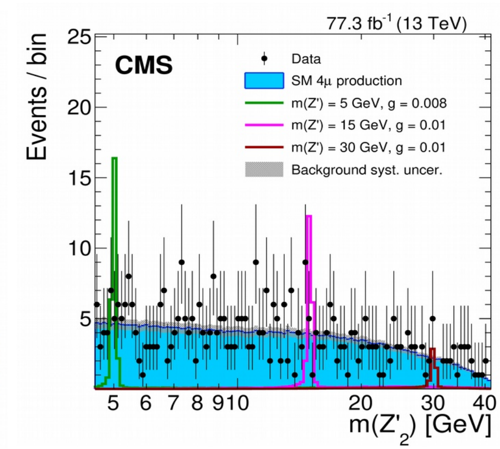
- pT>2GeV, $|\eta|$<2.4, loosely isolated.
- Associated to a muon if $\Delta R(\gamma,\mu)/(p_T^{\gamma})^2 < 0.012 GeV^{-2}$ and $\Delta R(\gamma,\mu)<0.5$



Event selection :

- Two OS muon pairs, $4 < M_{\mu+\mu-} < 120$ GeV for each pair and $80 < M_{4\mu} < 120$ GeV.
- **Z'_1 =** Highest invariant mass dimuon pair
- **Z'_2 =** Invariant mass of other two muons in the event, with highest scalar sum pT.



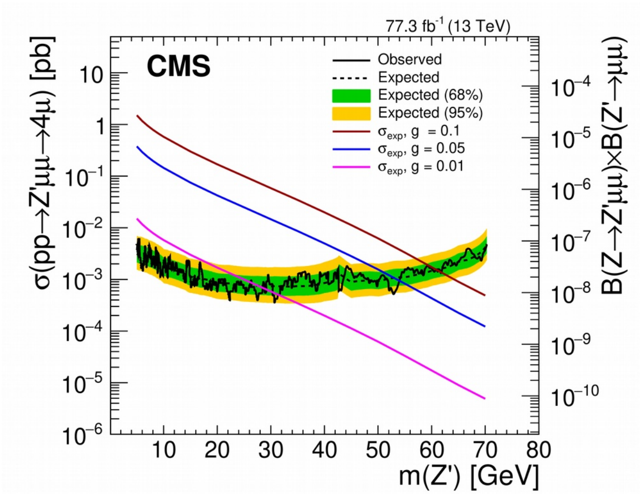


Phys. Lett. B 792 (2019) 345

$L_\mu - L_\tau$ local U(1) Gauge invariant Z'

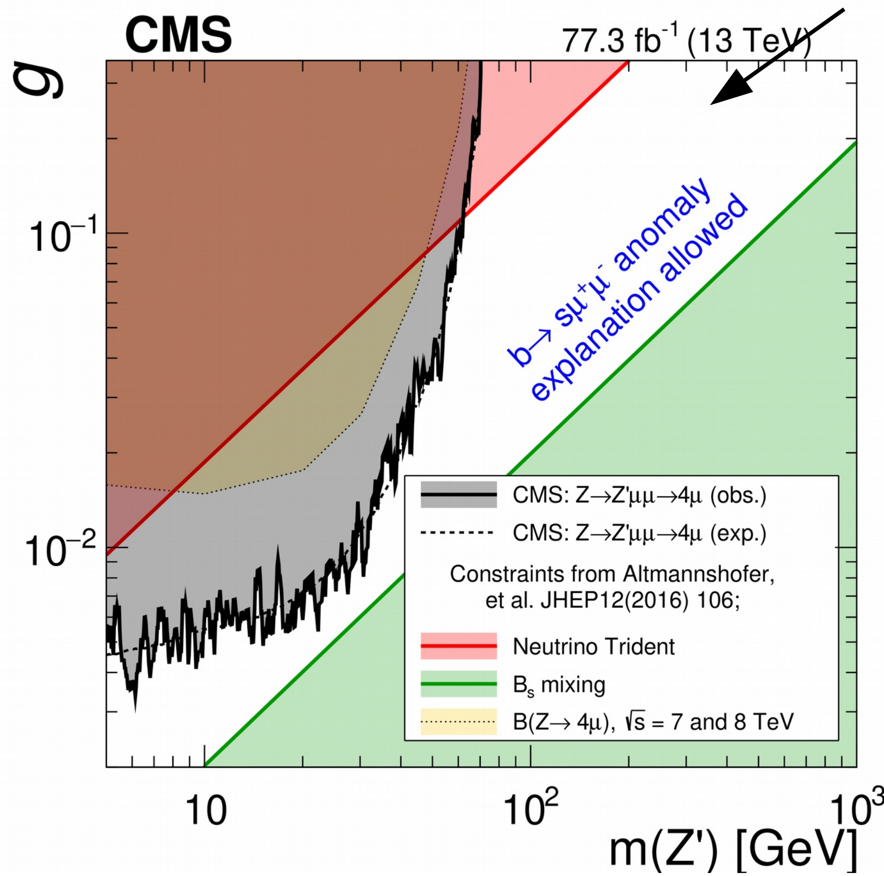
Analysis results : Counting experiment search based on reconstructed Z' mass.

- Z' is reconstructed as Z'_2 for m(Z')<42.65GeV, otherwise as Z'_1, with 2% mass resolution.
- Signal efficiency : ε=63% ($m_{Z'}$=5GeV), ε=25% ($m_{Z'}$=40GeV) and ε=67% ($m_{Z'}$=70GeV).



B(Z' → μμ) taken to be 1/3 for the theoretical predictions.

Upper limits on the gauge coupling strength g, as compared to other experimental constraints.



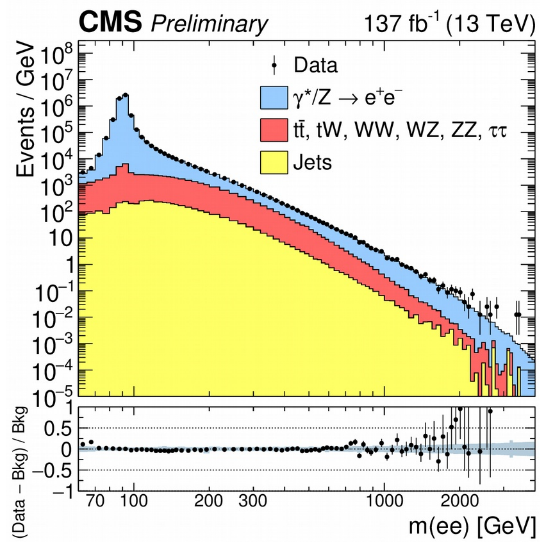
B(Z → Z'μμ)B(Z' → μμ) excluded above 10^{-8} –10^{-7} at 95% CL, depending on the Z' mass, excluding a Z' boson coupling strength to muons above 0.004–0.3.

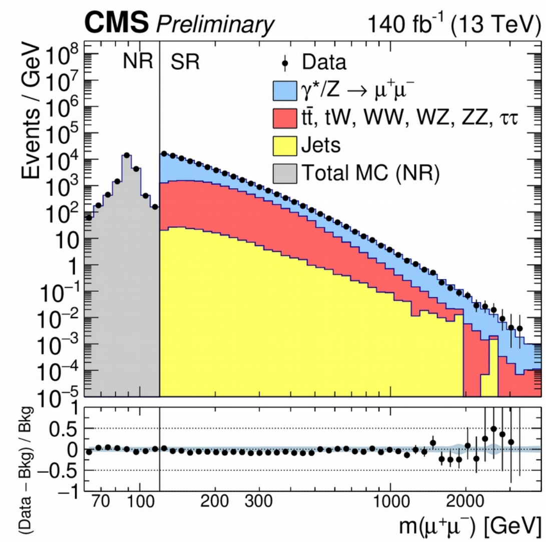
Two leptons

Z'_{SSM} & Z'_{ψ}

New Physics : Z'_{SSM}(Z'_{ψ}) arising in generalized sequential SM (superstring-inspired GUT model based on E_6 gauge group).

Manifests as : Narrow dilepton resonance.





Final states :- ee, μμ

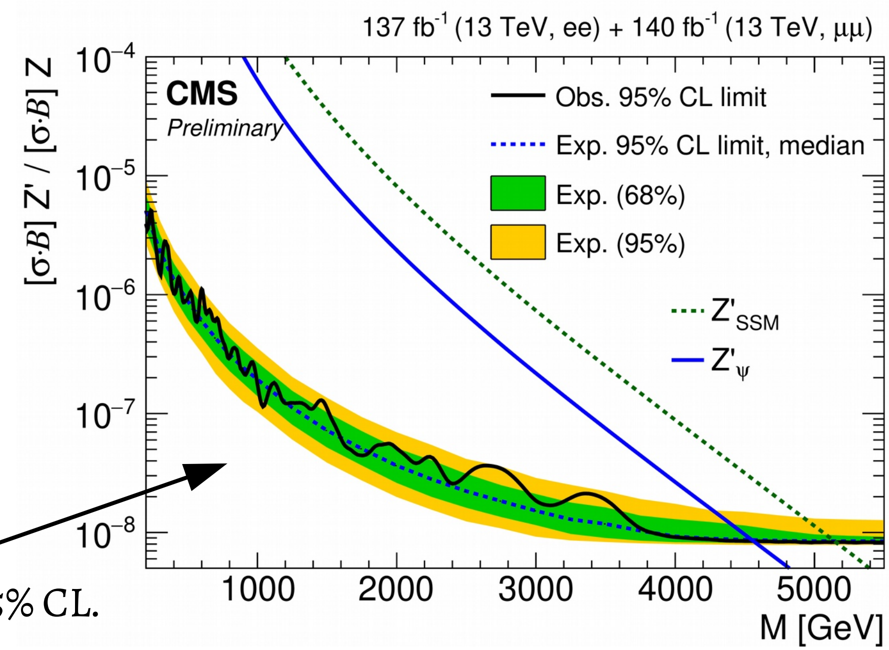
Data analyzed : 137 (140) fb^{-1} in ee (μμ)

Major SM Backgrounds :

- Z+jets, tt+jets, W+jets, VV, Single top…

These are estimated using simulation and overall yield is normalized to data around the Z boson peak i.e. ($60 < m_{\ell\ell} < 120$ GeV).

Limits set on the ratio of cross section times the branching fraction of the new Z' to SM Z boson, kills various experimental systematic uncertainties.

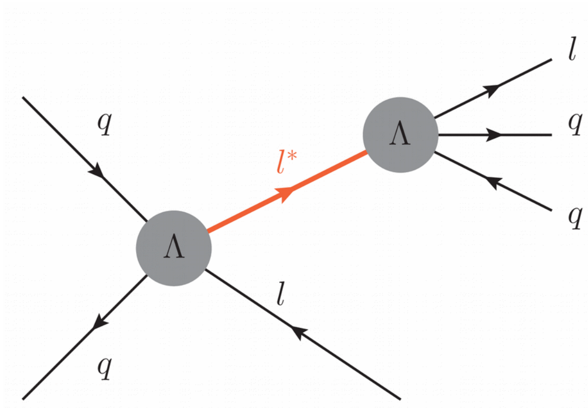


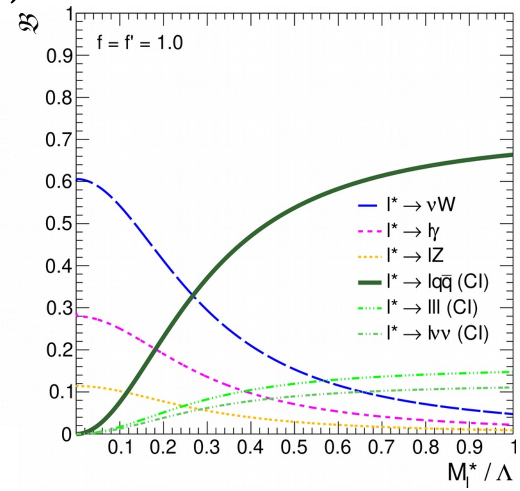
Excluded Z'_{SSM}(Z'_{ψ}) below a mass of 5.15 (4.56) TeV at 95% CL.

Excited Leptons

New Physics : Excited leptons due to compositeness and decay through CI.

Manifests as : Non-resonant excess in events with high p_T leptons and jets.





Production & Decay :

$pp \rightarrow \ell\ell^* \ (\ell^* \rightarrow \ell qq)$

Final states :- ***2e+2j, 2μ+2j***

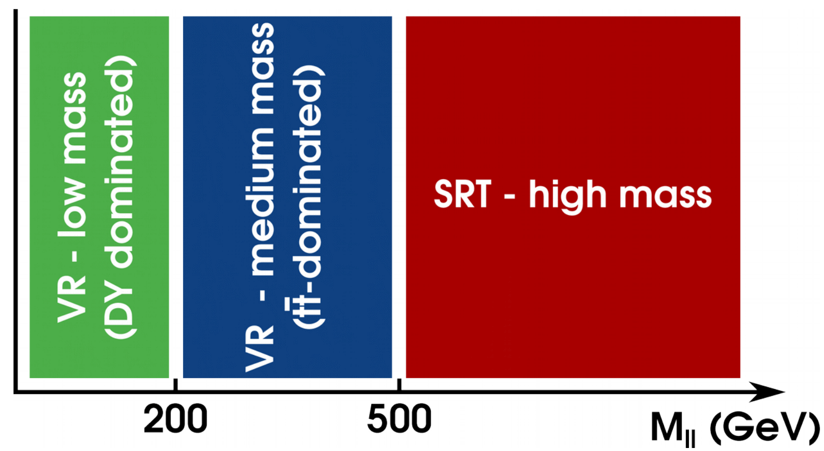
Data analyzed : 77 fb^{-1} (2016+2017)

Major SM Backgrounds :

Prompt sources – DY+jets, tt+jets, Single Top, VV

Misidentified electrons – W+jets

(All estimated from simulation)



Analysis requirements :

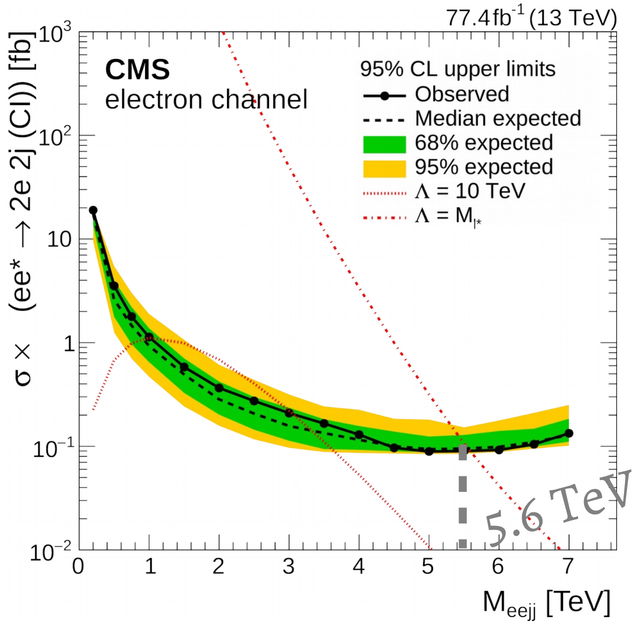
Trigger – High pT (>175 GeV) single electron and (>50 GeV) single muon trigger.

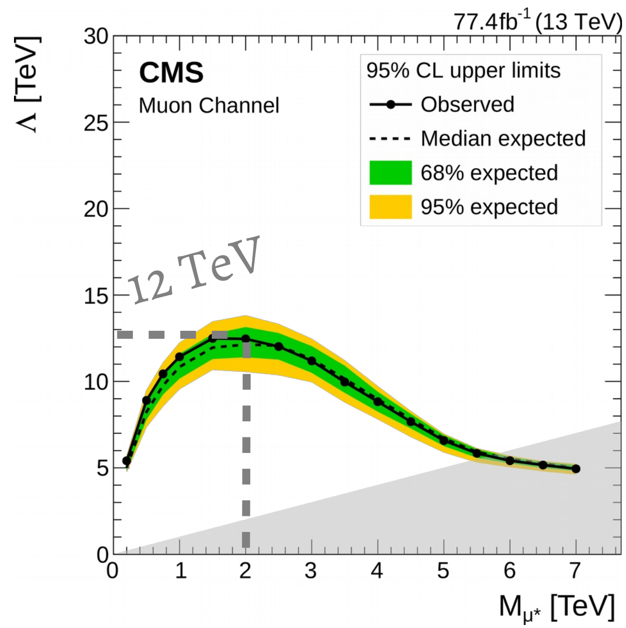
Objects – High pT, isolated & prompt electrons and muons. AK4 jets.

EXCITED LEPTONS

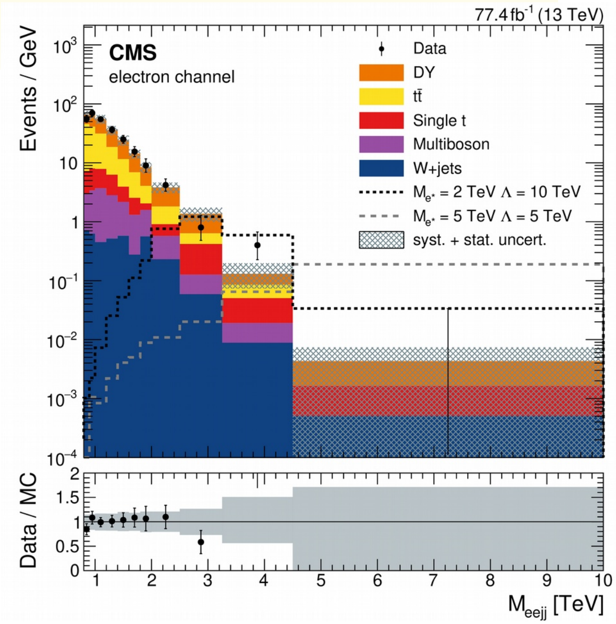
Results : Four body invariant mass used as final signal discriminating variable.

Excited ele (mu) up to $M_{e^*} = 5.6$ TeV ($M_{\mu^*} = 5.7$ TeV) are excluded.





Re-evaluating limits excludes substructure scale $\Lambda = 11$ (12) TeV for $M_{e^*} = M_{\mu^*} \sim 2$ TeV and coupling strength unity.



Excited leptons in $\ell\ell\gamma$ final state.

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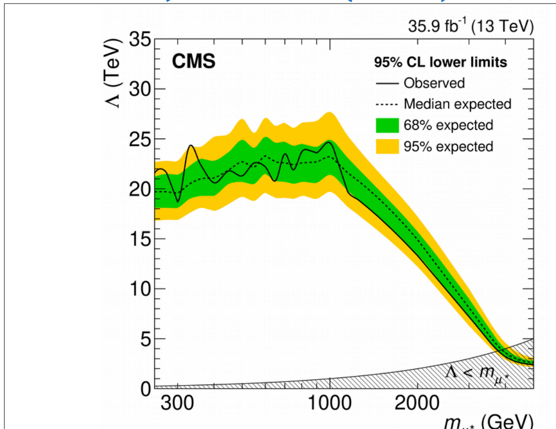


Best limits for Λ=25 TeV for $M_{e^*} = M_{\mu^*} \sim 1$ TeV

Conclusion

- CMS has a widespread research program for understanding SM as well as BSM physics.
- Many exotic signals, both resonant and non-resonant, manifest themselves in the leptonic final states.
- Good reconstruction and comparatively low noise from SM allows us to span a wider phase space with leptons, thereby improving the exclusions.
- Many new and existing results using better estimation procedures for SM processes, with full Run2 data are already on the way.
- Use of innovative techniques including machine learning are pushing the frontiers.
- Stay tuned for Run3 and beyond… and let's keep hunting for new physics!

Thank you !

Backup

Phys. Rev. D 99, 052002

First generation leptoquarks

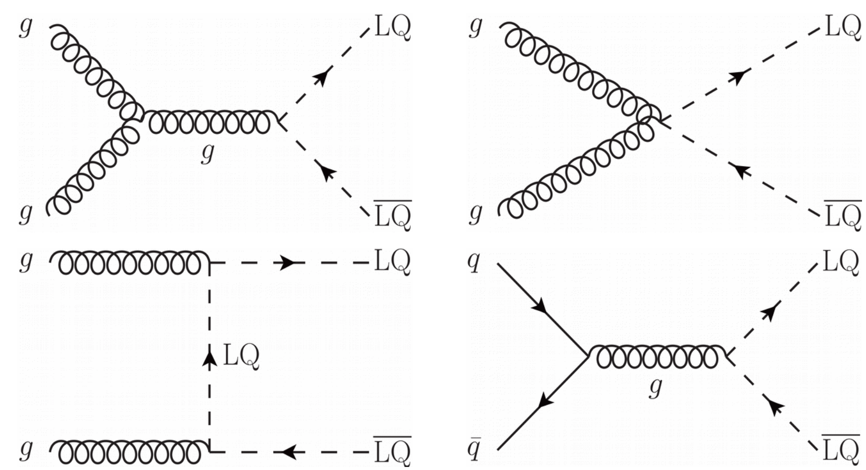
New Physics : Fractionally charged first-generation scalar leptoquark boson.

Manifests as : Non-resonant excess in events with high p_T leptons and jets or high $pT^{miss.}$

Production & Decay : pp → LQ LQ (LQ → ej/ν_ej)

(β=LQ coupling to ej)

Final states :- ***2e+2j, eν+jj***



Data analyzed : 36 fb^{-1} (2016)

Major SM Backgrounds :

- Prompt sources – DY+jets, tt+jets, Single Top, VV
- Misidentified – W+jets, ɣ+jets, multjet

Analysis requirements :

- **Trigger –** Combination of single electron (pT > 27 GeV) and single photon (pT > 115 GeV).
- **Objects –** Electron (pT > 50 GeV & |η|<2.5), AK4 Jets (pT > 50 GeV, |η|<2.4 & ΔR(ℓ,j)>0.3) and pT^{miss} are also used.
  Additionally, muons (pT > 35 GeV & |η|<2.4) are used for control region estimates.

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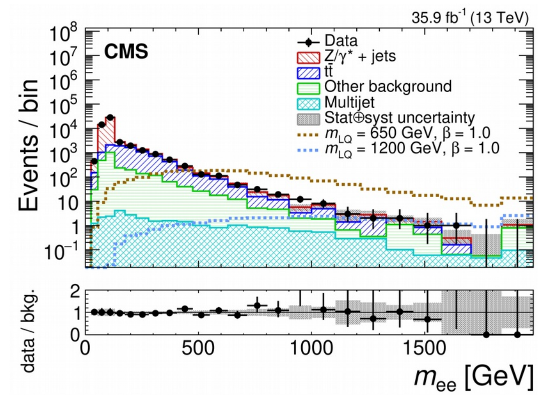
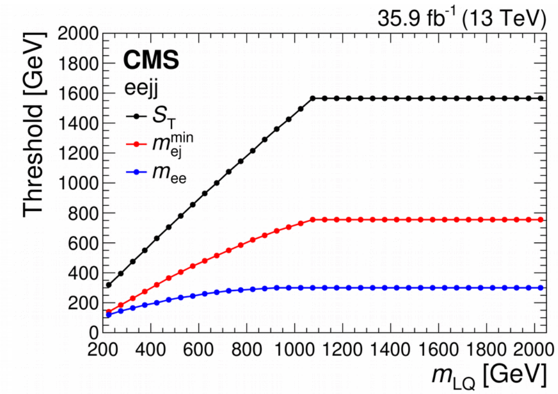
First generation leptoquarks

Analysis strategy :

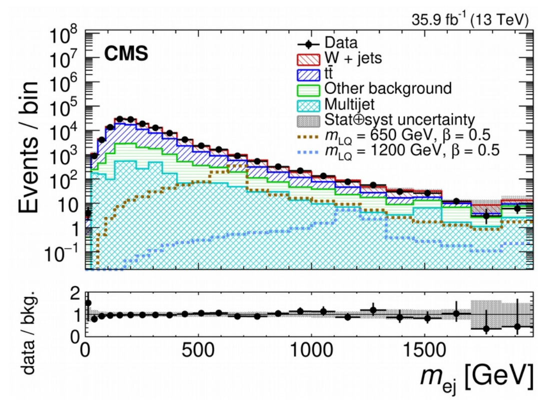
- **eejj channel**
  - Two highest pT electrons and jets
  - No charge requirement on electrons
  - $M_{ee} > 50$ GeV, $pT_{ee} > 70$ GeV
  - S_T ($= pT_{e1} + pT_{e2} + pT_{j1} + pT_{j2}$) > 300 GeV

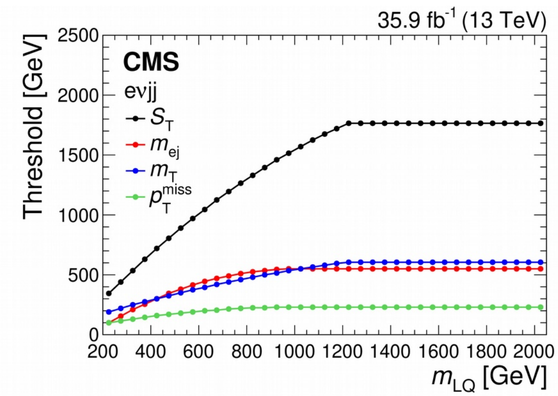




Punzi criterion is used to maximize final signal selection (upto 5σ), minimizing the difference in the two LQ masses with the help of m_{ej} .

- **eνjj channel**
  - One high pT electron and two jets
  - $pT^{miss} > 100$ GeV, $\Delta\varphi(pT^{miss}, j1) > 0.5$
  - For e-pT^{miss} system, M > 50 GeV, pT > 70 GeV and $\Delta\varphi > 0.8$
  - S_T ($= pT_{e1} + pT^{miss} + pT_{j1} + pT_{j2}$) > 300 GeV





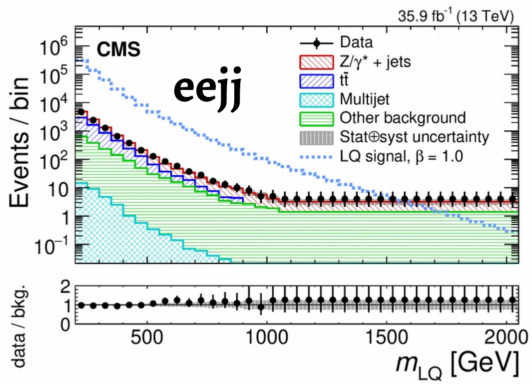
Punzi criterion is used similar to eejj channel, minimizing the difference in the M_T of two LQ with the help of e-pT^{miss} and e-jet system.

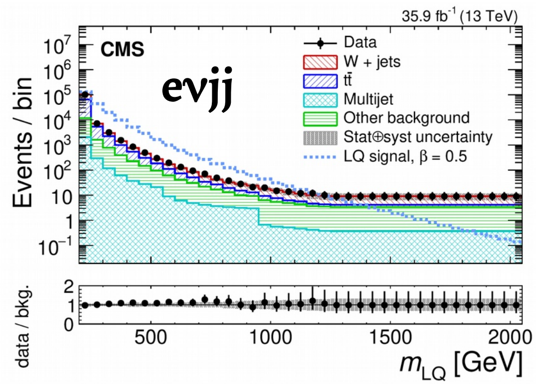
First generation leptoquarks

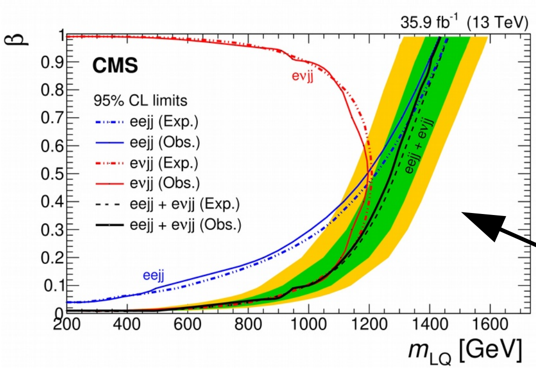
SM backgrounds :

- Z+jets using MC normalized in $80 < m_{ee} < 100$ GeV CR of each channel.
- tt+jets & W+jets MC normalized in $50 < m_T < 110$ GeV eμ + b-jets & eejj CR respectively.
- Multijet fakes (QCD) using data-driven fake rate method in $pT^{miss} < 100$ GeV of eejj channel.

Results :







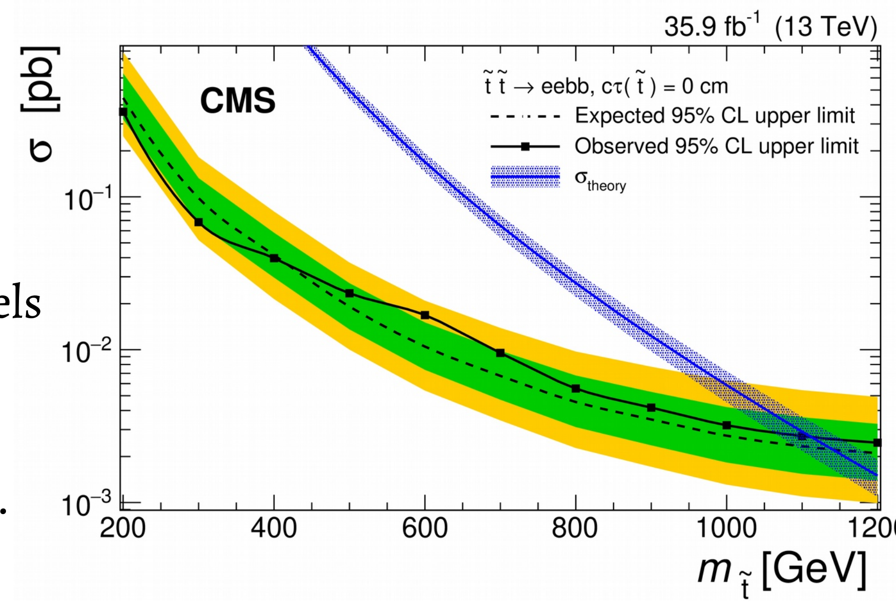
LQ for masses below 1435 GeV in eejj while 1195 GeV in evjj channels are excluded at 95% CL.

Combined exclusion is 1270 GeV.

RPV SUSY reinterpretation

where stop decays to LQ-like final states.

Top squarks excluded below 1100 GeV.



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Third generation LQ & RHN in LRSM

New Physics : Right-handed charged boson W_R in LRSM decaying to heavy majorana N_τ and third-generation scalar leptoquarks.

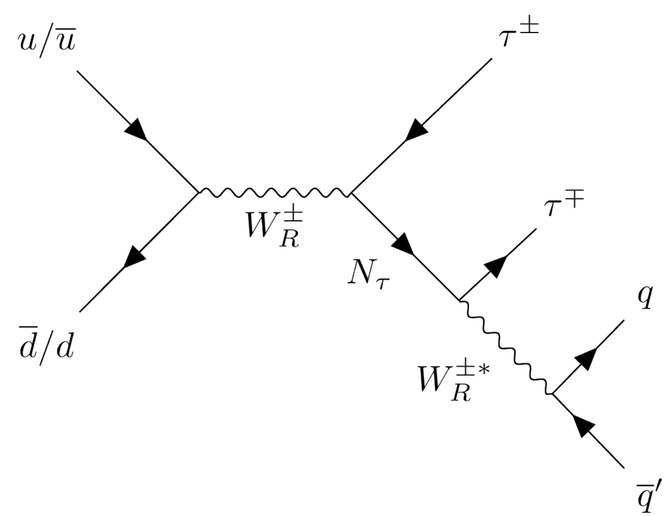
Manifests as : Excess in tails of S_T^{MET} for LQ and a broad enhancement in the partial mass distribution for N_τ.

Production & Decay :

Right handed heavy tau neutrino : $pp \rightarrow W_R \rightarrow N_\tau \tau$ ($N \rightarrow W\tau$)

Third generation scalar leptoquark : $pp \rightarrow LQ\ LQ$ ($LQ \rightarrow \tau b$)

Right-handed heavy Neutrino



Final states :- ***2τ+2j***

Data analyzed : 36 fb^{-1} (2016)

Major SM Backgrounds : Z+jets, tt+jets, QCD multijet

Analysis requirements :

Trigger – DiTau trigger (pT>32 GeV) is used.

Objects – Hadronic taus (MVA ID, pT > 70 GeV & $|\eta|<2.1$) and AK4 Jets (pT > 50 GeV & $|\eta|<2.4$) and pT^{miss} are used. All physics objects separated by $\Delta R>0.4$.

Additionally, good muons and electrons are used for control region studies.

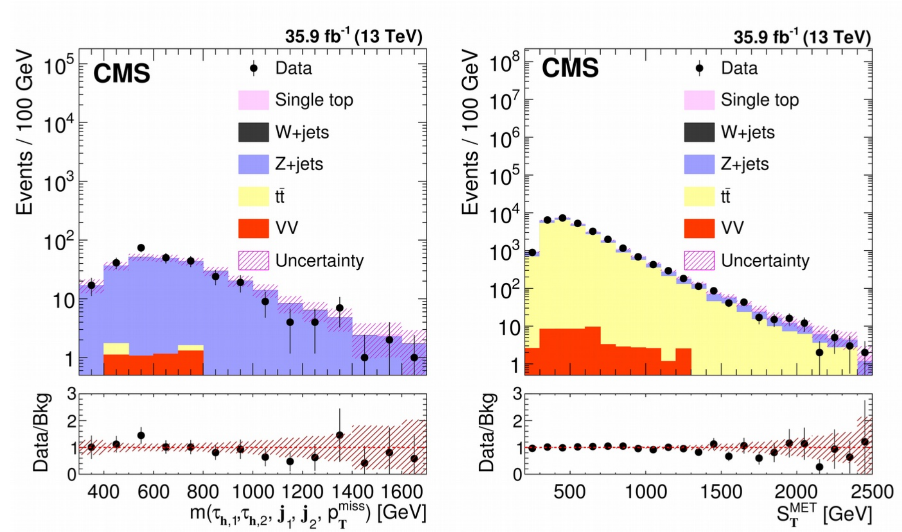
Third generation LQ & RHN in LRSM

Event selection :

- Events selected with two taus, two highest pT jets and pT^{miss}>50 GeV (rejects QCD).
- $M_{\tau\tau}$>100 GeV (rejects DY+jets).
- Partial mass for N_τ is expected to be ~ $m(W_R)$.

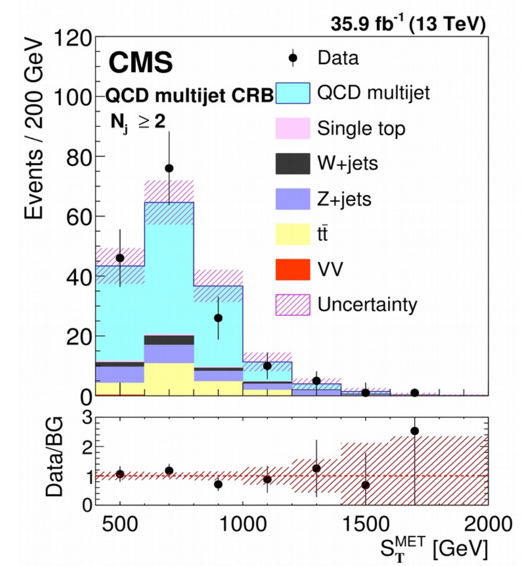
$$m(\tau_{h,1}, \tau_{h,2}, j_1, j_2, p_T^{miss}) = \sqrt{(E_{\tau_{h,1}} + E_{\tau_{h,2}} + E_{j_1} + E_{j_2} + p_T^{miss})^2 - (\vec{p}_{\tau_{h,1}} + \vec{p}_{\tau_{h,2}} + \vec{p}_{j_1} + \vec{p}_{j_2} + \vec{p}_T^{miss})^2}.$$

- $S_T^{MET} = pT_{\tau 1} + pT_{\tau 2} + pT_{j1} + pT_{j2} + pT^{miss}$ is expected to be large for LQ, ~M(LQ).



Background techniques : Estimated using CRs in data. Simulation is used to model the shape of W_R and LQ mass. Subdominant W+jets, Single Top are estimated using MC.

- DY : μμjj OnZ control sample in data, ττjj signal region yield for DY = $N^{Z\rightarrow\tau\tau}(MC)SF^{Z\rightarrow\mu\mu}(dijet)$.
- tt+jets : 2μ events with a b-jet and vetoeing Z boson peak at $80<m_{\mu\mu}<110$GeV.
- QCD multijet : Estimated using "ABCD" method in data with pT^{miss} and tau isolation.



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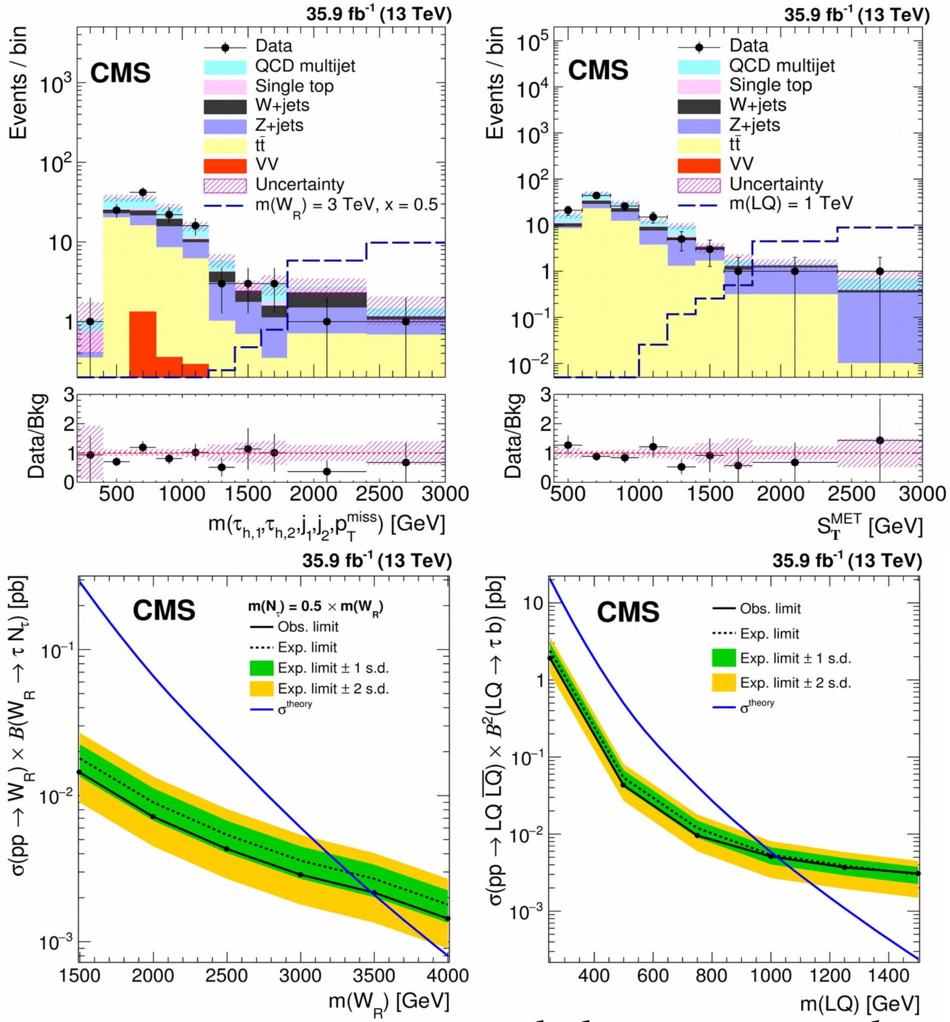
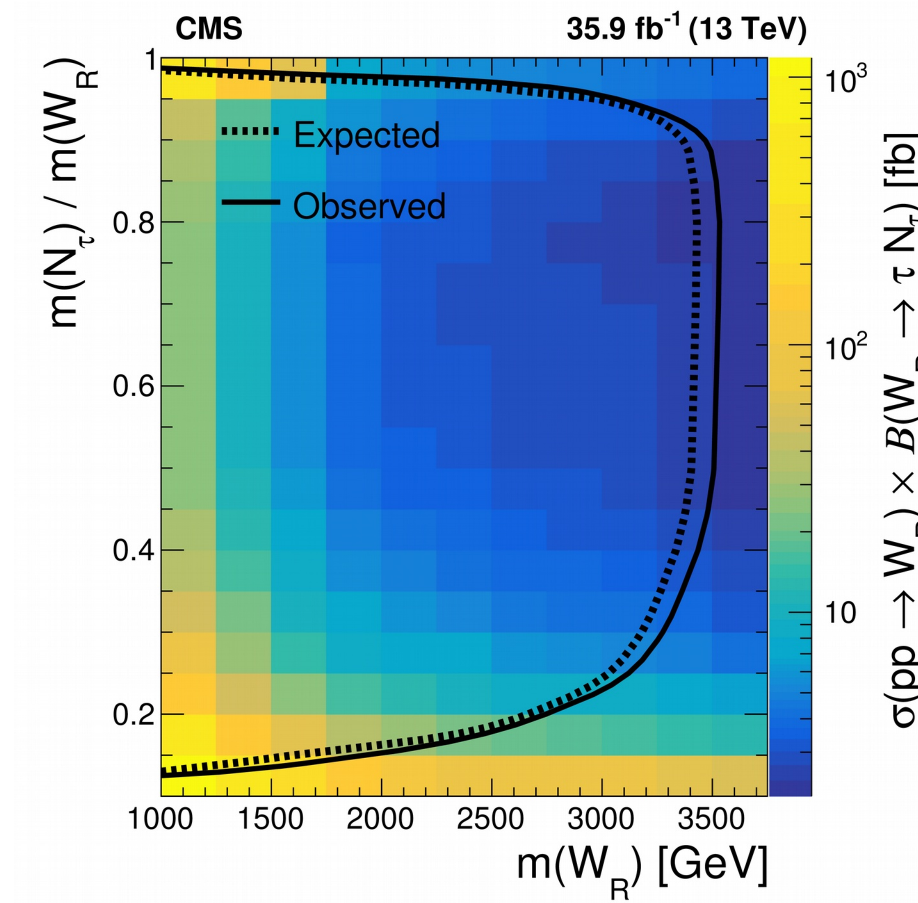
Third generation LQ & RHN in LRSM

Results : Observed data event rate and shapes are consistent with SM backgrounds. Binned maximum likelihood fit is used to set limits on the signal rate.



N_τ mass = 0.5 X m(W_R). W_R below 3.5 TeV and LQ below 1.02 TeV are excluded at 95% CL.



2D exclusion curve for W_R production cross section, as a function of its mass and ratio of N_τ to W_R mass at 95% CL.