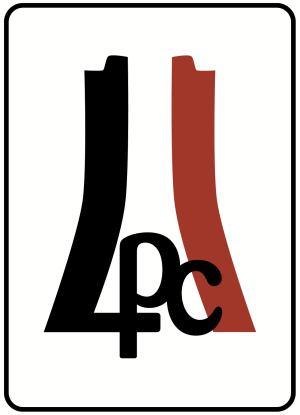
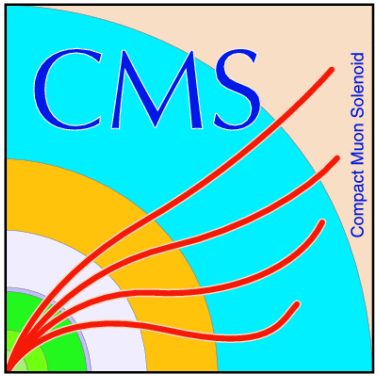
Search for Heavy Resonances in Leptonic Final States in CMS

John Stupak III on behalf of CMS

LHCP 2013

May 17, 2013





Outline

- Introduction
- $W_R \rightarrow \ell\ell jj$ [CMS-PAS-EXO-12-017]
- $W' \rightarrow \ell\nu$ [CMS-PAS-EXO-12-060] **New!**
- $Z' \rightarrow \ell^+\ell^-$ [CMS-PAS-EXO-12-061] **New!**
- $LQ_2LQ_2 \rightarrow \mu\nu jj$ / $\mu\mu jj$ [CMS-PAS-EXO-12-042] **Brand New!**
- Conclusion

Introduction

- A common approach to explain BSM physics is to extend the SM symmetry group
  - $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$ ➔ Additional neutral gauge boson (Z')
  - $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)'$ ➔ Additional charged (W') and neutral (Z') gauge bosons
    - $SU(2)' = SU(2)_R$
      - Left-Right Symmetric Model with $W' = W_R$ and right-handed neutrinos N_ℓ
- Another approach is to embed SM within a larger symmetry group
  - GUTs - E_6, SU(6), SO(10), …
    - Additional charged (W') and neutral (Z') gauge bosons
    - Leptons and quarks together within a multiplet ➔ Leptoquarks
      - Color triplets bosons carrying both lepton and baryon number
- Additional gauge bosons and/or leptoquarks also predicted by:
  - Models with extra dimensions
  - Composite models
  - RPV SUSY
  - Little Higgs models
  - Technicolor
  - …

Introduction

- Leptonic (ℓ = e,μ) final states are promising topologies for NP searches
  - Triggering
  - Background rejection
  - Large BR in many scenarios

} lepton

- Searches shown here based on data collected by CMS in 2012
  - $s^{1/2}$ = 8 TeV
  - $\int Ldt \approx 20$ fb^{-1} (except W_R search - based on 3.6 fb^{-1})
  - Single or di-lepton triggers

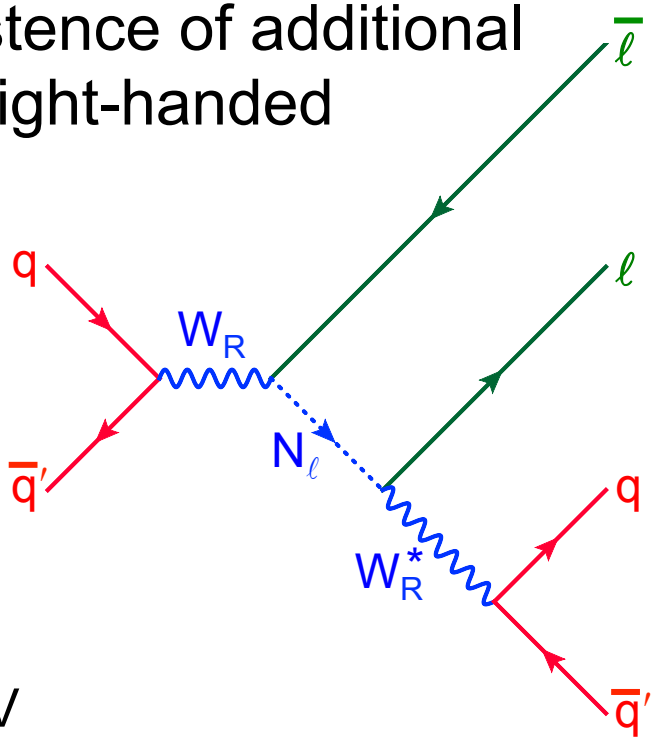
$W_R \rightarrow \ell\ell jj$

[CMS-PAS-EXO-12-017]

- Left-Right Symmetric model predicts existence of additional charged gauge bosons (W_R) and heavy right-handed neutrinos (N_ℓ)
  - W_R could decay according to:

$$W_R \rightarrow \ell N_\ell \rightarrow \ell\ell W_R^* \rightarrow \ell\ell qq'$$

    - Search for resonances in m($\ell\ell$jj)
- Event selection
  - ≥ 2 isolated SF leptons
    - Leading (sub-leading) lepton p_T > 60 (40) GeV
  - ≥ 2 jets (p_T > 40 GeV)
  - m($\ell\ell$) > 200 GeV
  - m($\ell\ell$jj) > 600 GeV



$W_R \rightarrow \ell\ell jj$

[CMS-PAS-EXO-12-017]

- Background modeling
  - Z+jets
    - Shape from MadGraph
    - Normalization from data in m(Z) window
  - ttbar
    - Shape and normalization from eμjj events in data
  - QCD
    - Data-driven "fake-rate" method
  - Other backgrounds
    - Modeled with MC

Pythia
$m(W_R) = 1.8$ TeV
$m(N_\ell) = 0.9$ TeV

$\int Ldt = 3.6\, fb^{-1}$

Electron Channel

Selection Stage	Data	Signal	Total Bkgd	$t\bar{t}$	Z+jets	QCD	Other
Two electron, two jets	8807	61	8943	968	7821	8	146
$e_1\ p_T > 60$ GeV	6054	61	5905	767	5014	3	121
$M_{ee} > 200$ GeV	310	59	296	199	75	3	20
$M_{eejj} > 600$ GeV	144	59 ± 12	135 ± 30	83 ± 18	43 ± 23	2 ± 1	9 ± 3

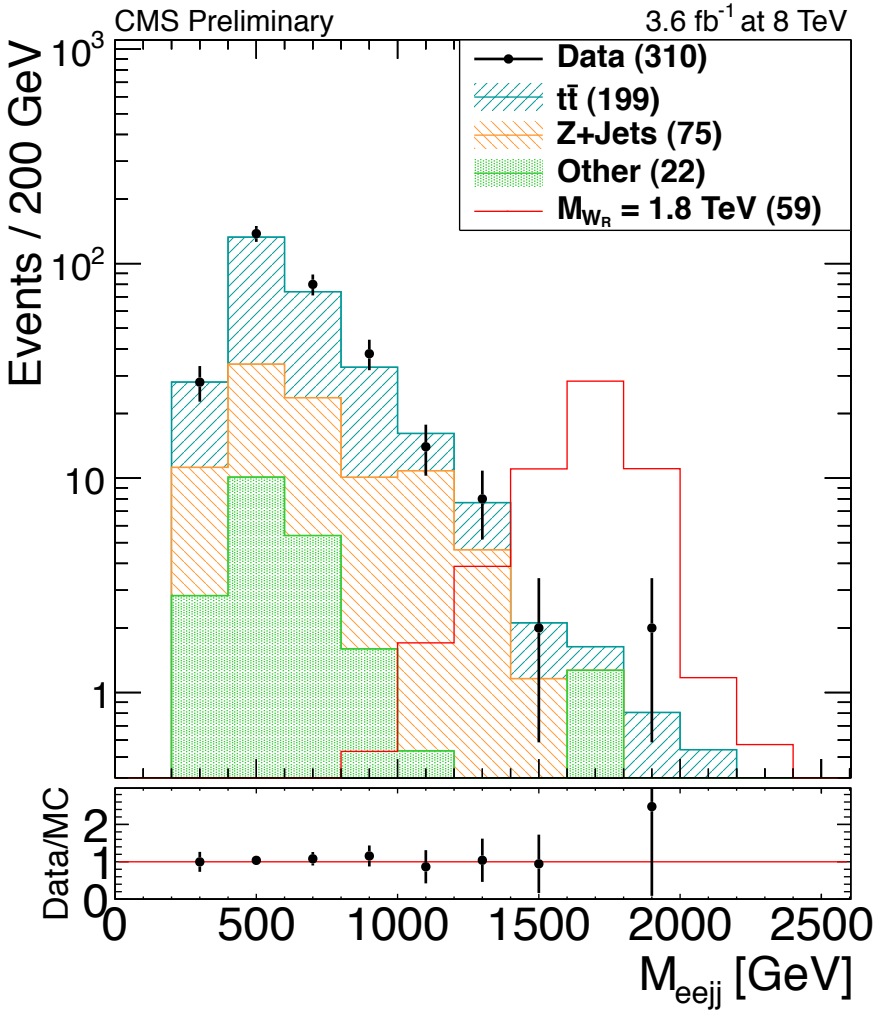
Muon Channel

Selection Stage	Data	Signal	Total Bkgd	$t\bar{t}$	Z+jets	QCD	Other
Two muons, two jets	10333	75	10016	968	8830	3	215
$\mu_1\ p_T > 60$ GeV	7058	75	6873	767	5933	2	171
$M_{\mu\mu} > 200$ GeV	352	72	294	199	71	0.7	23
$M_{\mu\mu jj} > 600$ GeV	144	72 ± 13	130 ± 24	83 ± 17	35 ± 17	0.7 ± 0.4	11 ± 4

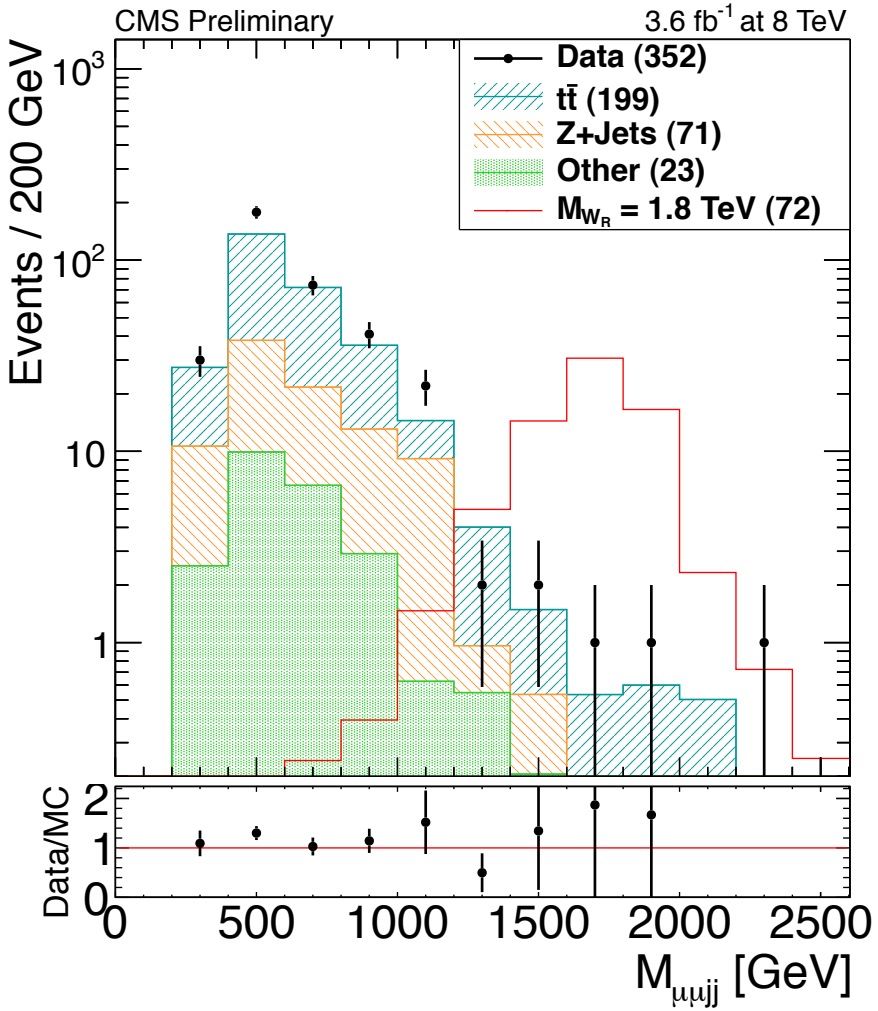
[CMS-PAS-EXO-12-017]

$W_R \rightarrow \ell\ell jj$ Results

Electron channel



Muon channel

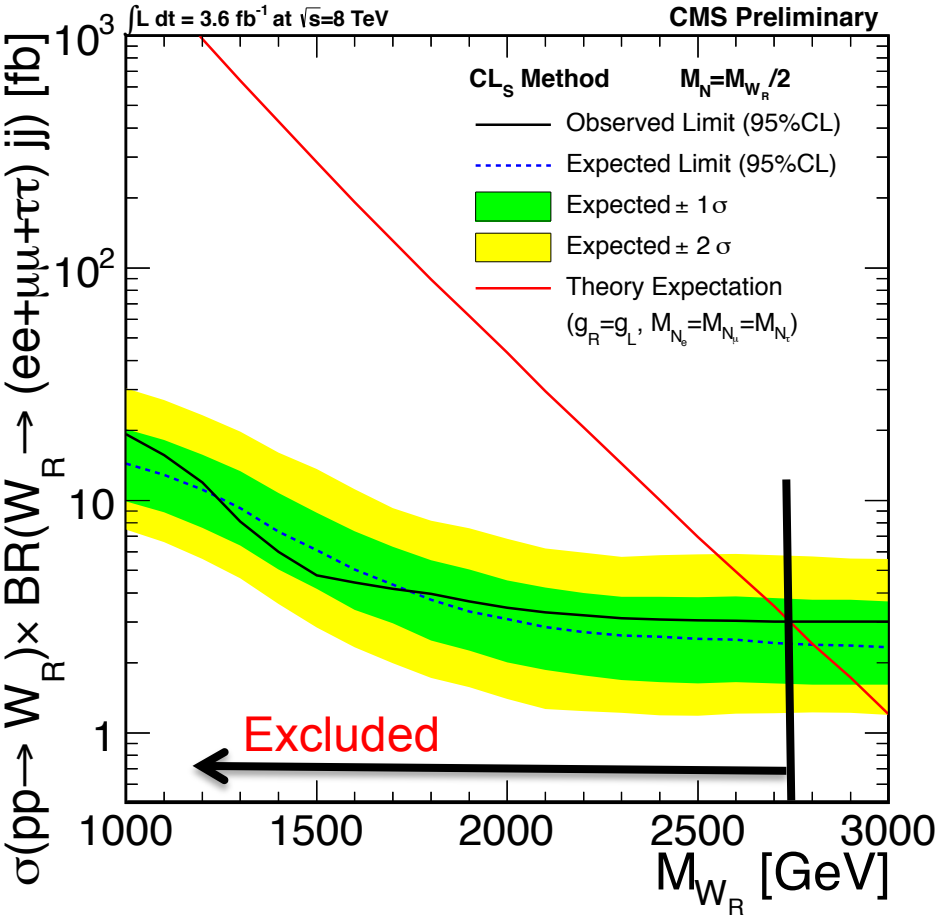


Data is consistent with background expectation

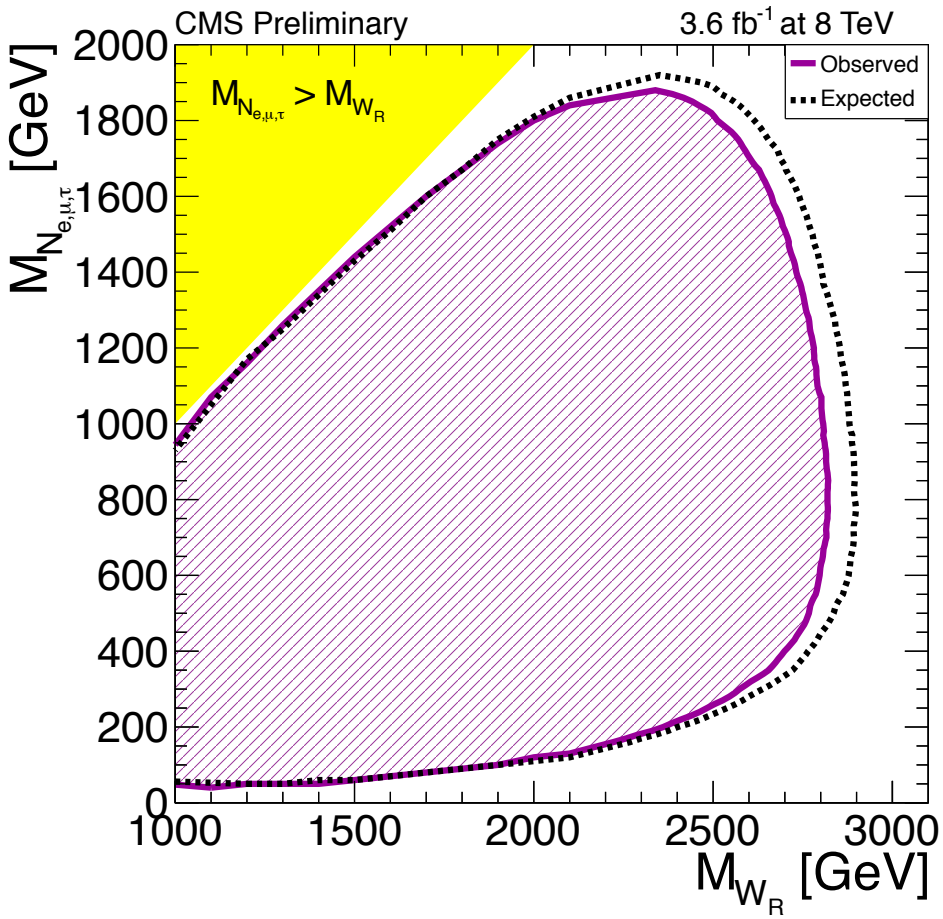
$W_R \rightarrow \ell\ell jj$ Limits

[CMS-PAS-EXO-12-017]

Combined cross section exclusion for:
$m(N_\ell) = 0.5 * m(W_R)$



Exclusion in $m(N_\ell)$ vs $m(W_R)$ plane



Assuming degenerate N_e, N_μ, N_τ

$W' \rightarrow \ell\nu$

[CMS-PAS-EXO-12-060]

- Search for Jacobian peak in SM m_T tail
- Event selection

$$m_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{miss} \cdot (1 - \cos\Delta\phi_{\ell,\nu})}$$

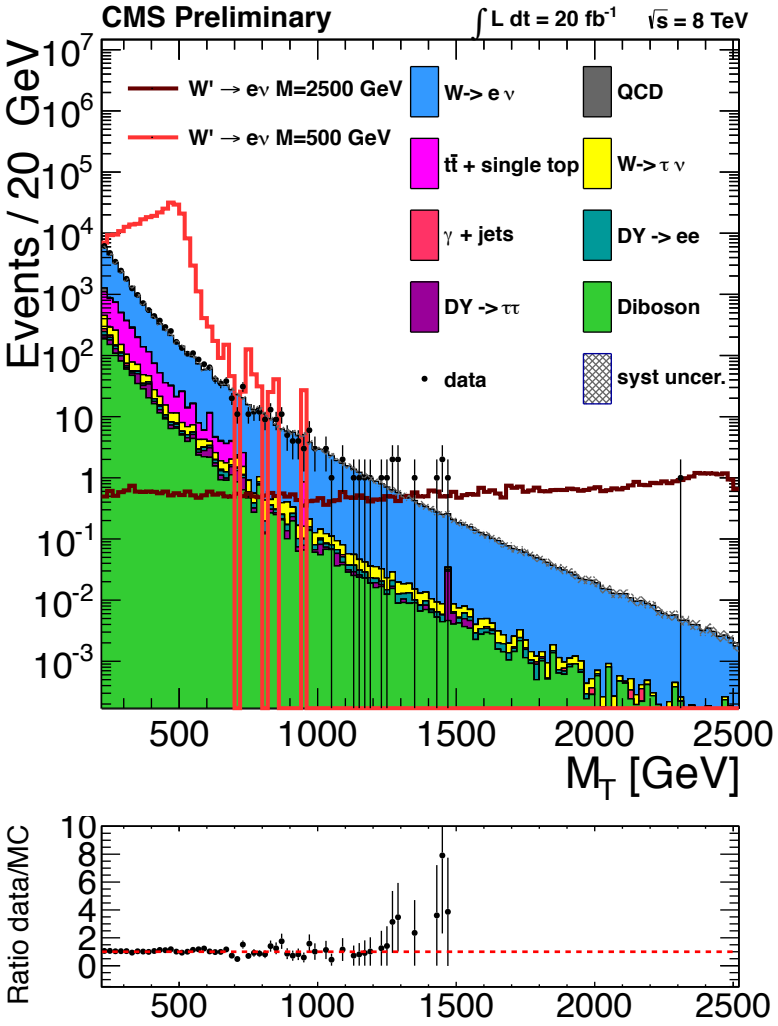
  - 1 isolated lepton
    - Electron (muon) p_T > 100 (45) GeV
  - 0.4 < $p_T(\ell)$/MET < 1.5
  - $\Delta\phi(\ell,\text{MET}) > 0.8\pi$
- Background modeling
  - W+jets
    - Pythia
    - NLO K-factor(m_T)
    - Normalized to σ_{NNLO}
  - Other backgrounds
    - Modeled with MC
  - Final background expectation obtained from fit to MC:

$$f(m_T) = \frac{a}{(m_T^3 + bm_T + c)^d}$$

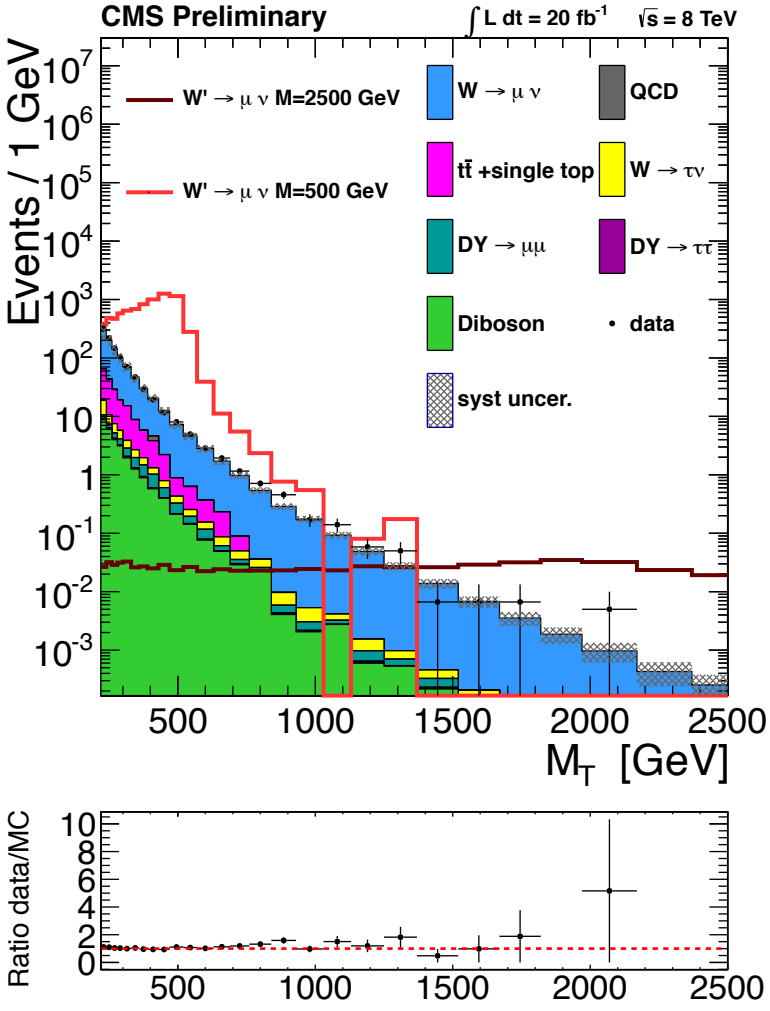
[CMS-PAS-EXO-12-060]

W′ → ℓν Results

Electron channel



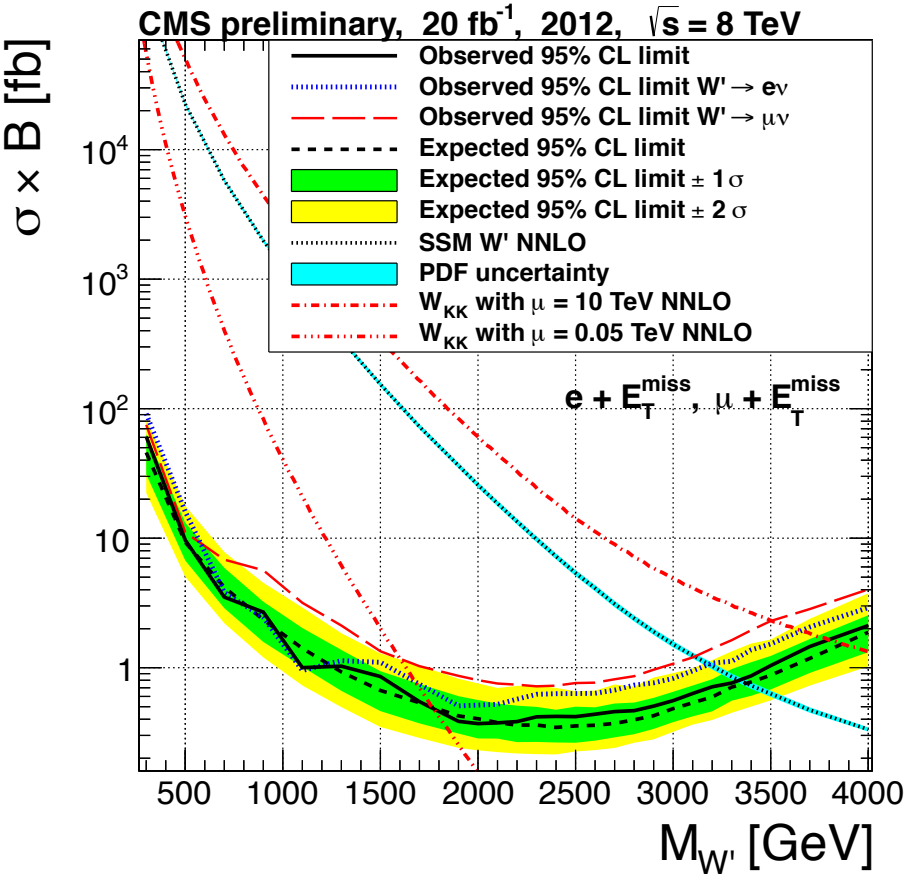
Muon channel



Data is consistent with background expectation

W′ → ℓν Limits

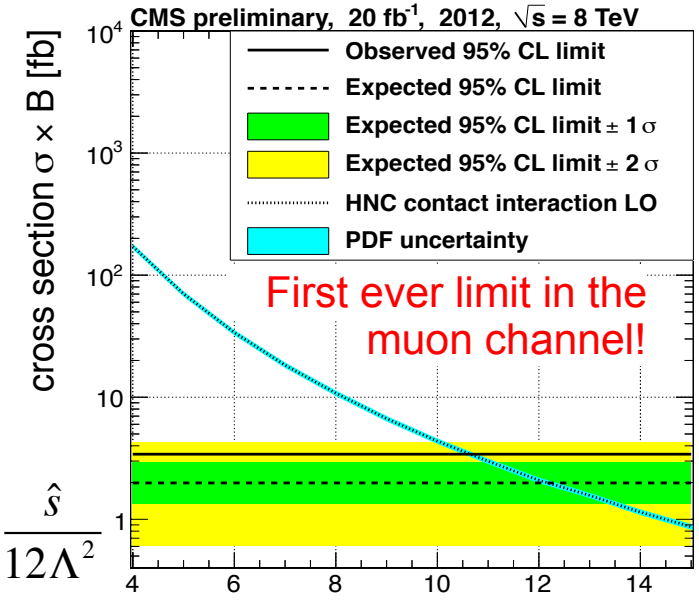
[CMS-PAS-EXO-12-060]



Model	Channel	Observed limit	Expected limit
SSM	e	$m_{W'} < 3.20$TeV	$m_{W'} < 3.25$TeV
SSM	μ	$m_{W'} < 3.15$TeV	$m_{W'} < 3.10$TeV
SSM	combined	$m_{W'} < 3.35$TeV	$m_{W'} < 3.40$TeV
SSMO	e	$m_{W'} < 3.60$TeV	$m_{W'} < 3.60$TeV
SSMO	μ	$m_{W'} < 3.05$TeV	$m_{W'} < 3.30$TeV
SSMO	combined	$m_{W'} < 3.60$TeV	$m_{W'} < 3.60$TeV
SSMS	e	$m_{W'} < 3.00$TeV	$m_{W'} < 3.10$TeV
SSMS	μ	$m_{W'} < 2.80$TeV	$m_{W'} < 2.90$TeV
SSMS	combined	$m_{W'} < 3.10$TeV	$m_{W'} < 3.20$TeV
W^2_{KK}	μ=0.05 TeV, combined	$m_{W^2_{KK}} < 1.7$TeV	$m_{W^2_{KK}} < 1.7$TeV
W^2_{KK}	μ=10.0 TeV, combined	$m_{W^2_{KK}} < 3.7$TeV	$m_{W^2_{KK}} < 3.6$TeV
HNC CI	e	$\Lambda < 13.0$ TeV	$\Lambda < 13.3$ TeV
HNC CI	μ	$\Lambda < 10.9$ TeV	$\Lambda < 12.2$ TeV

SSM = Sequential Standard Model
SSMO = constructive interference w/ SM
SSMS = destructive interference w/ SM
W_{KK} = KK excitations of W in split-UED
HNC = Helicity Non-Conserving CI model

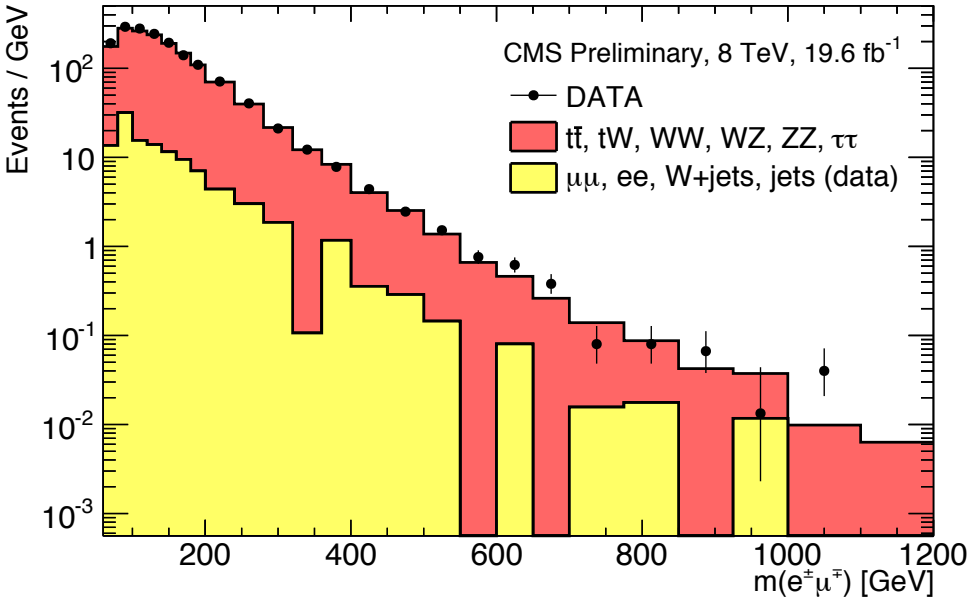
$$\sigma_{CI\to\ell\upsilon} = \pi \frac{\hat{s}}{12\Lambda^2}$$



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

[CMS-PAS-EXO-12-061]

- Search for resonance in SM m($\ell^+\ell^-$) tail
- Event selection
  - 2 SF isolated leptons
    - Electron (muon) p_T > 35 (40) GeV
    - Muons are required to have OS, originate from common vertex
  - Cosmic / beam halo veto
- Signal Modeling
  - Pythia
  - Mass-dependent NNLO k-factors
- Background modeling
  - Z+jets
    - Powheg
    - Normalized to σ_{NNLO}
  - Total background normalized to data in Z mass window
  - Final background expectation obtained from fit: $m^{\kappa} e^{\alpha m + \beta m^2}$
  - QCD
    - Data-driven "fake-rate" method
  - Other backgrounds
    - Modeled with MC
- Separate barrel-barrel and barrel-endcap events (electron channel)

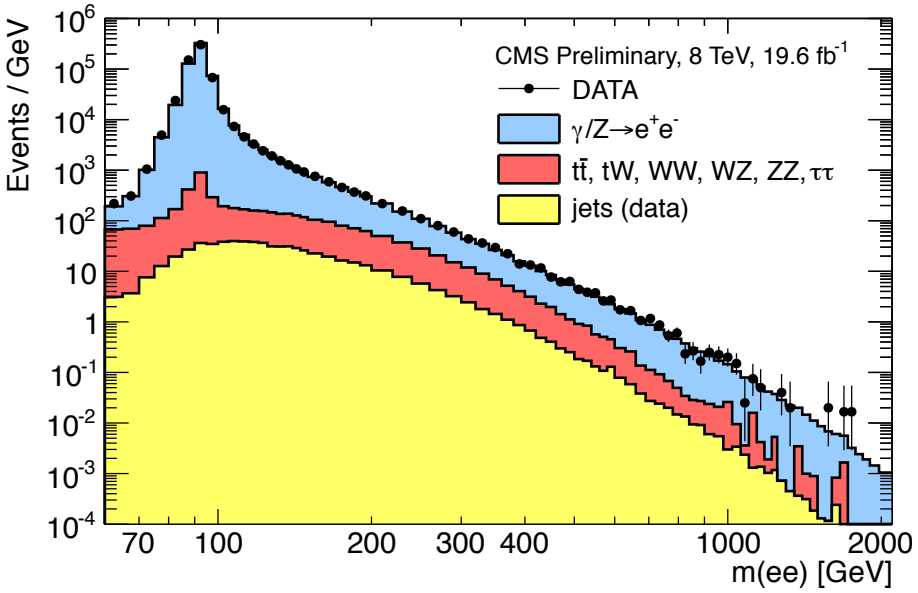


$Z' \rightarrow \ell^+\ell^-$ Results

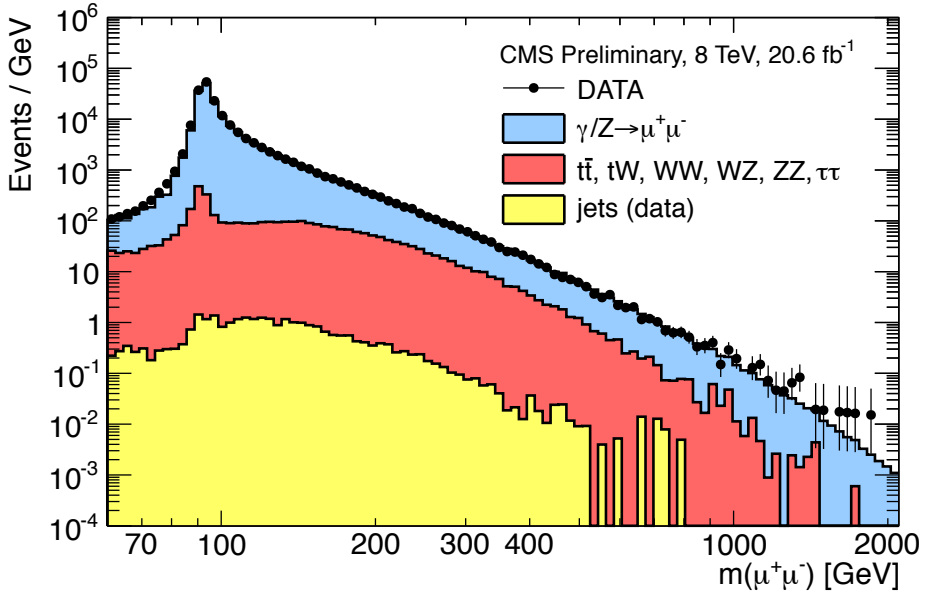
[CMS-PAS-EXO-12-061]

	Dielectron sample				Dimuon sample	
	barrel-barrel		barrel-endcap			
M_{ll} Range (GeV)	120–200	> 200	120–200	> 200	120–200	> 200
Data	41953	8947	28523	7995	78100	20000
Total Bkg.	42700 ± 1900	8900 ± 400	28600 ± 1400	7800 ± 400	78400 ± 3500	20100 ± 800
Z/γ^*	37800 ± 1900	7000 ± 400	25200 ± 1300	5600 ± 300	72200 ± 3500	16300 ± 800
$t\bar{t}$ + others	4300 ± 300	1700 ± 100	2100 ± 100	1500 ± 100	6200 ± 300	3800 ± 200
jets	500 ± 200	120 ± 50	1300 ± 500	700 ± 300	60 ± 10	30 ± 5

Electron channel



Muon channel

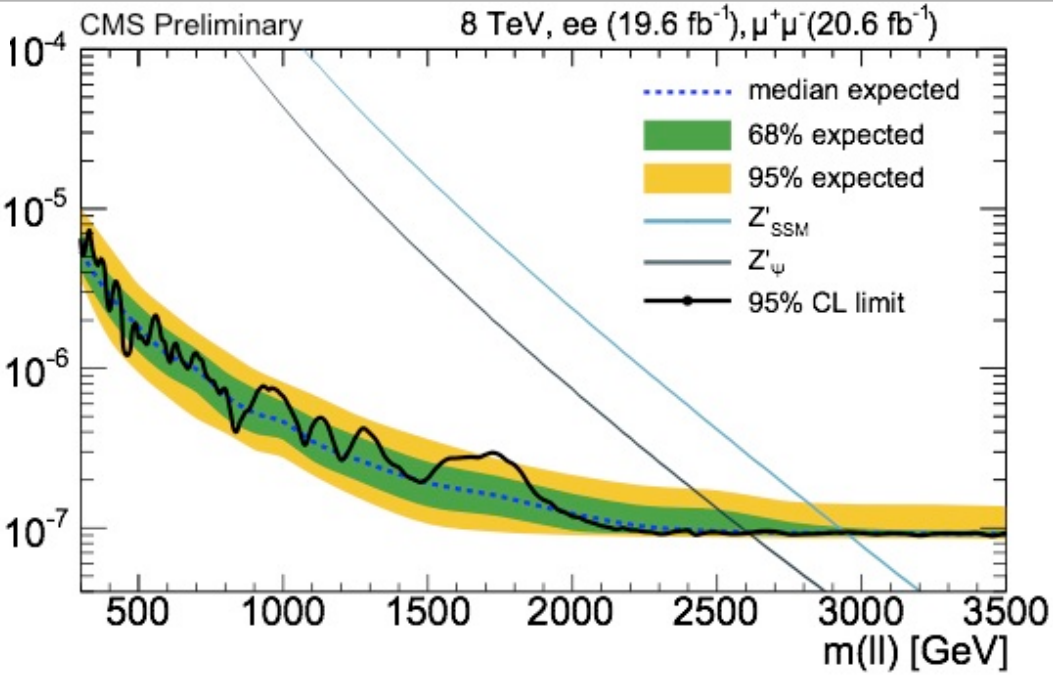


Data is consistent with background expectation

[CMS-PAS-EXO-12-061]

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

$$R_\sigma = \frac{\sigma(pp \rightarrow Z' + X \rightarrow \ell\ell + X)}{\sigma(pp \rightarrow Z + X \rightarrow \ell\ell + X)}$$



Channel	Observed m(Z') Limit [TeV]	
	SSM	GUT
Electron channel (barrel-barrel)	2.65	2.31
Electron channel (barrel-endcap)	2.18	1.90
Muon channel	2.77	2.43
Combination	**2.96**	**2.60**

Most stringent in existence!

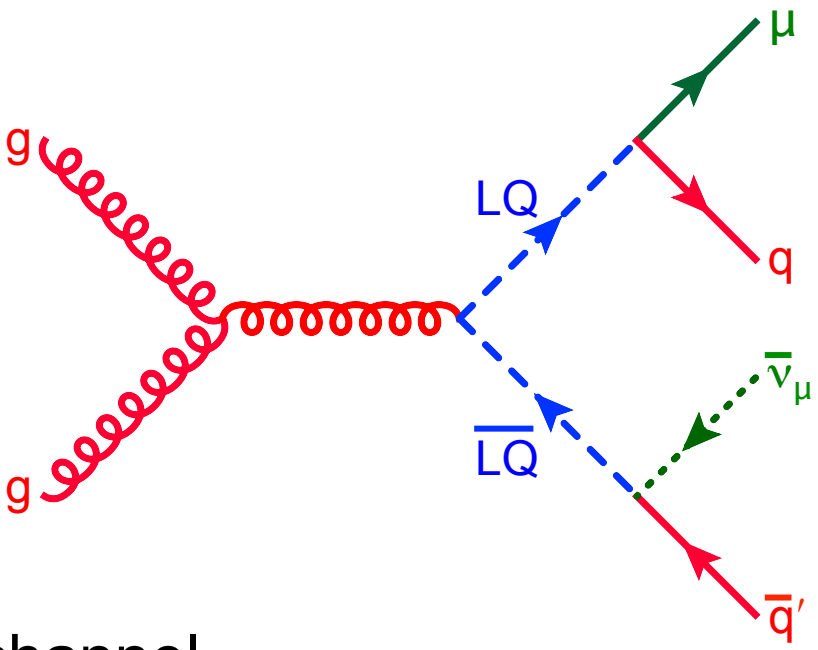
[CMS-PAS-EXO-12-042]

$LQ_2LQ_2 \rightarrow \mu\nu jj$ / $\mu\mu jj$

- Search for pair production of scalar 2nd generation leptoquarks
- Event pre-selection
  - ≥ 2 jets
    - Leading (2nd leading) jet p_T > 125 (45) GeV
  - S_T > 300 GeV

$$S_T^{\mu\mu jj} \equiv p_T(j_1) + p_T(j_2) + p_T(\mu_1) + p_T(\mu_2)$$

$$S_T^{\mu\nu jj} \equiv p_T(j_1) + p_T(j_2) + p_T(\mu_1) + MET$$



  - μνjj channel
    - 1 isolated muon (p_T > 45 GeV)
    - 0 electrons
    - MET > 55 GeV
      - Δϕ(MET,jet$_1$) > 0.5
      - Δϕ(MET,μ) > 0.8
    - m_T(MET,μ) > 50 GeV

$$m_T = \sqrt{2 \cdot p_T^{\mu} \cdot E_T^{miss} \cdot (1 - \cos\Delta\phi_{\mu,\nu})}$$

  - μμjj channel
    - ≥ 2 isolated muons (p_T > 45 GeV)
    - m(μμ) > 50 GeV

LQ_2LQ_2 → μνjj / μμjj

[CMS-PAS-EXO-12-042]

- Event selection
  - Mass-dependent optimization
  - μνjj channel
    - S_T, m(j, μ), m_T(MET,μ)
  - μμjj channel
    - S_T, $m_{min}(j,\mu_i)$, $m(\mu_1, \mu_2)$

M_{LQ} (GeV)	300	350	400	450	500	550	600	650	700	750	800	850	900	950	≥1000
$S_T >$ (GeV)	455	540	625	715	800	890	980	1070	1160	1250	1345	1435	1530	1625	1720
$M^T_{\mu\nu} >$ (GeV)	155	180	205	225	245	260	275	290	300	310	315	320	320	325	320
$M(\mu, \text{jet}) >$ (GeV)	125	150	175	200	225	250	280	305	330	355	380	410	435	465	490

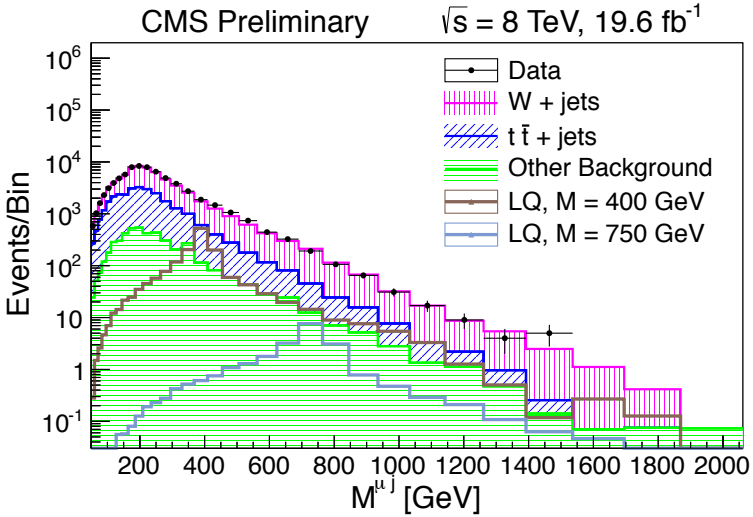
M_{LQ} (GeV)	300	350	400	450	500	550	600	650	700	750	800	850	900	950	≥1000
$S_T >$ (GeV)	380	460	540	615	685	755	820	880	935	990	1040	1090	1135	1175	1210
$M_{\mu\mu} >$ (GeV)	100	115	125	140	150	165	175	185	195	205	215	220	230	235	245
$M_{min}(\mu, \text{jet}) >$ (GeV)	115	115	120	135	155	180	210	250	295	345	400	465	535	610	690

- Background modeling
  - μνjj channel
    - W+jets and ttbar
      - Shape from MadGraph
      - Simultaneously normalized with preselected data in W transverse mass window
  - μμjj channel
    - Z+jets
      - Shape from Madgraph
      - Normalization from preselected data in Z mass window
    - ttbar
      - Shape and normalization from from eμ data

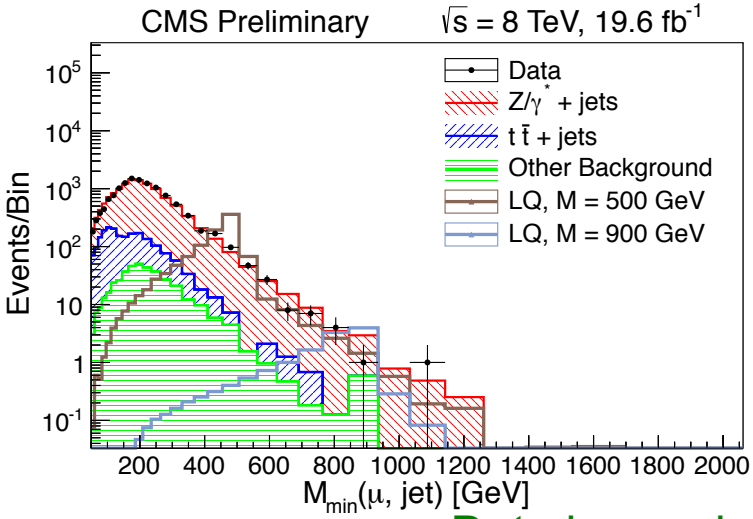
[CMS-PAS-EXO-12-042]

LQ_2LQ_2 → μνjj / μμjj Results

Pre-selected events

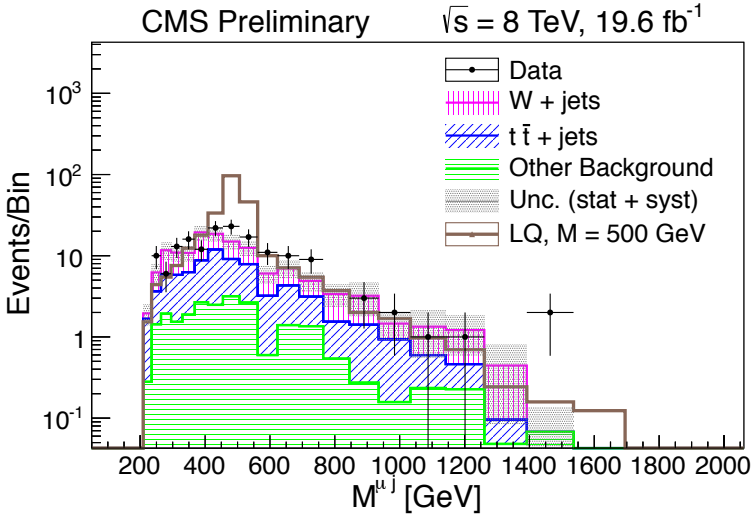


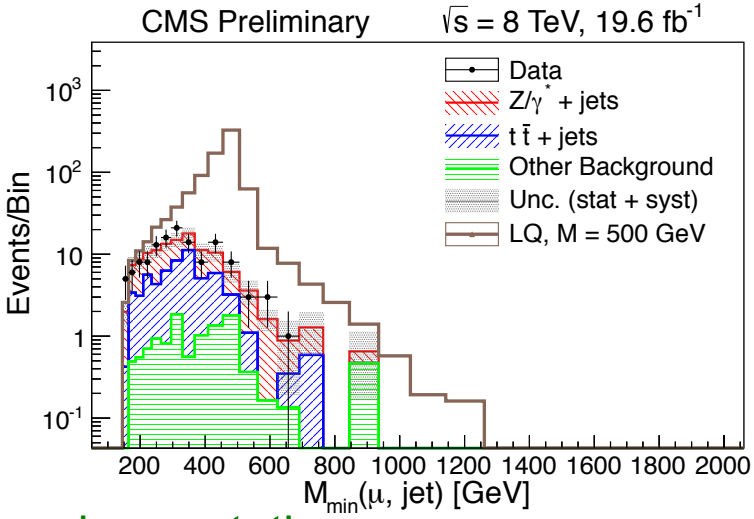
μνjj



μμjj

Selected events

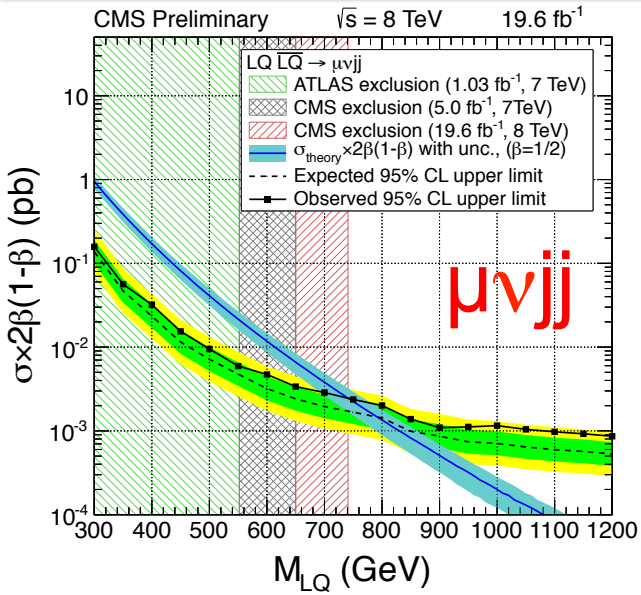


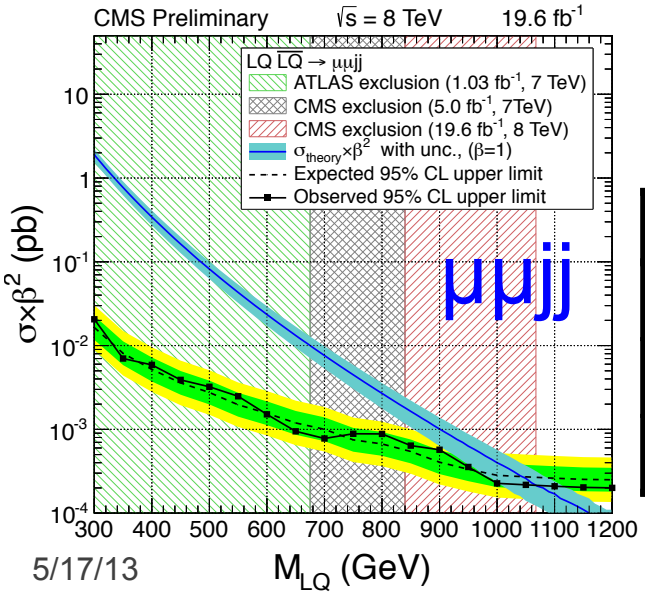


Data is consistent with background expectation

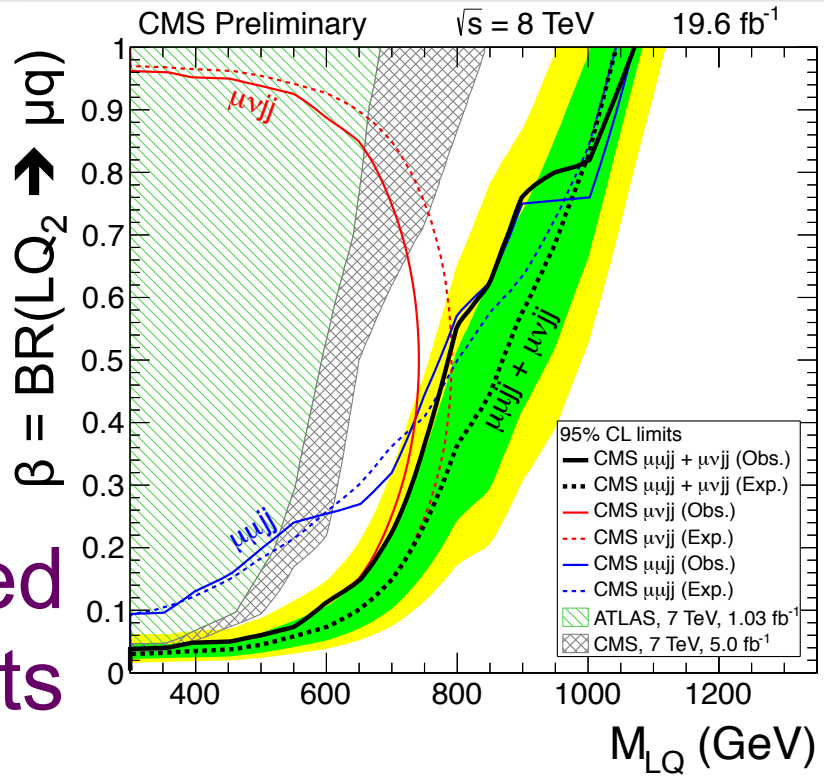
[CMS-PAS-EXO-12-042]

$LQ_2LQ_2 \rightarrow \mu\nu jj$ / $\mu\mu jj$ Limits





Combined Limits

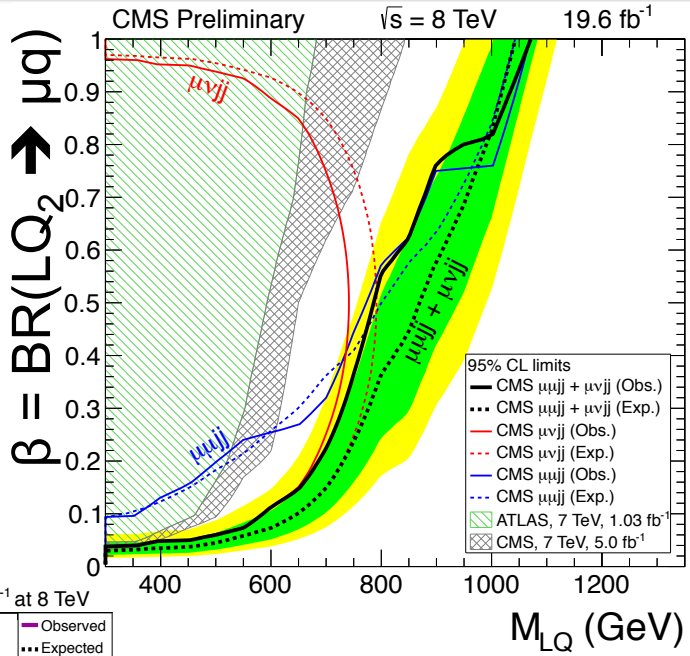


Channel	β	Observed (Expected) Limit [GeV]
μνjj	0.5	740 (790)
μμjj	1	1070 (1045)
Combination	**0.5**	**785 (870)**

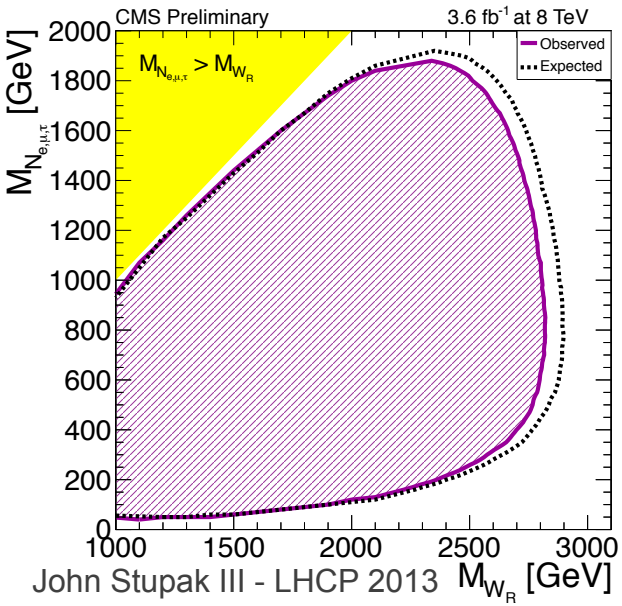
Most stringent in existence!

Conclusion

- CMS is pursuing broad program of BSM searches
  - Sensitive to variety of NP scenarios
- No sign of BSM physics yet
  - Setting strong cross section and mass exclusions
    - In many cases, most stringent in existence
    - Strongly constrain NP scenarios



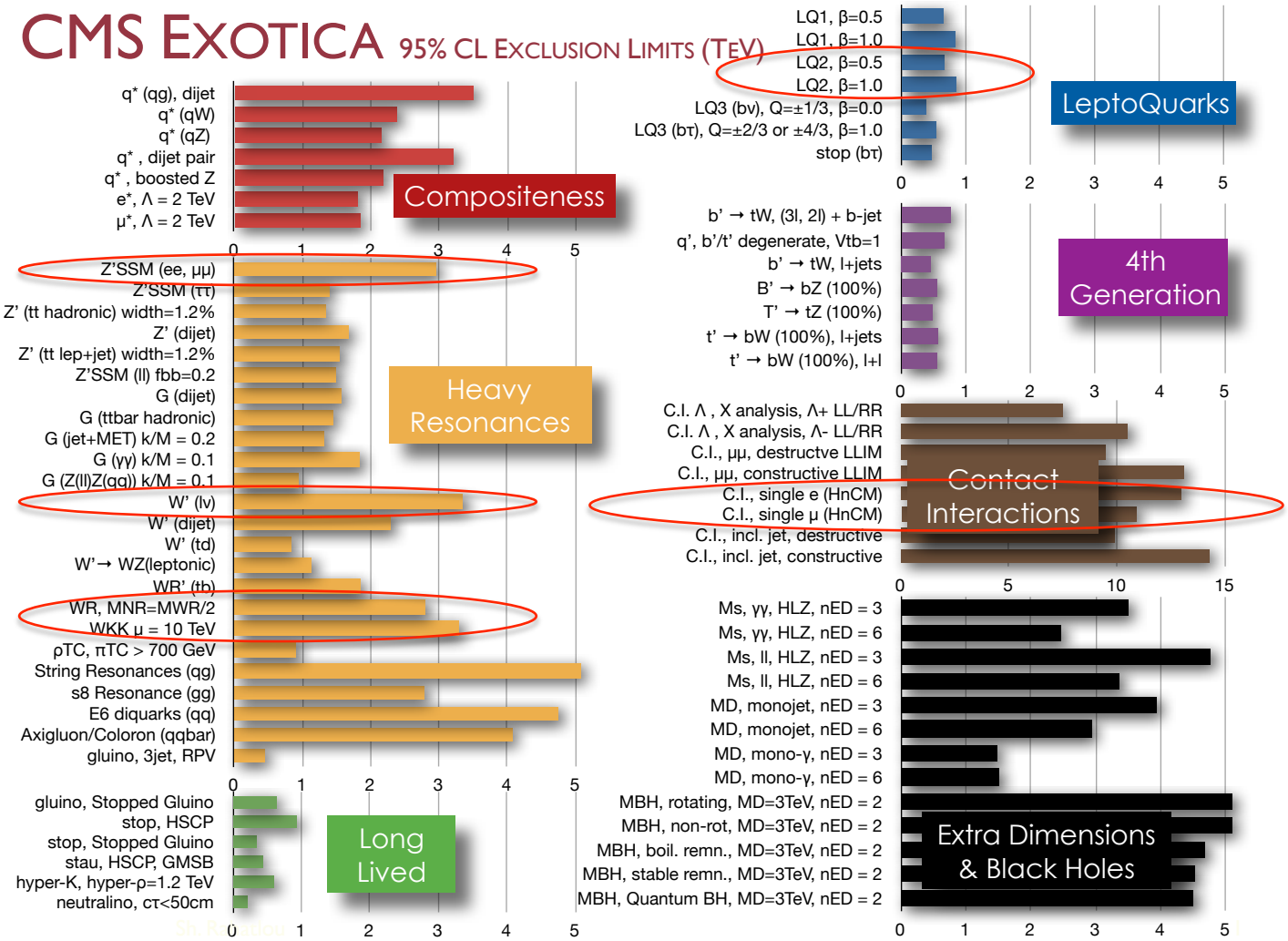
Model		Observed Limit [TeV]
W′	SSM	3.55
	SSMO	3.6
	SSMS	3.1
W^2_{KK}	μ = 0.05 TeV	1.7
	μ = 10 TeV	3.7
HNC CI	e	13
	μ	10.9



Observed m(Z') Limit [TeV]	
SSM	GUT
2.96	2.60

Backup

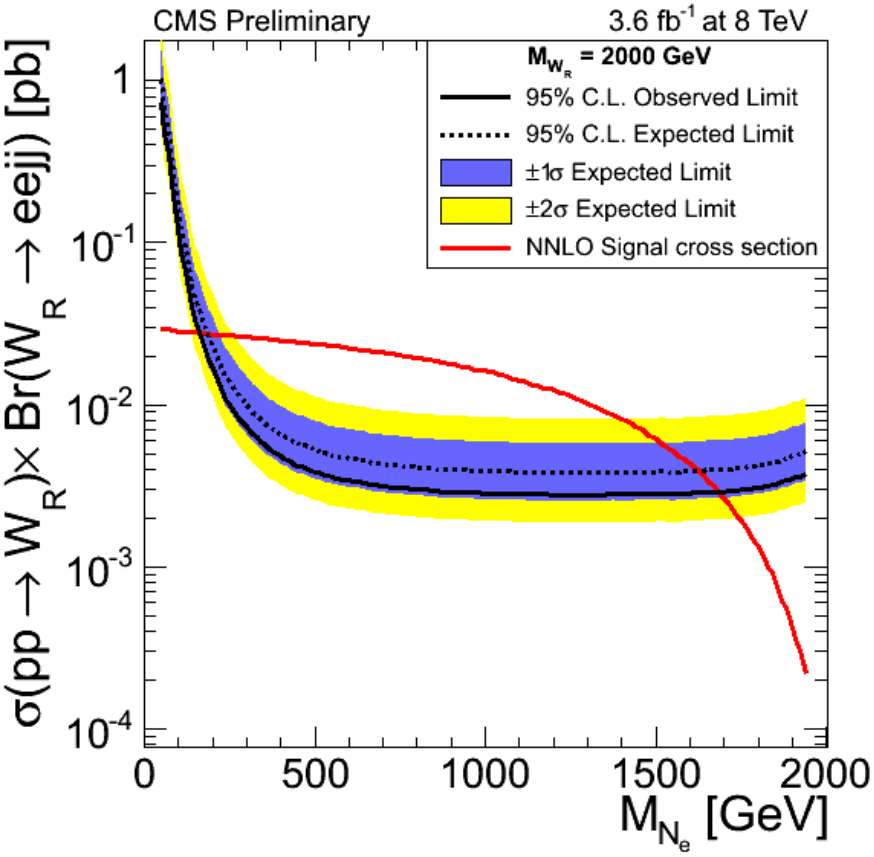
As of Moriond



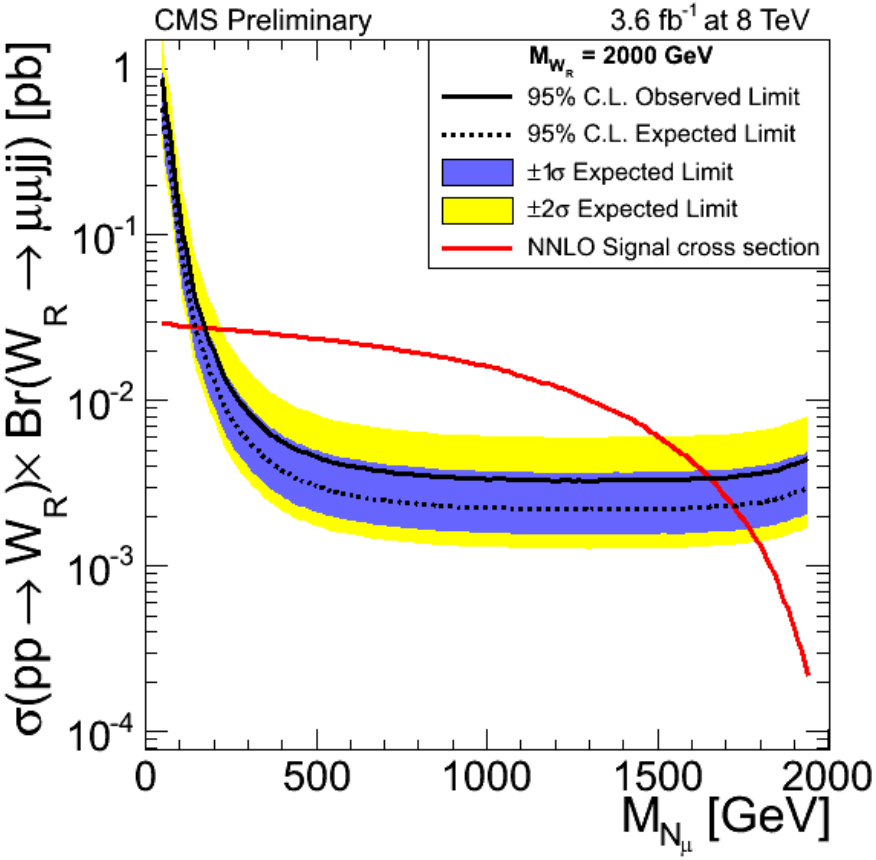
[CMS-PAS-EXO-12-017]

$W_R \rightarrow \ell\ell jj$ Cross Section Limits

Electron channel



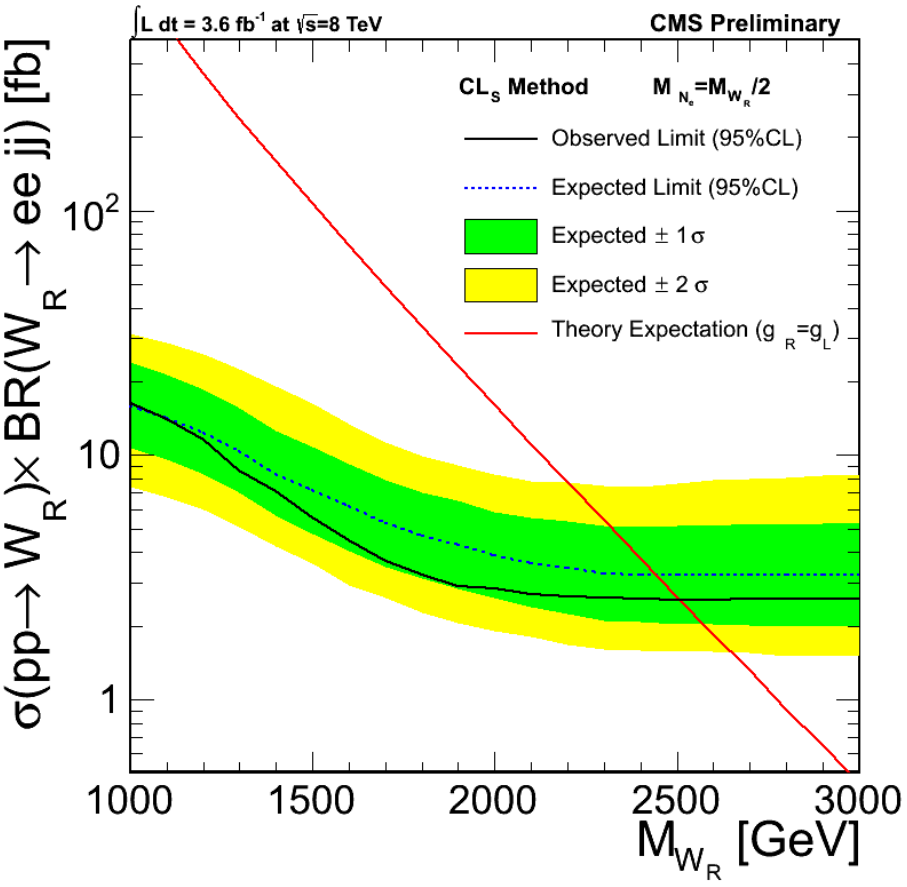
Muon channel



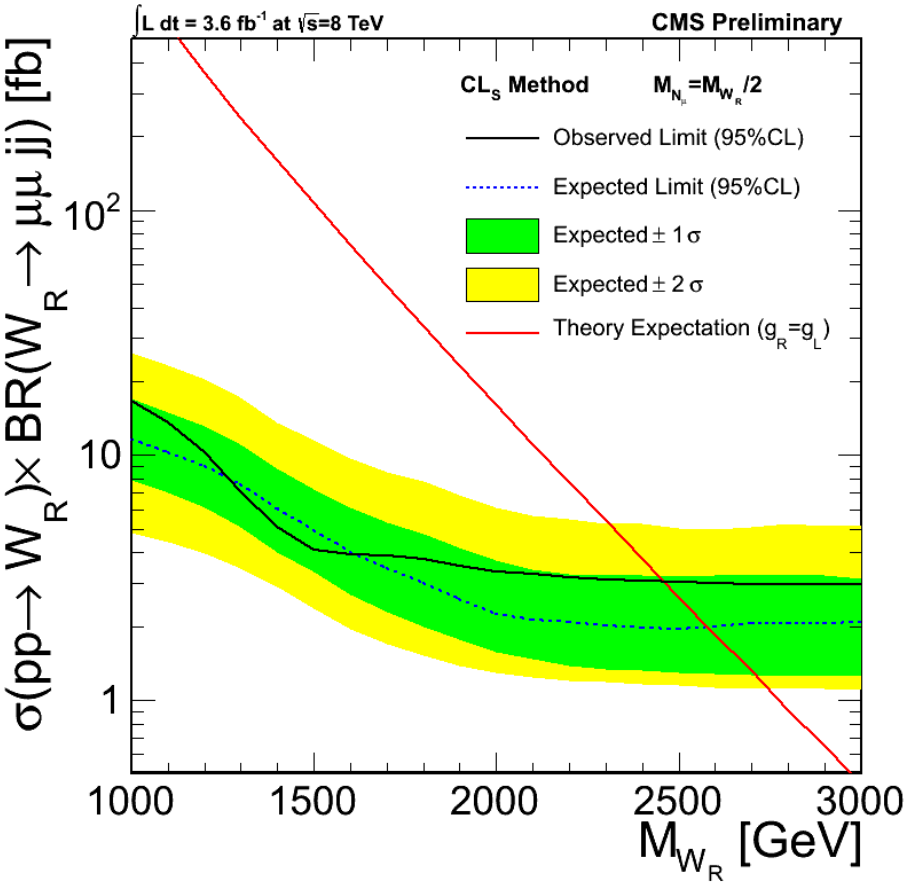
[CMS-PAS-EXO-12-017]

$W_R \rightarrow \ell\ell jj$ Cross Section Limits

Electron channel



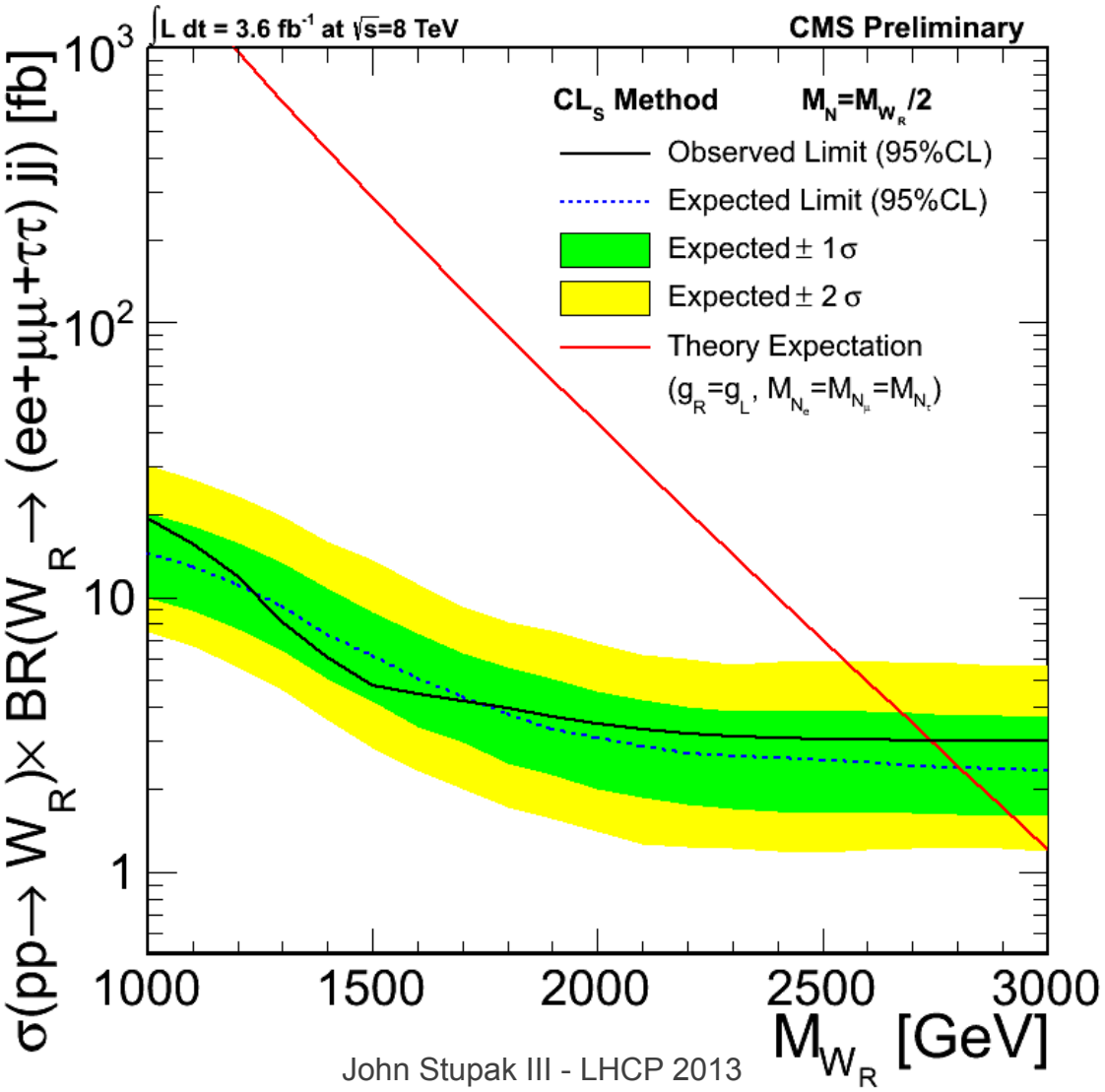
Muon channel



[CMS-PAS-EXO-12-017]

$W_R \rightarrow \ell\ell jj$ Cross Section Limits

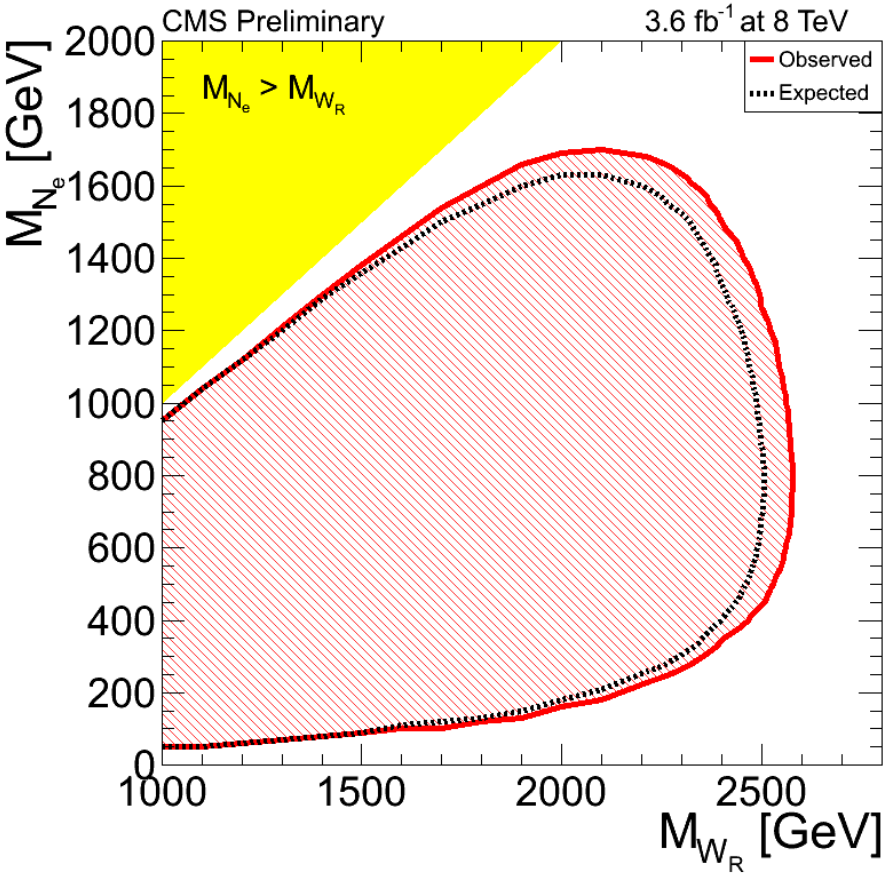
2012 data alone



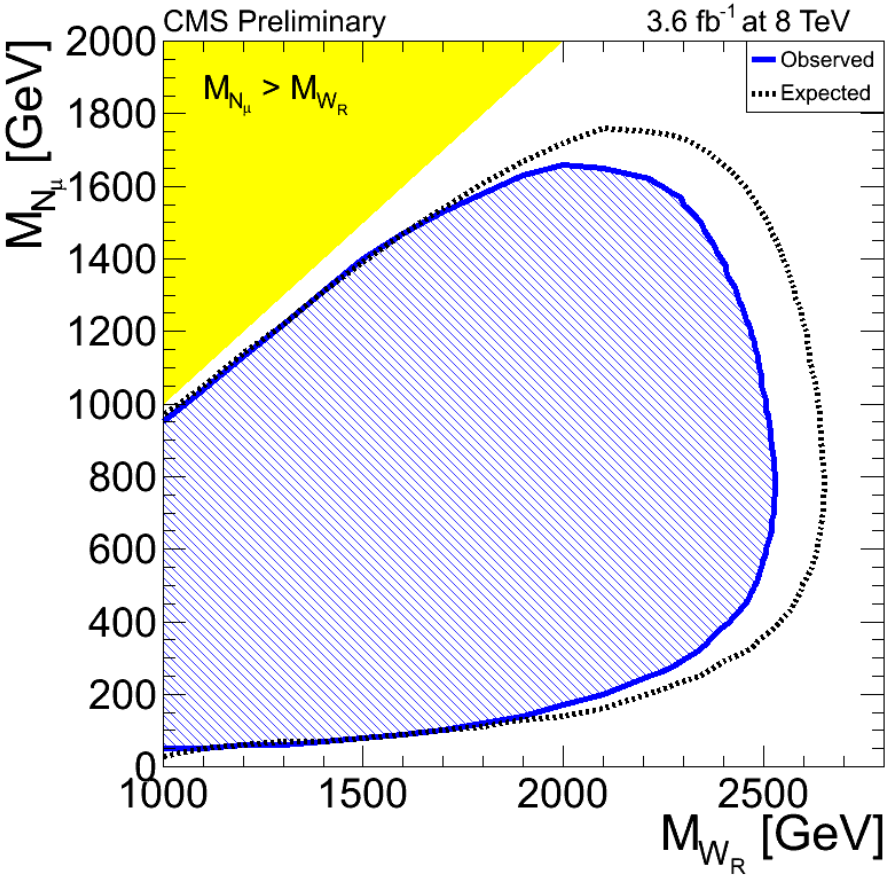
[CMS-PAS-EXO-12-017]

$W_R \rightarrow \ell\ell jj$ Mass Limits

Electron channel



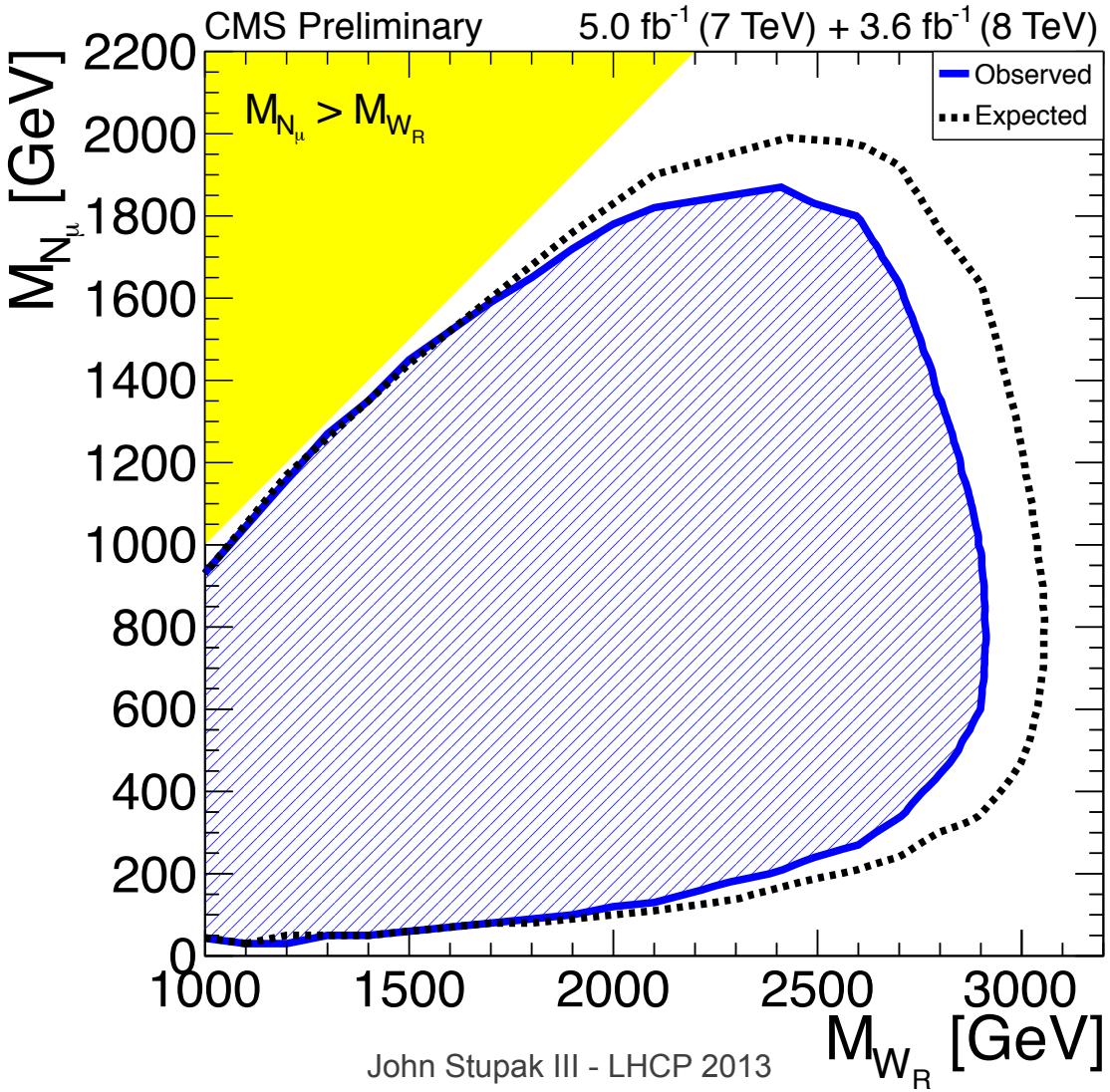
Muon channel



[CMS-PAS-EXO-12-017]

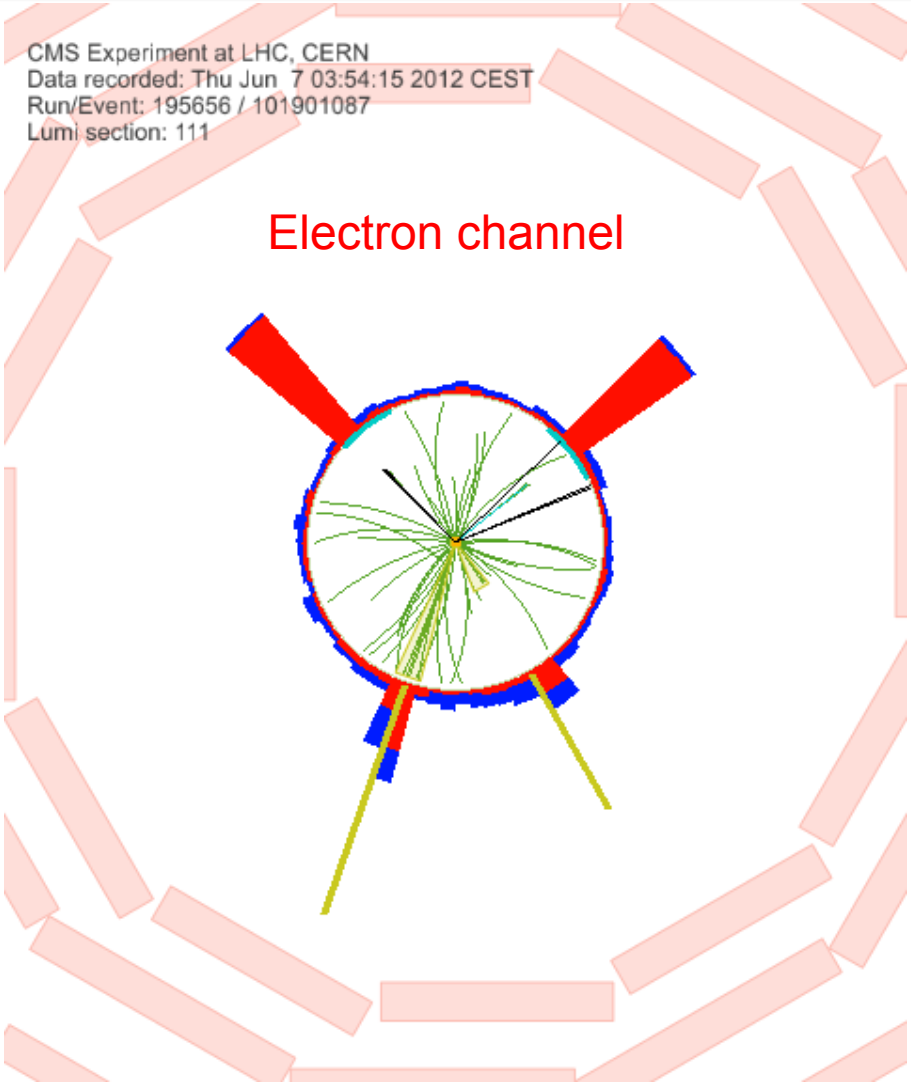
$W_R \rightarrow \ell\ell jj$ Mass Limits

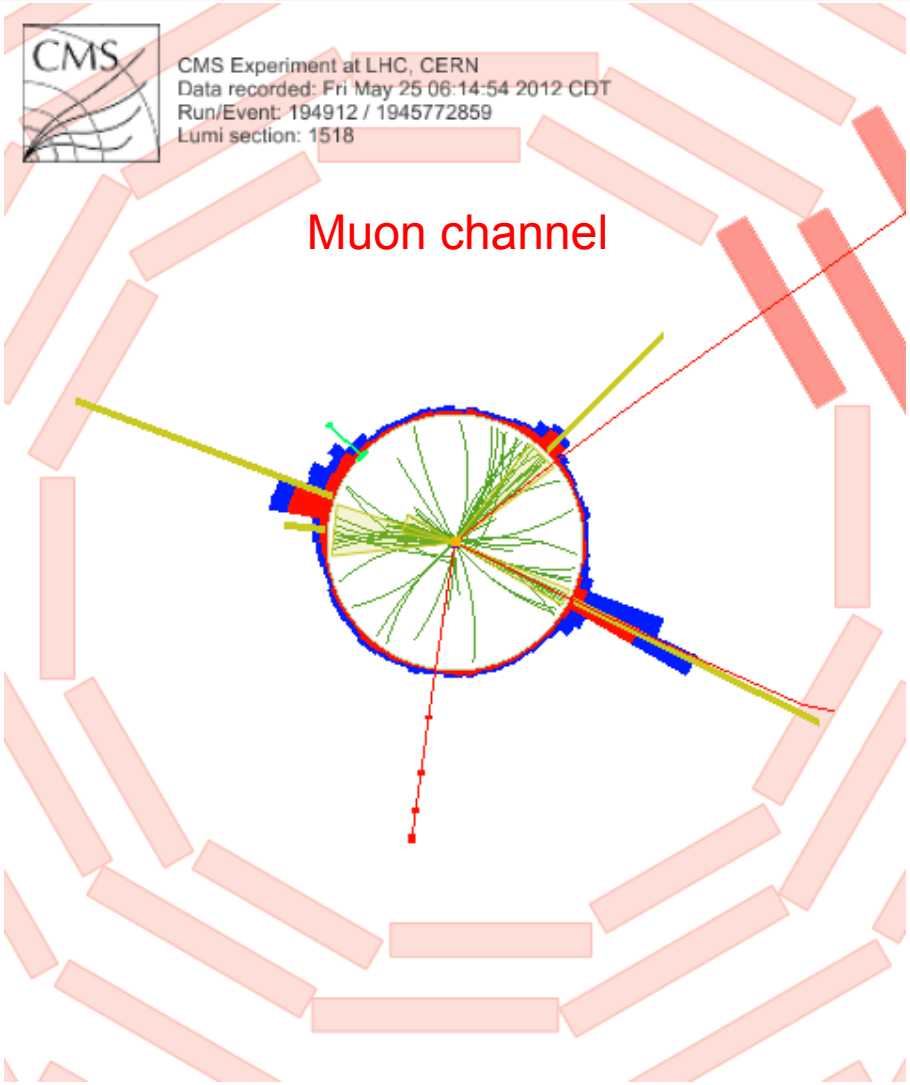
Muon channel – 2011 + 2012



[CMS-PAS-EXO-12-017]

$W_R \rightarrow \ell\ell jj$ Event Display

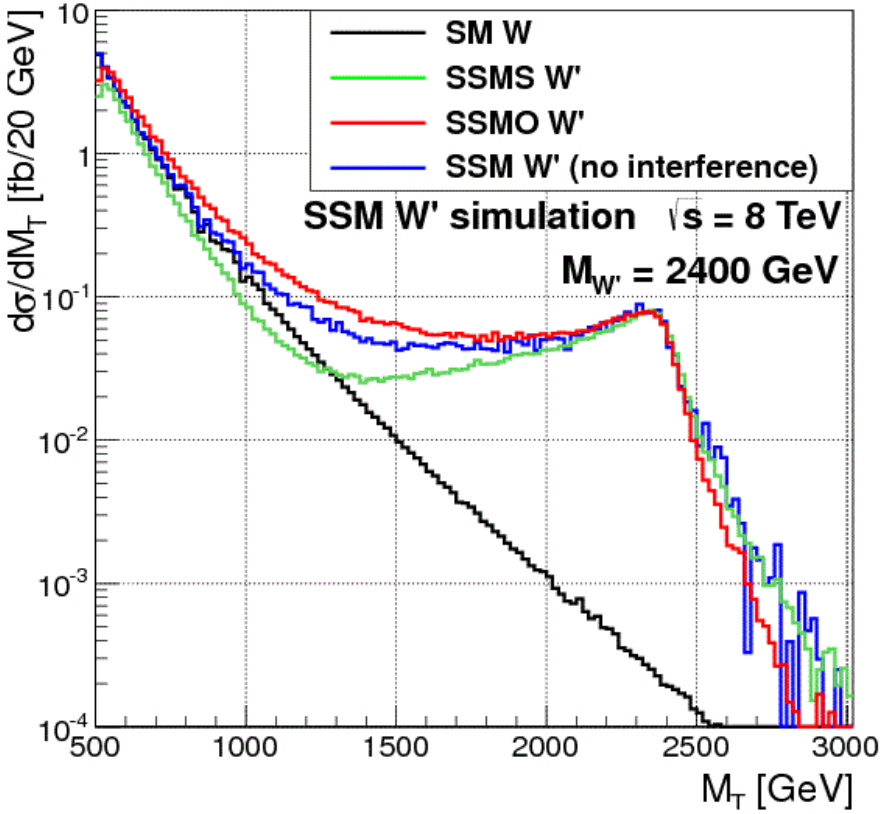




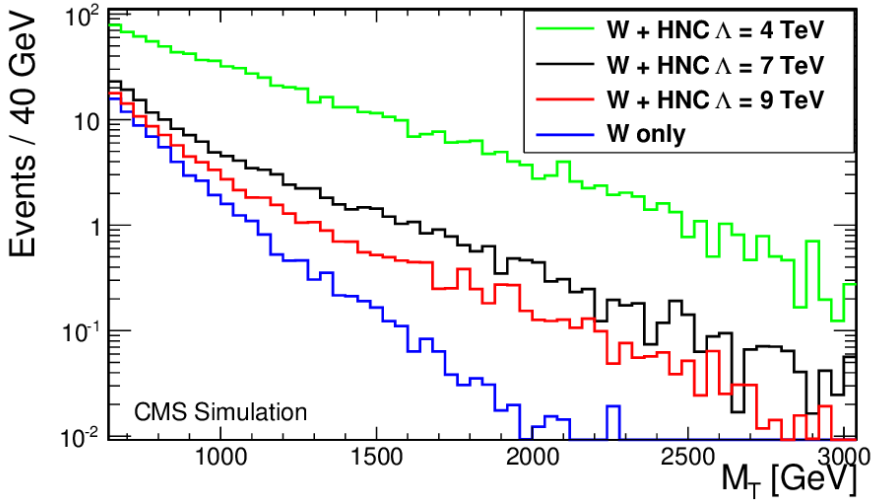
W′ → ℓν Signals

[CMS-PAS-EXO-12-060]

W′ including SM interference



Helicity Non-Conserving model (contact interaction)



[CMS-PAS-EXO-12-060]

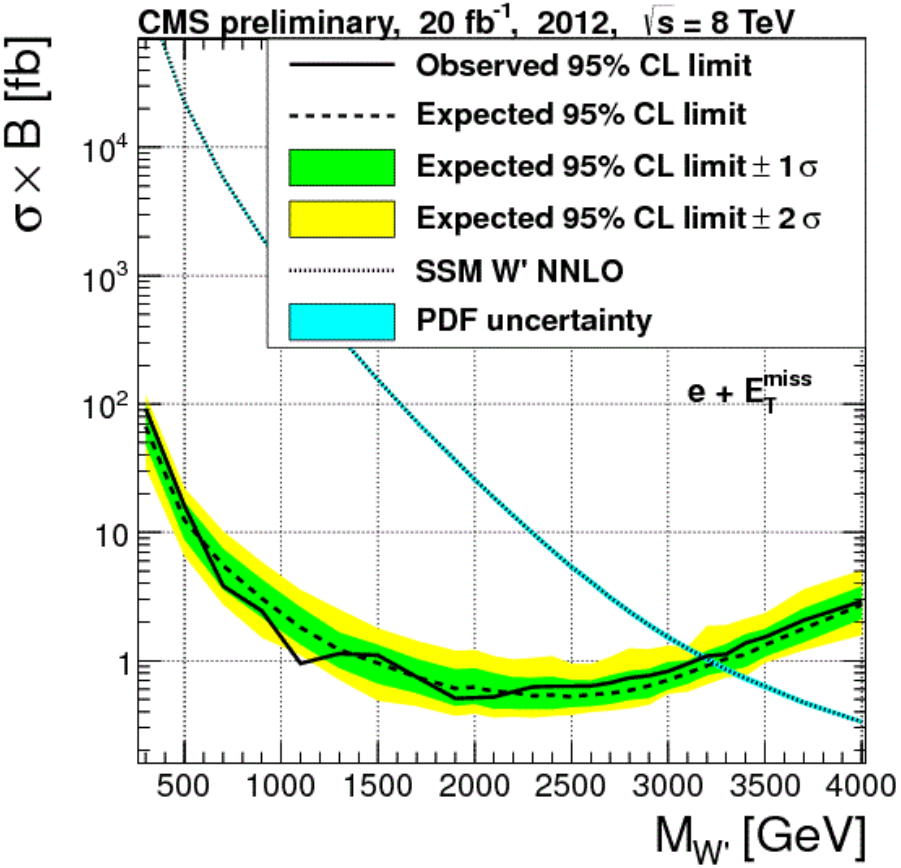
$W' \rightarrow \ell\nu$ Event Yield

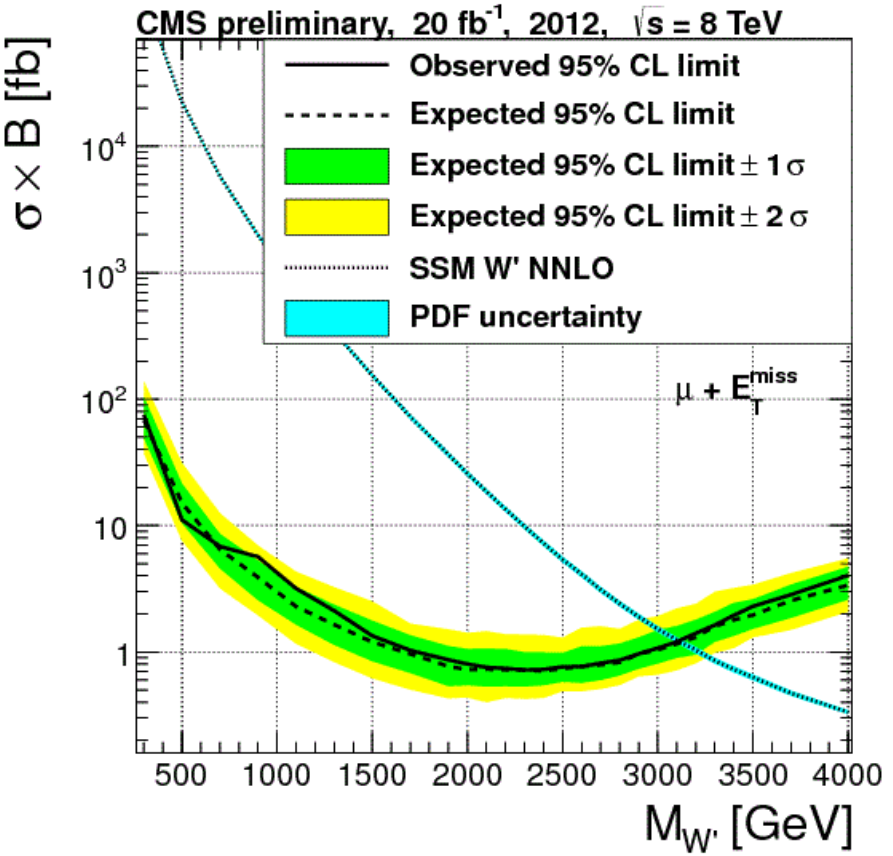
	$M_T > 1.0$ TeV	$M_T > 1.5$ TeV	$M_T > 2.0$ TeV
Electron channel			
Data	22	1	1
SM background	$26^{+2.6}_{-2.4}$	$1.99^{+0.27}_{-0.24}$	$0.218^{+0.037}_{-0.032}$
W', $M_{W'} = 2.5$ TeV	$51^{+1.2}_{-1.2}$	$39^{+0.96}_{-0.94}$	$24^{+0.74}_{-0.72}$
W', $M_{W'} = 3$ TeV	$10^{+0.25}_{-0.25}$	$8.03^{+0.2}_{-0.2}$	$5.91^{+0.17}_{-0.16}$
CI $\Lambda = 4$ TeV	1205^{+26}_{-26}	398^{+13}_{-13}	$114^{+5.9}_{-5.6}$
CI $\Lambda = 9$ TeV	46^{+1}_{-1}	$15^{+0.52}_{-0.5}$	$4.45^{+0.23}_{-0.22}$
Muon channel			
Data	33	3	1
SM background	$26^{+4}_{-3.5}$	$2.27^{+0.62}_{-0.49}$	$0.33^{+0.15}_{-0.1}$
W', $M_{W'} = 2.5$ TeV	$47^{+5.4}_{-4.8}$	$35^{+4.9}_{-4.3}$	$20^{+4.8}_{-3.8}$
W', $M_{W'} = 3$ TeV	$9.9^{+1.5}_{-1.3}$	$7.4^{+1.3}_{-1.1}$	$5.15^{+1.2}_{-0.99}$
CI $\Lambda = 4$ TeV	1120^{+91}_{-84}	366^{+62}_{-53}	119^{+34}_{-26}
CI $\Lambda = 9$ TeV	$43^{+3.5}_{-3.3}$	$14^{+2.4}_{-2.1}$	$4.6^{+1.3}_{-1}$

[CMS-PAS-EXO-12-060]

W′ → ℓν Cross Section Limits

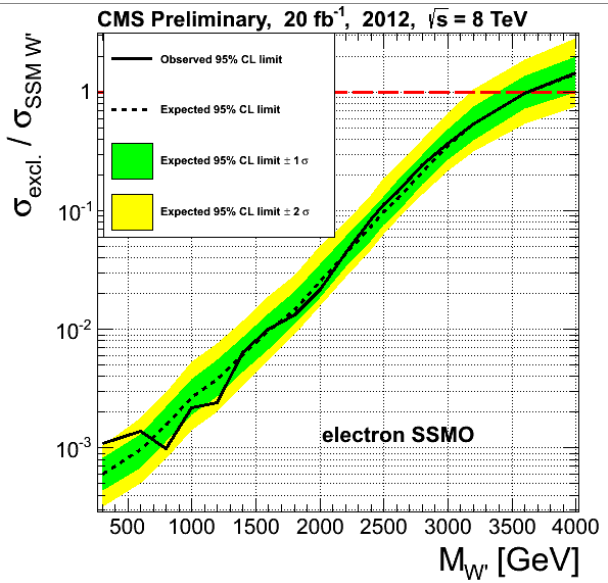
Electron and muon channels separately





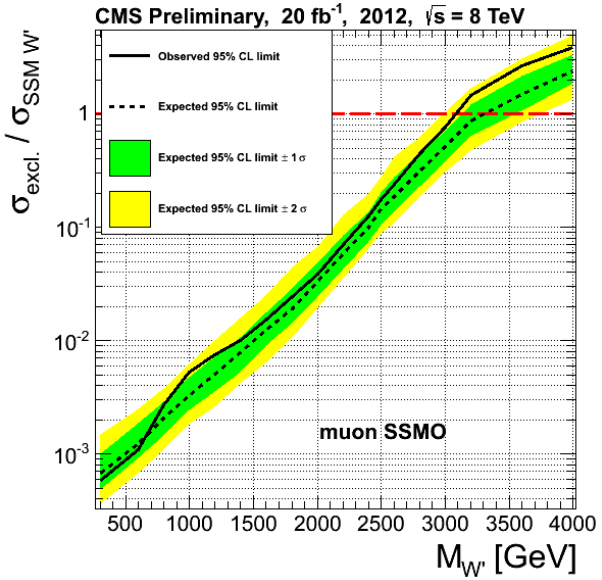
[CMS-PAS-EXO-12-060]

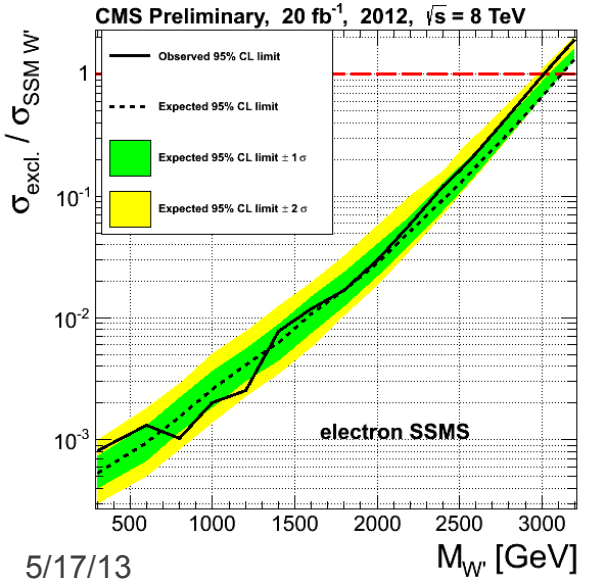
W′ → ℓν Cross Section Limits



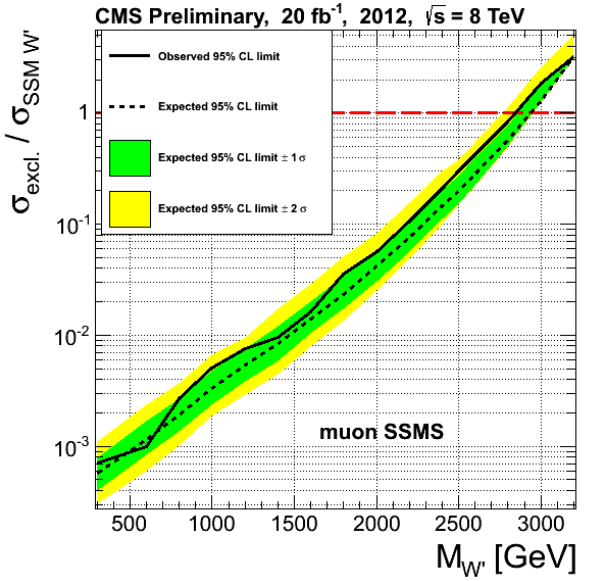
Including Interference with SM

Constructive





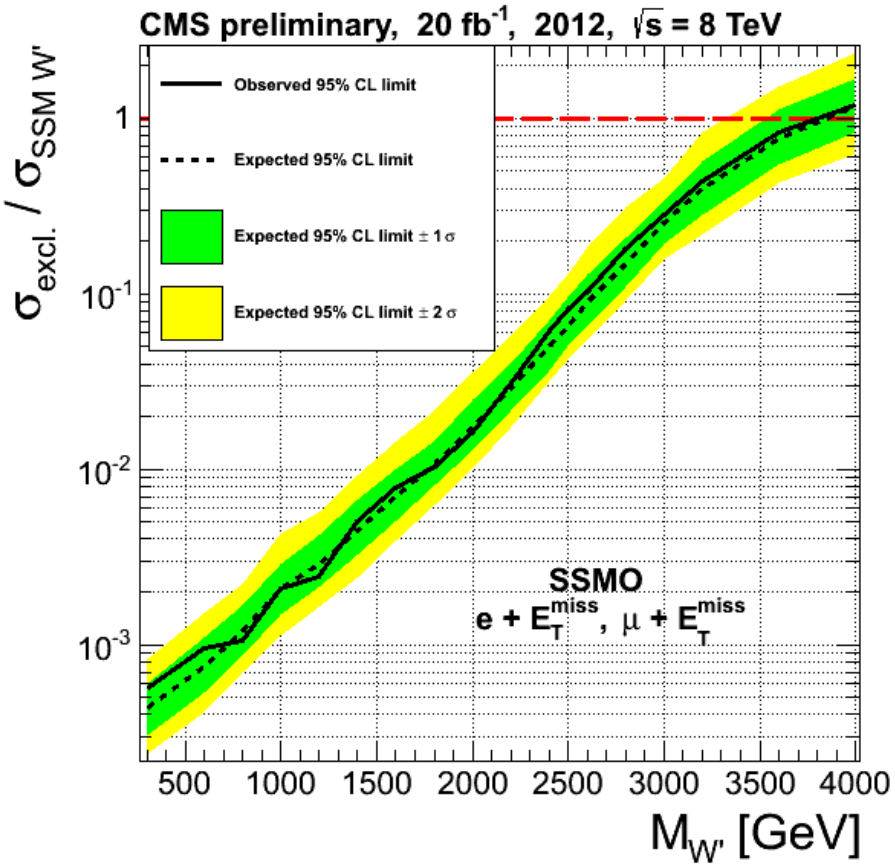
Destructive



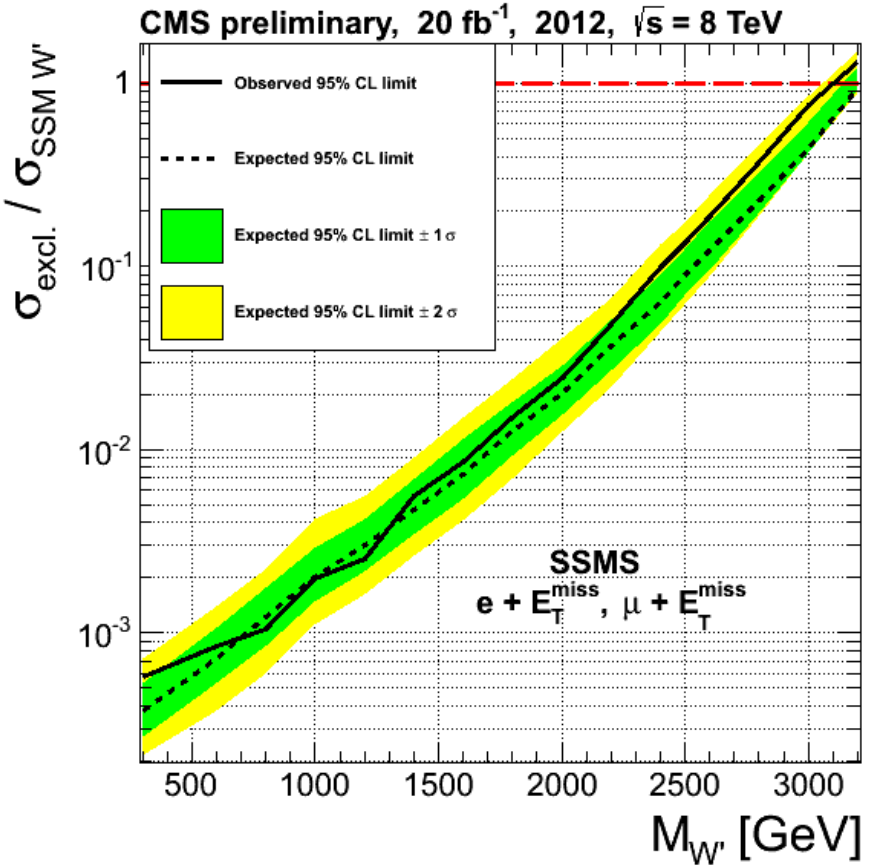
[CMS-PAS-EXO-12-060]

W′ → ℓν Cross Section Limits

Including Interference with SM – Electron and muon channels combined



Constructive

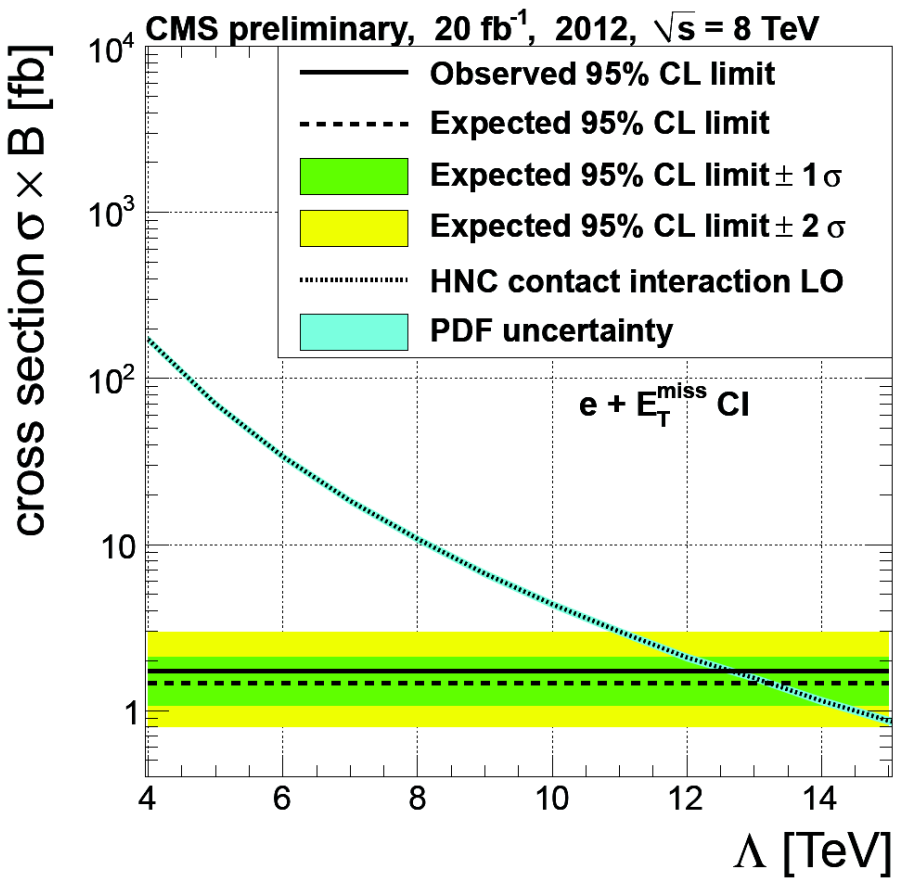


Destructive

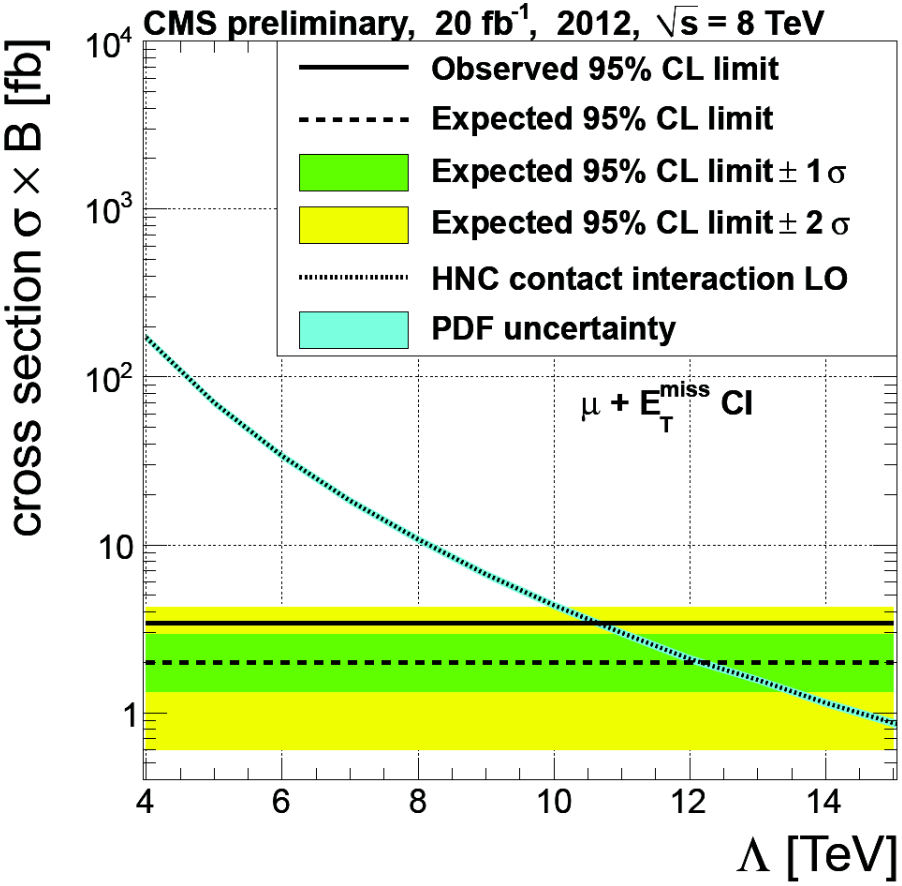
[CMS-PAS-EXO-12-060]

W′ → ℓν Cross Section Limits

Helicity Non-Conserving model (contact interaction)



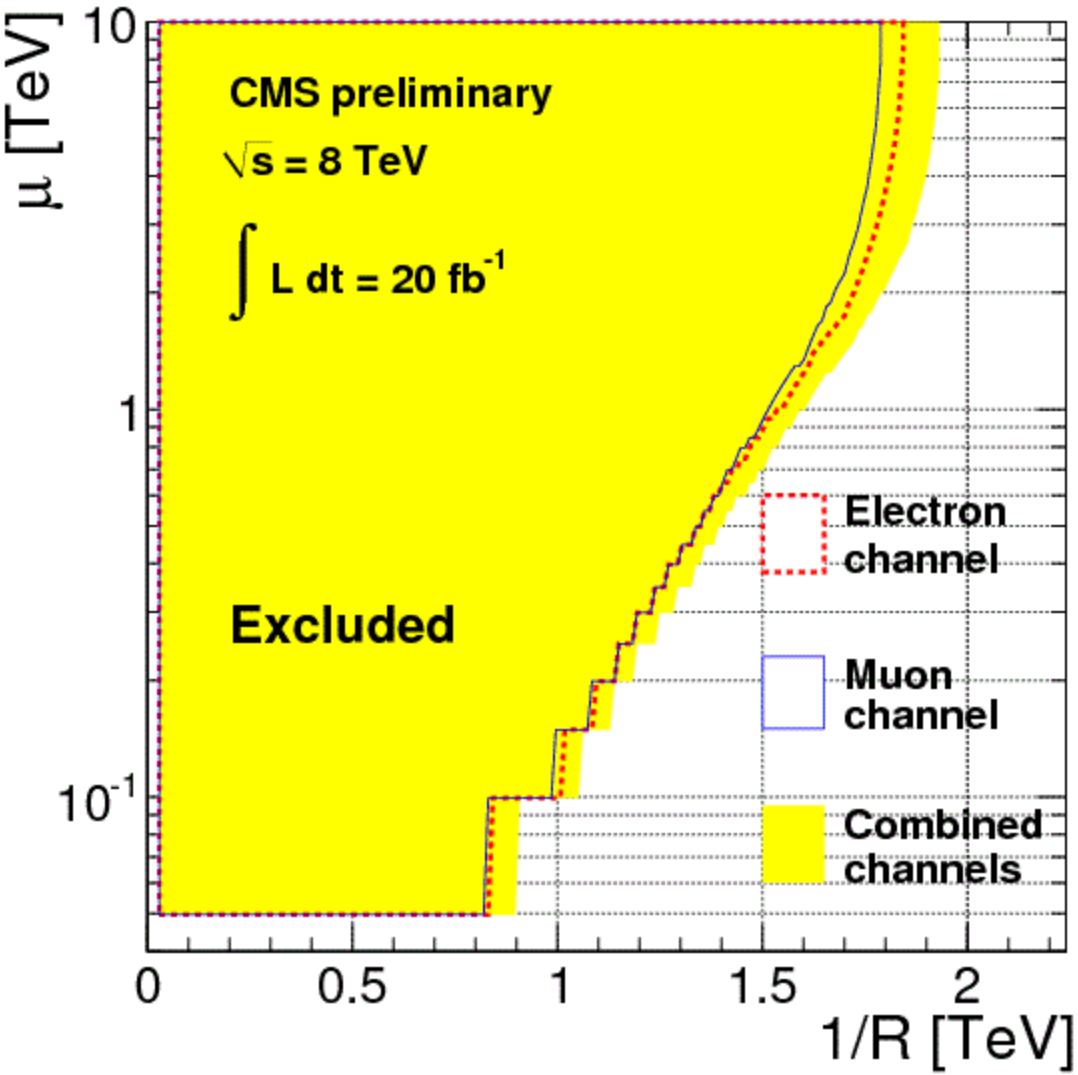
Λ > 13.0 TeV



Λ > 10.9 TeV

[CMS-PAS-EXO-12-060]

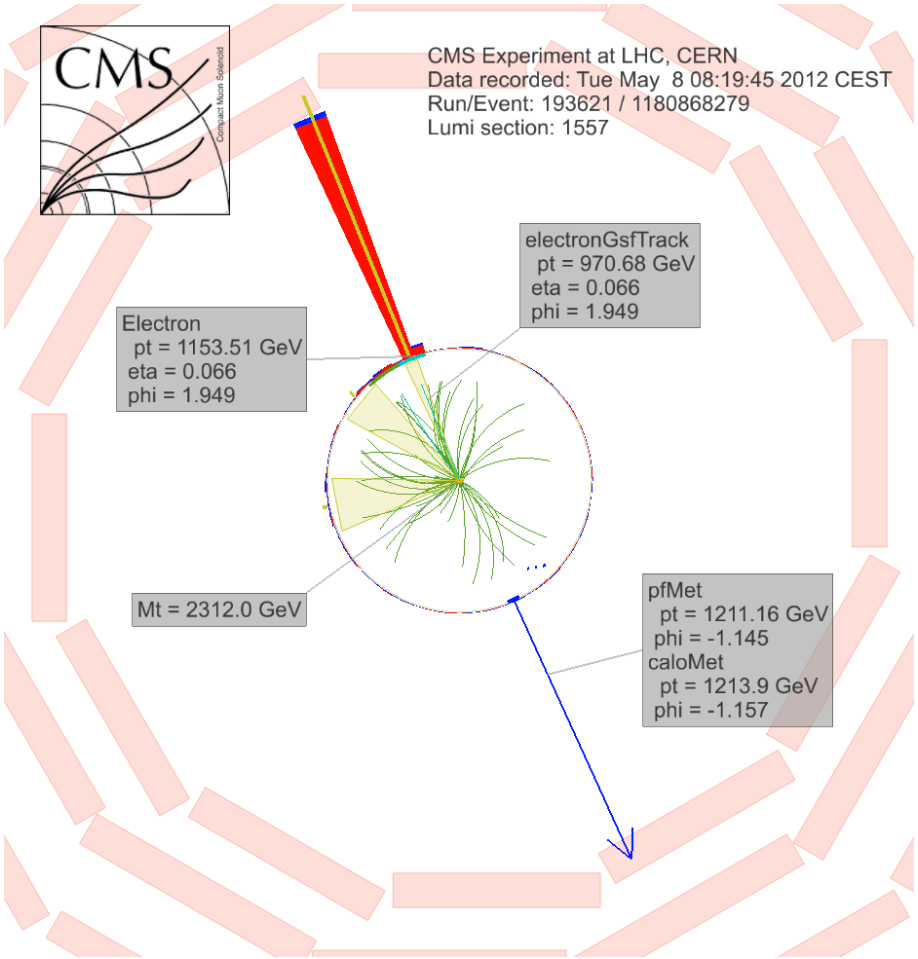
W′ → ℓν Split-UED Limits

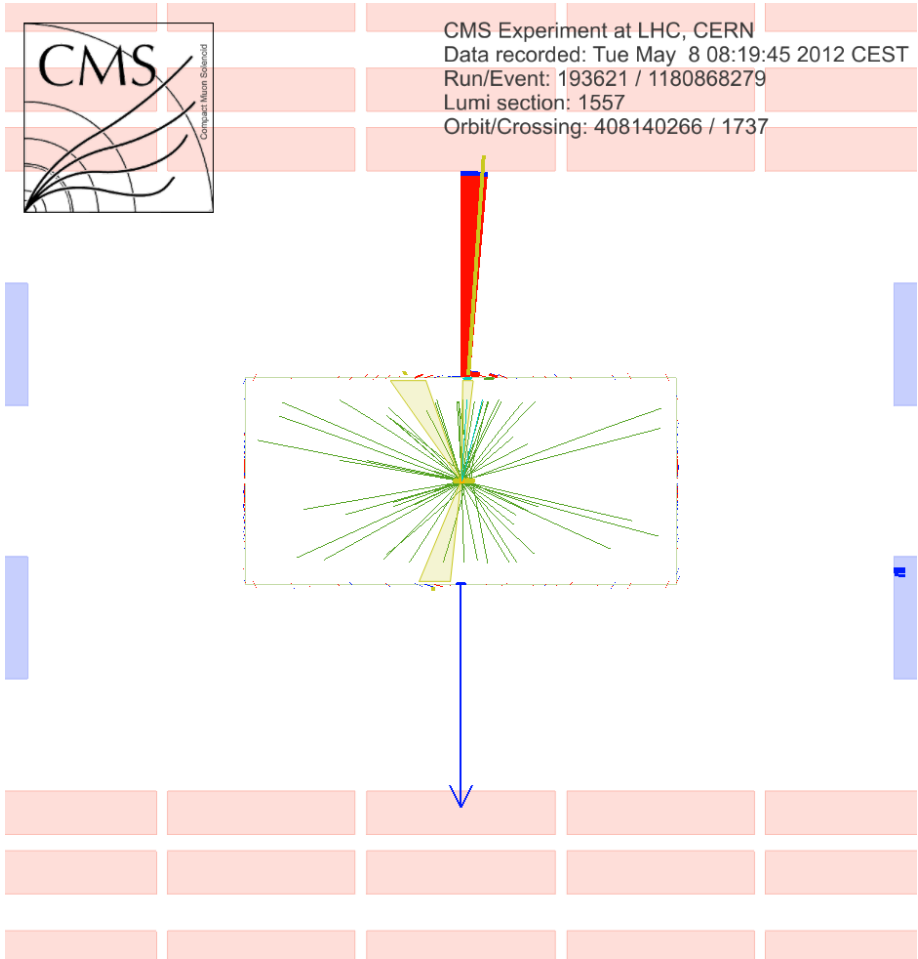


[CMS-PAS-EXO-12-060]

W′ → ℓν Event Display

Electron channel

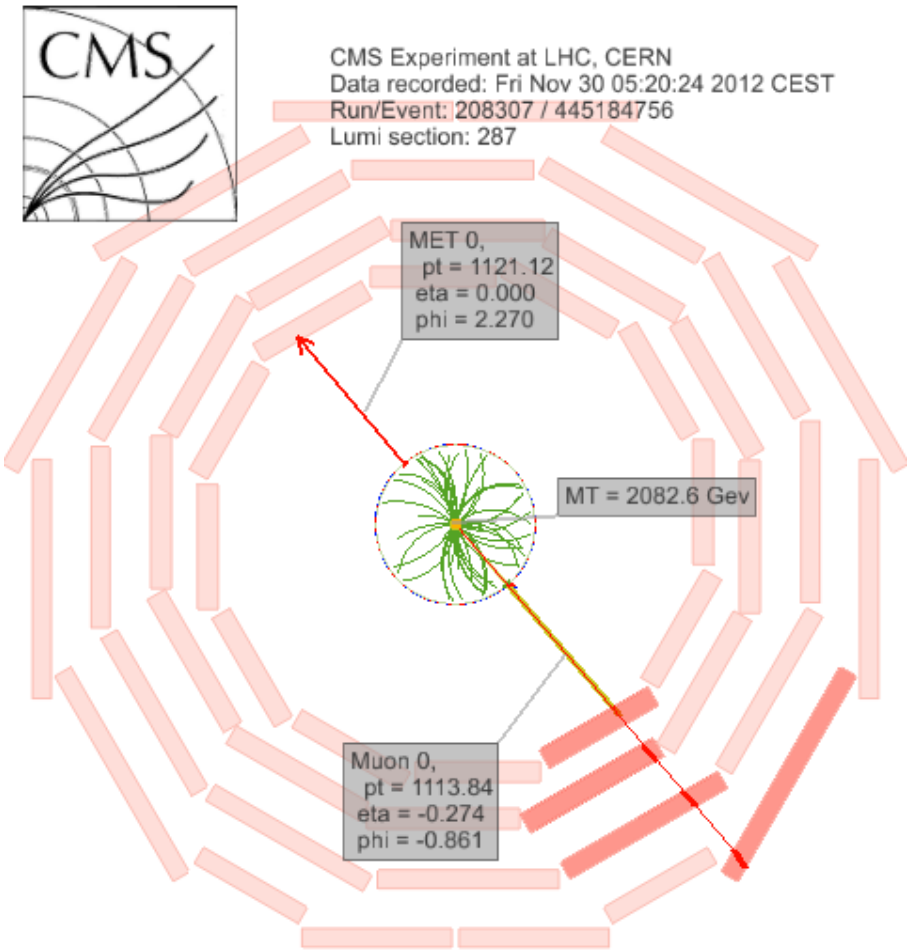


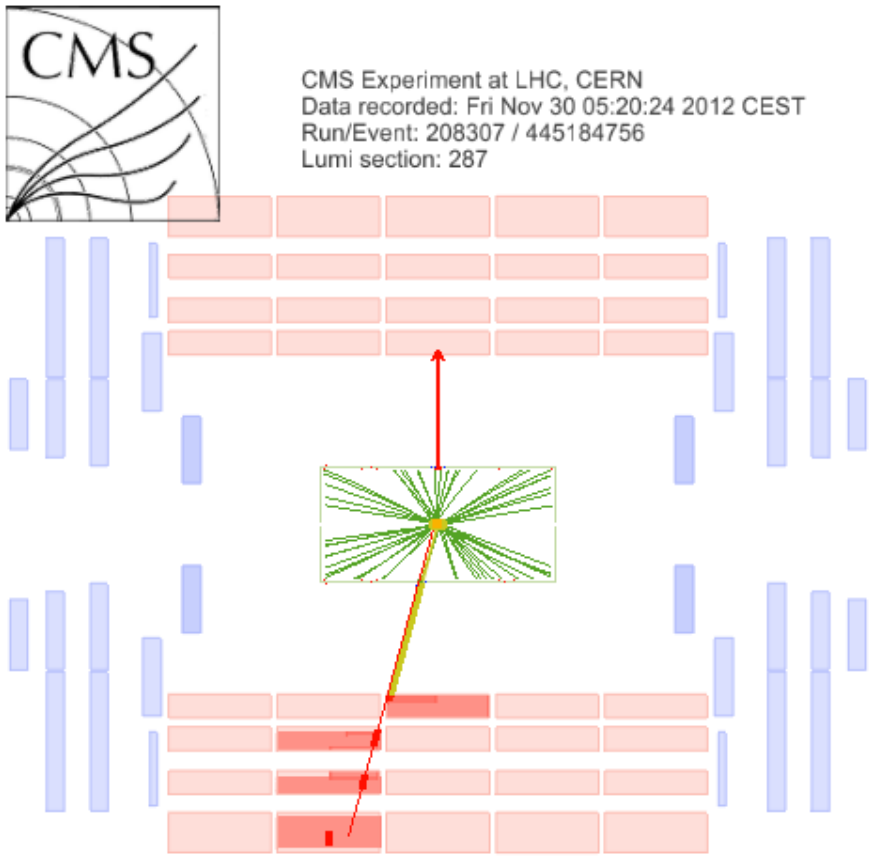


[CMS-PAS-EXO-12-060]

W′ → ℓν Event Display

Muon channel

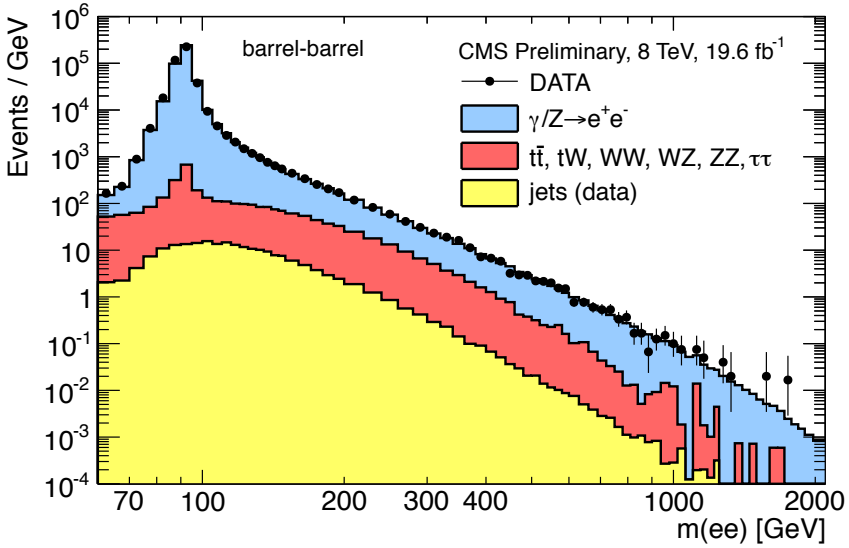




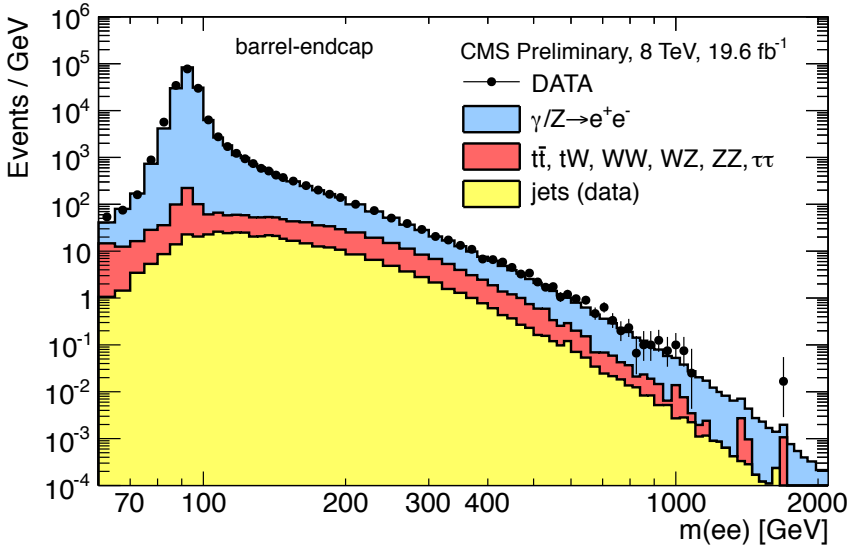
$Z' \rightarrow \ell^+\ell^-$

[CMS-PAS-EXO-12-061]

barrel-barrel events



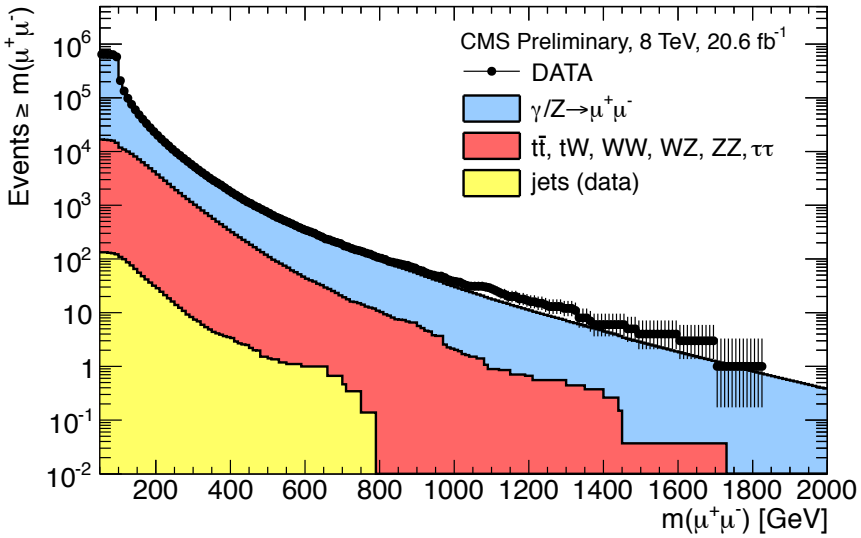
barrel-endcap events

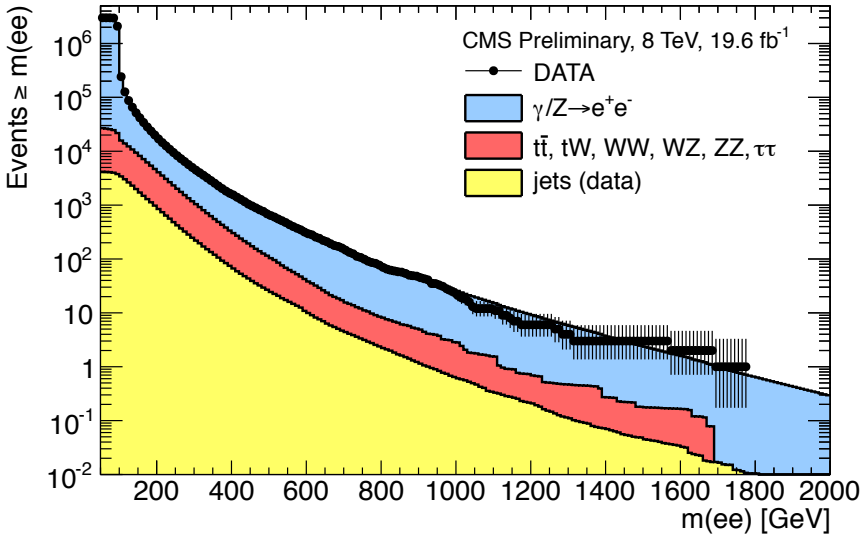


event classification for limit setting

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

[CMS-PAS-EXO-12-061]

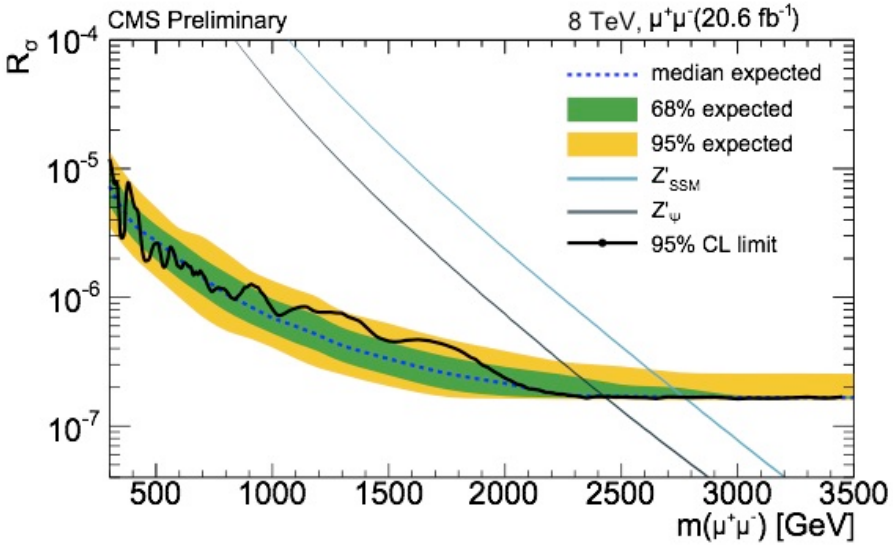




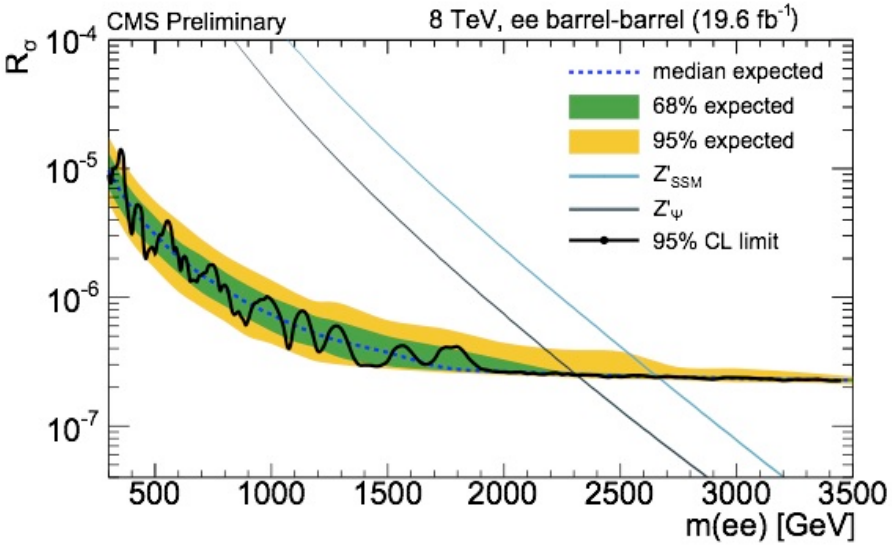
$Z' \rightarrow \ell^+\ell^-$

[CMS-PAS-EXO-12-061]

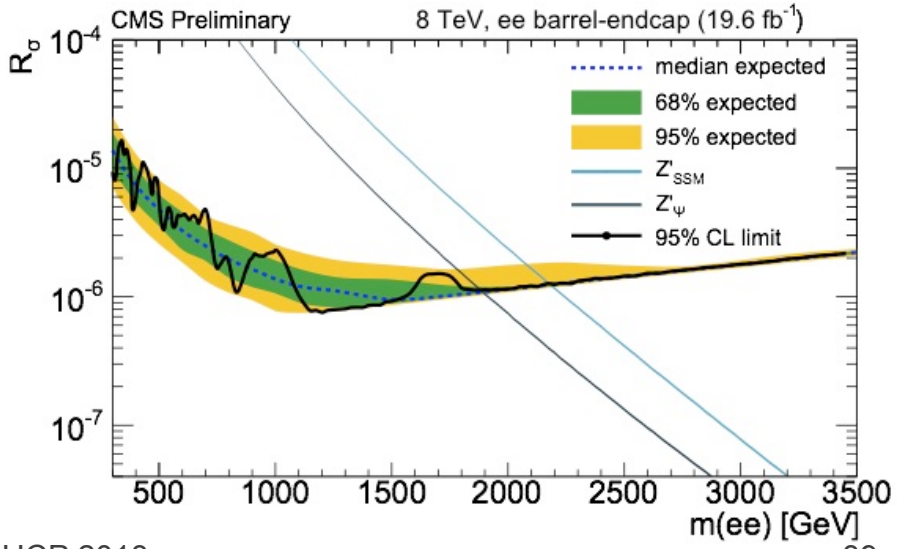
muon channel



barrel-barrel



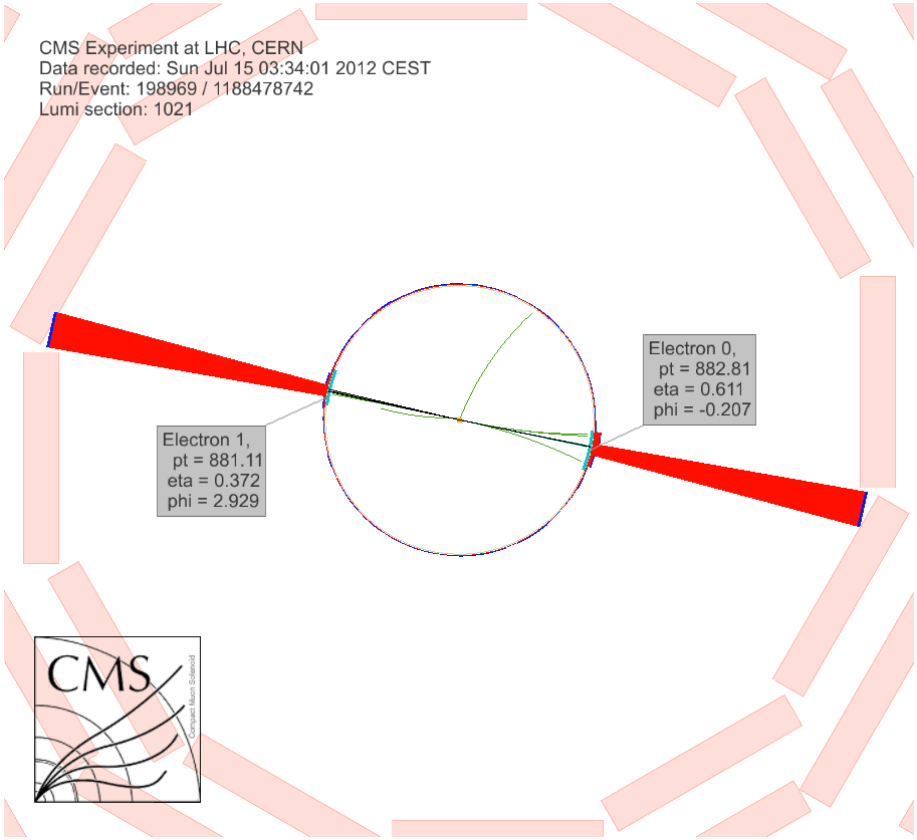
barrel-endcap

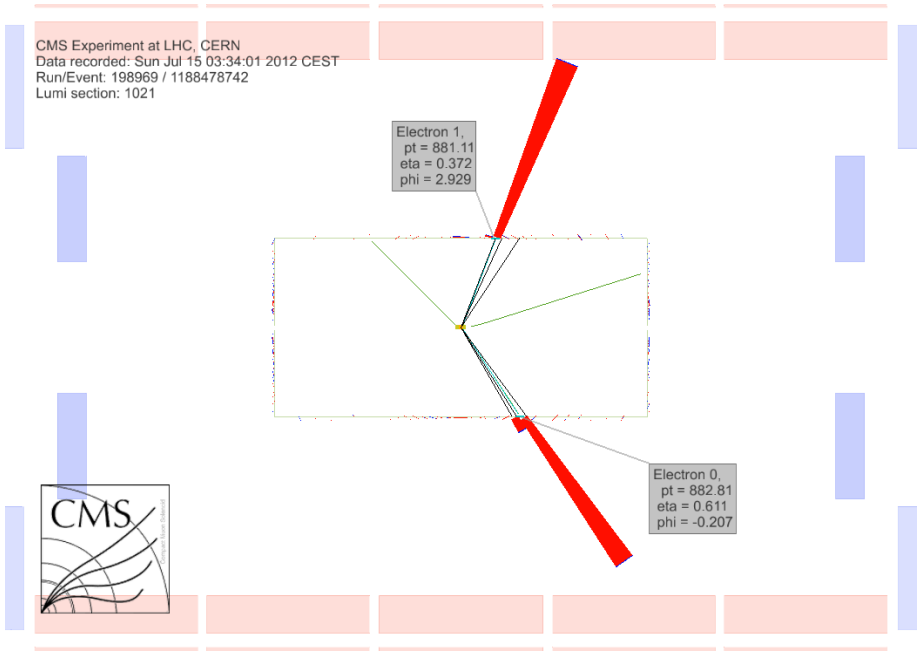


[CMS-PAS-EXO-12-061]

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

electron channel



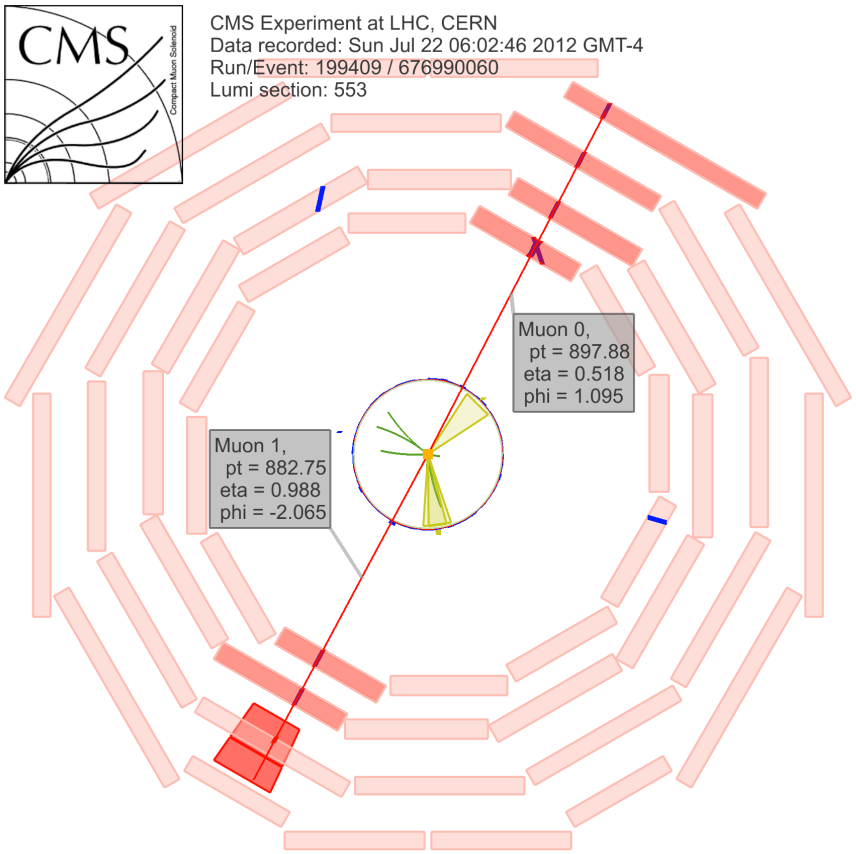


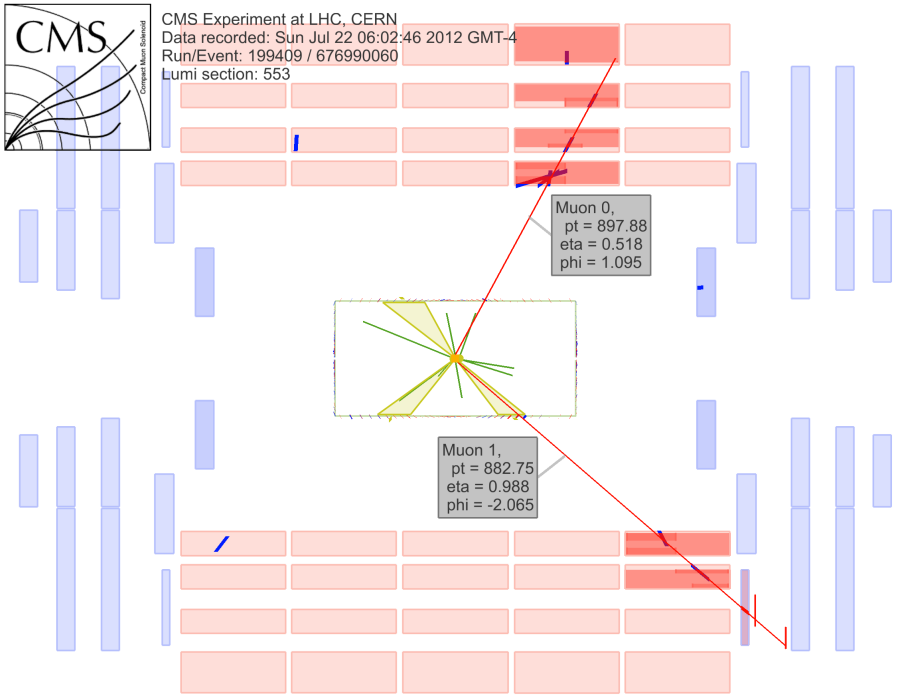
m_{ee} = 1.78 TeV

[CMS-PAS-EXO-12-061]

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

muon channel





$m_{\mu\mu}$ = 1.82 TeV

$LQ_2LQ_2 \rightarrow \mu\nu jj$

[CMS-PAS-EXO-12-042]

Selection cuts

M_{LQ} (GeV)	300	350	400	450	500	550	600	650	700	750	800	850	900	950	≥1000
$S_T >$ (GeV)	455	540	625	715	800	890	980	1070	1160	1250	1345	1435	1530	1625	1720
$M^T_{\mu\nu} >$ (GeV)	155	180	205	225	245	260	275	290	300	310	315	320	320	325	320
$M(\mu, \text{jet}) >$ (GeV)	125	150	175	200	225	250	280	305	330	355	380	410	435	465	490

Selected event yield

M_{LQ}	Signal	W+Jets	$t\bar{t}$	VV, Z, Single Top	All BG	Data
300	5032 ± 69	990 ± 21	1741 ± 14	362 ± 11	$3093 \pm 27 \pm 383$	3276
350	2322 ± 28	418 ± 14	604.5 ± 8.1	201.8 ± 9.5	$1224 \pm 18 \pm 137$	1315
400	1032 ± 11	195.8 ± 9.1	243.6 ± 5.1	75.8 ± 4.1	$515 \pm 11 \pm 60$	594
450	512.8 ± 8.6	101.4 ± 6.6	110.4 ± 3.5	41.6 ± 2.9	$253.3 \pm 8.0 \pm 28$	289
500	257.6 ± 2.7	59.3 ± 5.0	53.9 ± 2.4	23.6 ± 2.1	$136.8 \pm 5.9 \pm 15$	158
550	139.2 ± 1.6	37.1 ± 3.9	24.5 ± 1.6	14.1 ± 1.7	$75.8 \pm 4.6 \pm 8.7$	87
600	75.77 ± 0.8	19.2 ± 2.7	13.7 ± 1.2	7.4 ± 1.1	$40.3 \pm 3.2 \pm 4.8$	53
650	43.18 ± 0.45	12.1 ± 2.2	7.48 ± 0.89	3.98 ± 0.71	$23.6 \pm 2.5 \pm 3.6$	32
700	24.51 ± 0.26	7.2 ± 1.7	4.82 ± 0.71	$2.37\ ^{+0.77}_{-0.45}$	$14.4\ ^{+2.0}_{-1.9} \pm 2.6$	22
750	14.63 ± 0.15	5.3 ± 1.5	2.87 ± 0.55	$1.87\ ^{+0.76}_{-0.42}$	$10\ ^{+1.7}_{-1.6} \pm 2.3$	16
800	8.879 ± 0.097	3.8 ± 1.4	1.41 ± 0.39	$1.6\ ^{+0.74}_{-0.4}$	$6.9\ ^{+1.6}_{-1.5} \pm 1.9$	12
850	5.346 ± 0.056	0.92 ± 0.53	0.75 ± 0.28	$1.16\ ^{+0.72}_{-0.36}$	$2.83\ ^{+0.94}_{-0.7} \pm 0.98$	6
900	3.265 ± 0.036	0.6 ± 0.43	0.63 ± 0.26	$0.86\ ^{+0.7}_{-0.32}$	$2.09\ ^{+0.86}_{-0.59} \pm 0.92$	4
950	2.056 ± 0.022	0.39 ± 0.39	0.42 ± 0.21	$0.73\ ^{+0.7}_{-0.3}$	$1.54\ ^{+0.83}_{-0.54} \pm 0.54$	4
1000	1.287 ± 0.014	0.39 ± 0.39	0.252 ± 0.145	$0.61\ ^{+0.69}_{-0.28}$	$1.25\ ^{+0.8}_{-0.5} \pm 0.38$	4
1050	0.9091 ± 0.0091	0.39 ± 0.39	0.252 ± 0.145	$0.61\ ^{+0.69}_{-0.28}$	$1.25\ ^{+0.8}_{-0.5} \pm 0.38$	4
1100	0.6274 ± 0.0061	0.39 ± 0.39	0.252 ± 0.145	$0.61\ ^{+0.69}_{-0.28}$	$1.25\ ^{+0.8}_{-0.5} \pm 0.38$	4
1150	0.4292 ± 0.0043	0.39 ± 0.39	0.252 ± 0.145	$0.61\ ^{+0.69}_{-0.28}$	$1.25\ ^{+0.8}_{-0.5} \pm 0.38$	4
1200	0.2989 ± 0.0027	0.39 ± 0.39	0.252 ± 0.145	$0.61\ ^{+0.69}_{-0.28}$	$1.25\ ^{+0.8}_{-0.5} \pm 0.38$	4

$LQ_2LQ_2 \rightarrow \mu\mu jj$

[CMS-PAS-EXO-12-042]

Selection cuts

M_{LQ} (GeV)	300	350	400	450	500	550	600	650	700	750	800	850	900	950	≥1000
$S_T >$ (GeV)	380	460	540	615	685	755	820	880	935	990	1040	1090	1135	1175	1210
$M_{\mu\mu} >$ (GeV)	100	115	125	140	150	165	175	185	195	205	215	220	230	235	245
$M_{min}(\mu, \text{jet}) >$ (GeV)	115	115	120	135	155	180	210	250	295	345	400	465	535	610	690

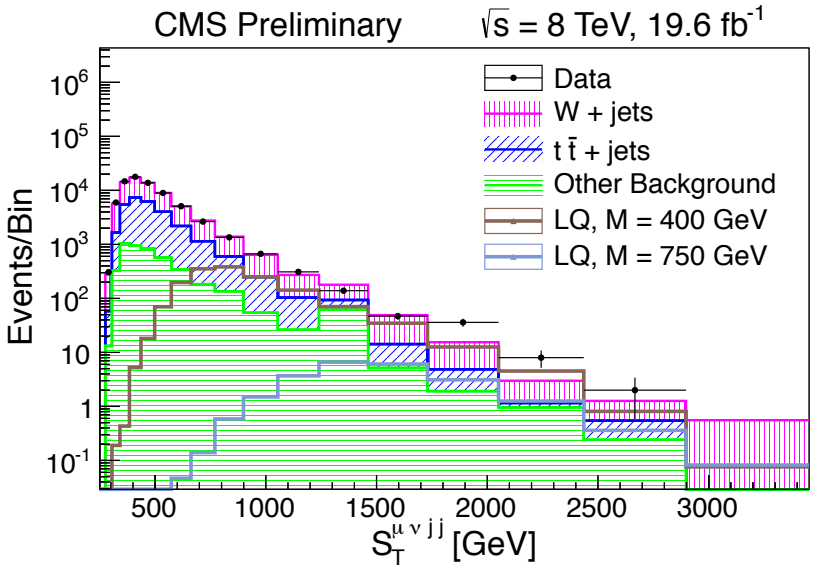
Selected event yield

M_{LQ}	Signal	Z+Jets	$t\bar{t}$	VV, W, Single Top	All BG	Data
300	14980 ± 110	716.2 ± 8.4	612 ± 18	86.7 ± 5.0	$1415 \pm 20 \pm 45$	1461
350	6975 ± 46	307.2 ± 5.5	368 ± 14	54.2 ± 4.1	$730 \pm 15 \pm 16$	714
400	3369 ± 22	176.5 ± 4.1	178.7 ± 9.4	29.6 ± 3.0	$384.8 \pm 10.7 \pm 9.3$	394
450	1664 ± 10	97 ± 3.0	89.3 ± 6.6	18.9 ± 2.4	$205.3 \pm 7.6 \pm 5.5$	210
500	859.4 ± 5.2	61.9 ± 2.4	48.5 ± 4.8	11.2 ± 1.9	$121.6 \pm 5.7 \pm 4.8$	128
550	459.3 ± 2.8	35.1 ± 1.8	25.5 ± 3.4	7.5 ± 1.6	$68.1 \pm 4.2 \pm 2.7$	75
600	252.3 ± 1.5	23 ± 1.4	15.84 ± 2.76	5.85 ± 1.41	$44.7 \pm 3.4 \pm 2.0$	44
650	143.87 ± 0.86	15.1 ± 1.13	8.86 ± 1.98	$4.08^{+1.32}_{-1.25}$	$28 \pm 2.6 \pm 1.3$	24
700	82.02 ± 0.49	9.66 ± 0.91	5.97 ± 1.72	$2.99^{+1.12}_{-1.04}$	$18.6 \pm 2.2 \pm 1.3$	15
750	48.06 ± 0.29	6.37 ± 0.74	1.41 ± 0.7	$1.54^{+0.78}_{-0.67}$	$9.32^{+1.29}_{-1.22} \pm 0.87$	11
800	28.73 ± 0.17	3.85 ± 0.58	1.55 ± 0.77	$1.13^{+0.71}_{-0.59}$	$6.53^{+1.2}_{-1.13} \pm 0.85$	9
850	17.43 ± 0.11	2.2 ± 0.42	0.56 ± 0.56	$1.12^{+0.72}_{-0.59}$	$3.88^{+1.0}_{-0.92} \pm 0.67$	5
900	10.337 ± 0.064	1.19 ± 0.31	$0.0^{+0.59}_{-0.0}$	$0.28^{+0.45}_{-0.2}$	$1.47^{+0.81}_{-0.37} \pm 0.43$	3
950	6.333 ± 0.04	0.71 ± 0.24	$0.0^{+0.59}_{-0.0}$	$0.117^{+0.658}_{-0.117}$	$0.83^{+0.91}_{-0.26} \pm 0.29$	1
1000	3.845 ± 0.025	0.38 ± 0.17	$0.0^{+0.59}_{-0.0}$	$0.0^{+0.65}_{-0.0}$	$0.383^{+0.894}_{-0.171} \pm 0.031$	0
1050	2.557 ± 0.016	0.38 ± 0.17	$0.0^{+0.59}_{-0.0}$	$0.0^{+0.65}_{-0.0}$	$0.383^{+0.894}_{-0.171} \pm 0.031$	0
1100	1.714 ± 0.01	0.38 ± 0.17	$0.0^{+0.59}_{-0.0}$	$0.0^{+0.65}_{-0.0}$	$0.383^{+0.894}_{-0.171} \pm 0.031$	0
1150	1.1465 ± 0.0069	0.38 ± 0.17	$0.0^{+0.59}_{-0.0}$	$0.0^{+0.65}_{-0.0}$	$0.383^{+0.894}_{-0.171} \pm 0.031$	0
1200	0.7554 ± 0.0045	0.38 ± 0.17	$0.0^{+0.59}_{-0.0}$	$0.0^{+0.65}_{-0.0}$	$0.383^{+0.894}_{-0.171} \pm 0.031$	0

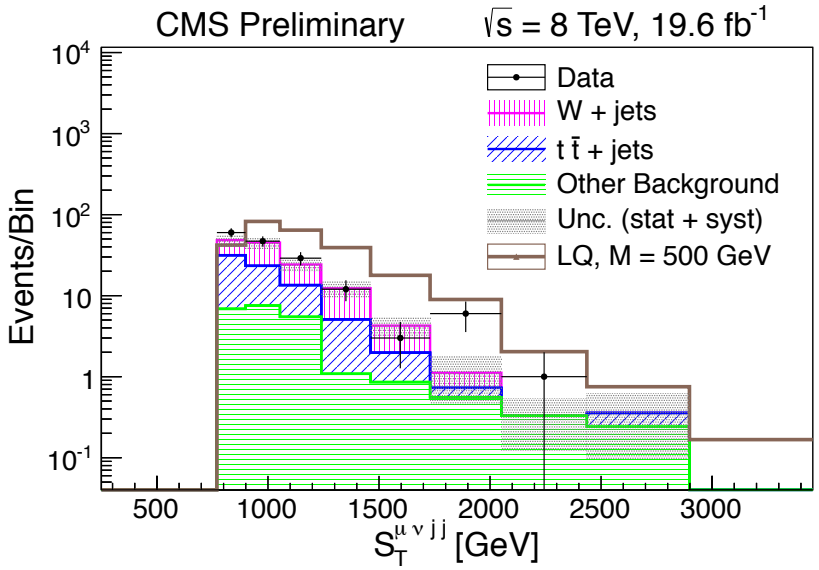
$LQ_2LQ_2 \rightarrow \mu\nu jj$

[CMS-PAS-EXO-12-042]

Pre-selected events



Selected events

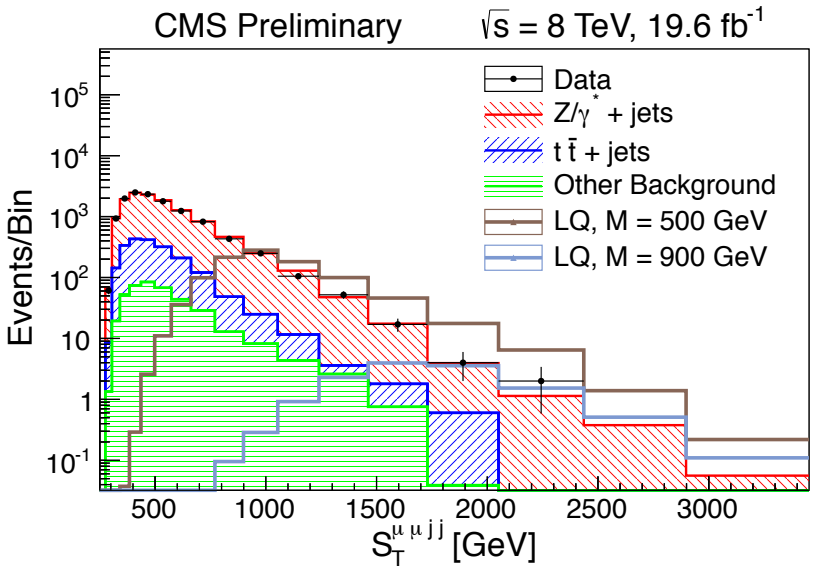


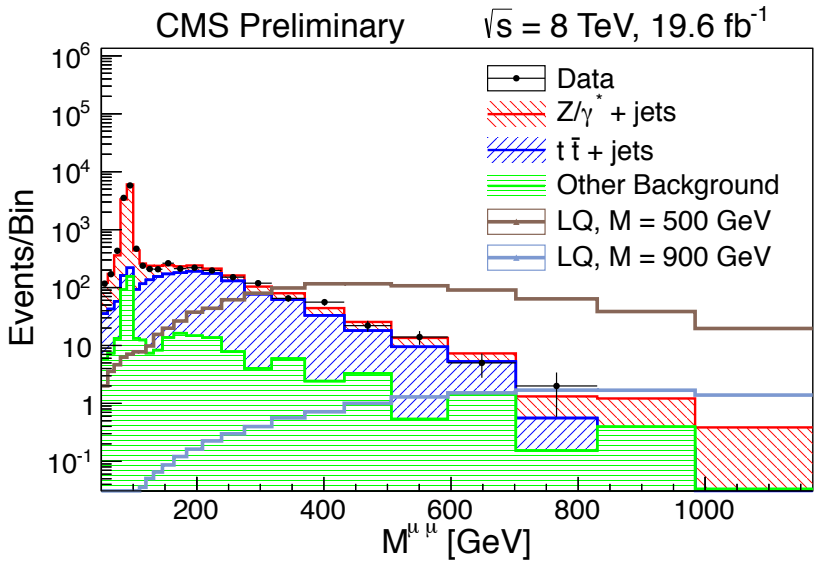
m(LQ) = 500 GeV

$LQ_2LQ_2 \rightarrow \mu\mu jj$

[CMS-PAS-EXO-12-042]

Pre-selected events

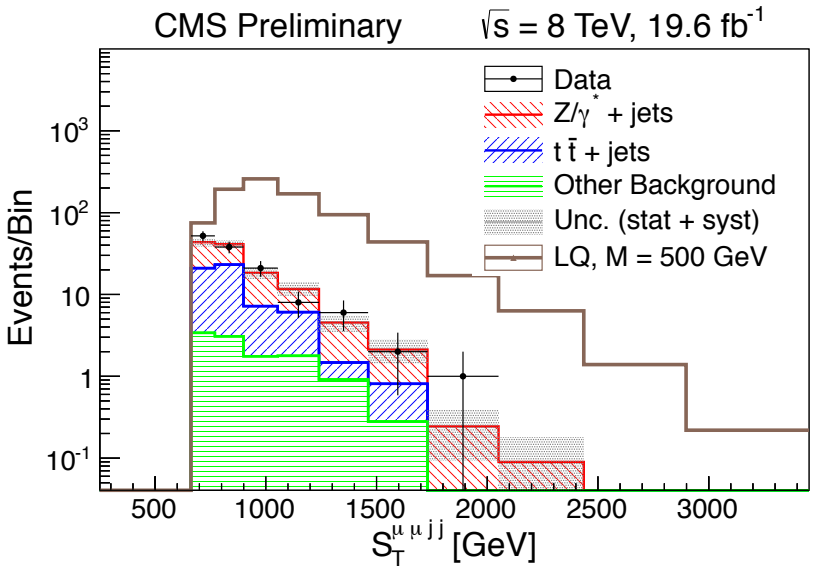




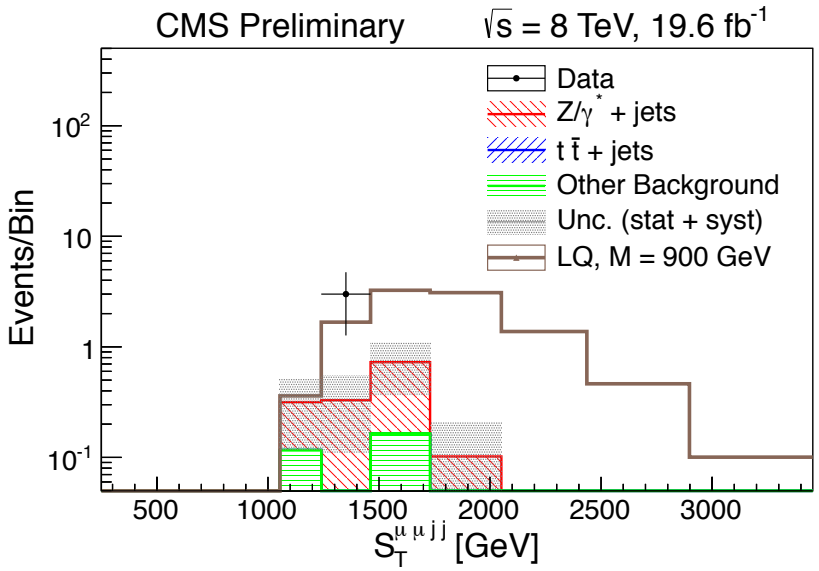
$LQ_2LQ_2 \rightarrow \mu\mu jj$

[CMS-PAS-EXO-12-042]

Selected Events



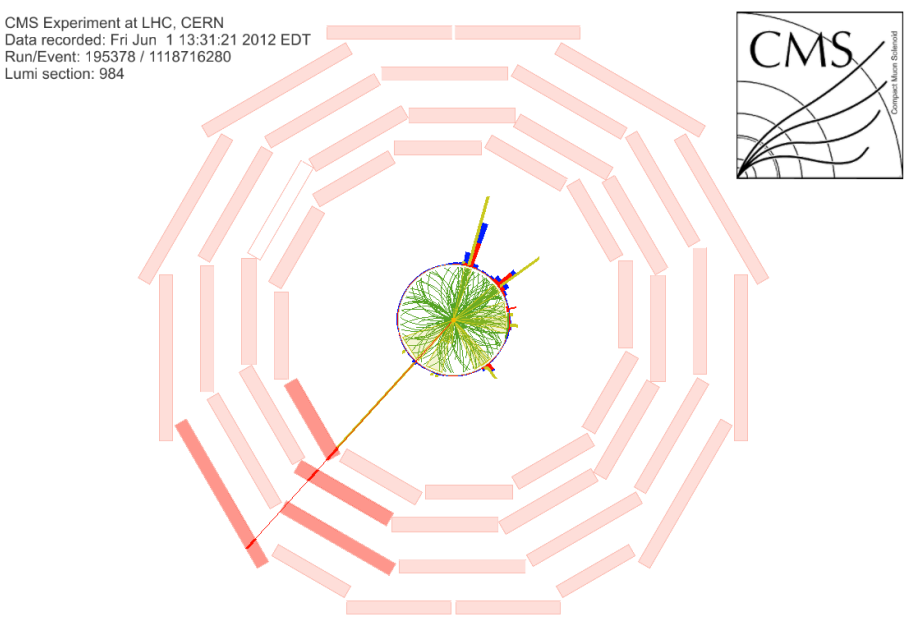
m(LQ) = 500 GeV

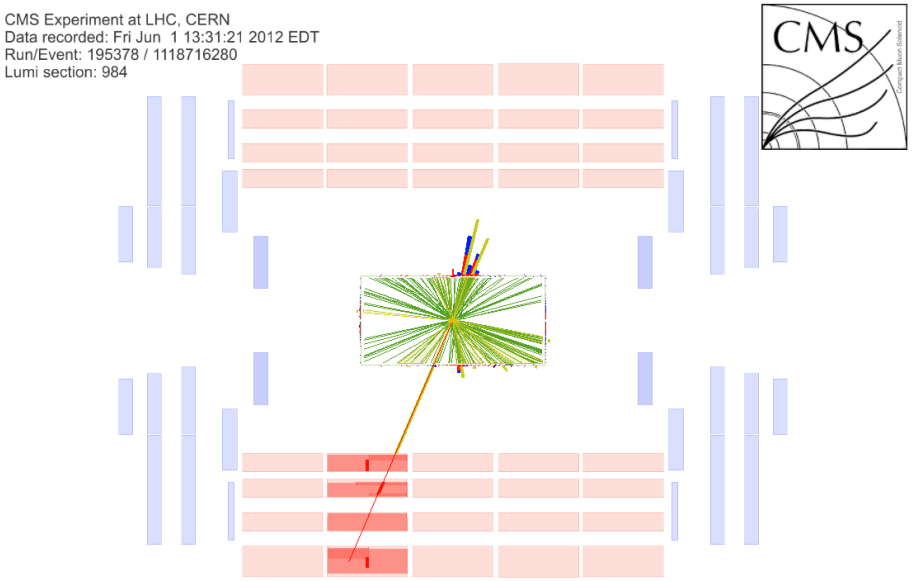


m(LQ) = 900 GeV

[CMS-PAS-EXO-12-042]

LQ_2LQ_2 → μνjj Event Display

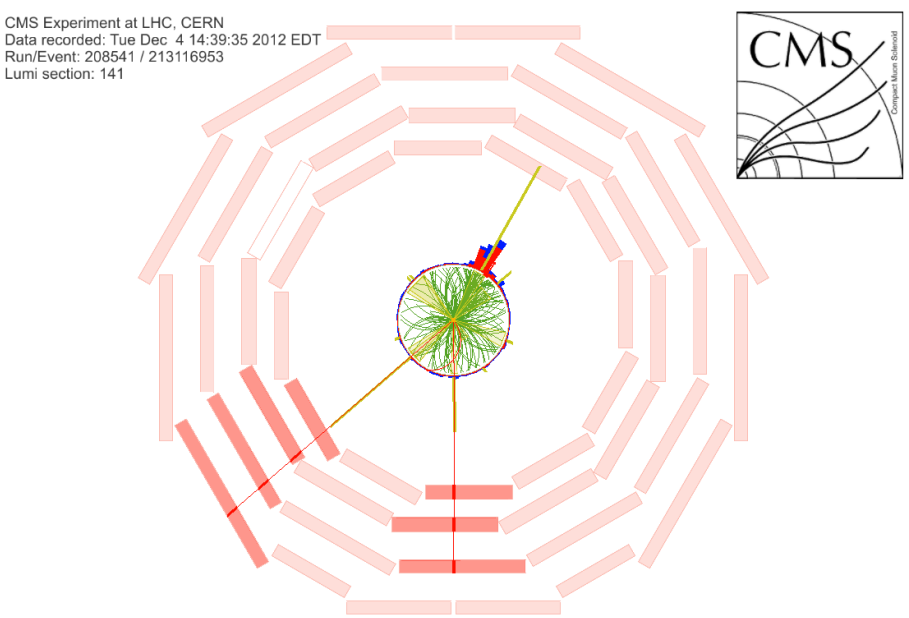


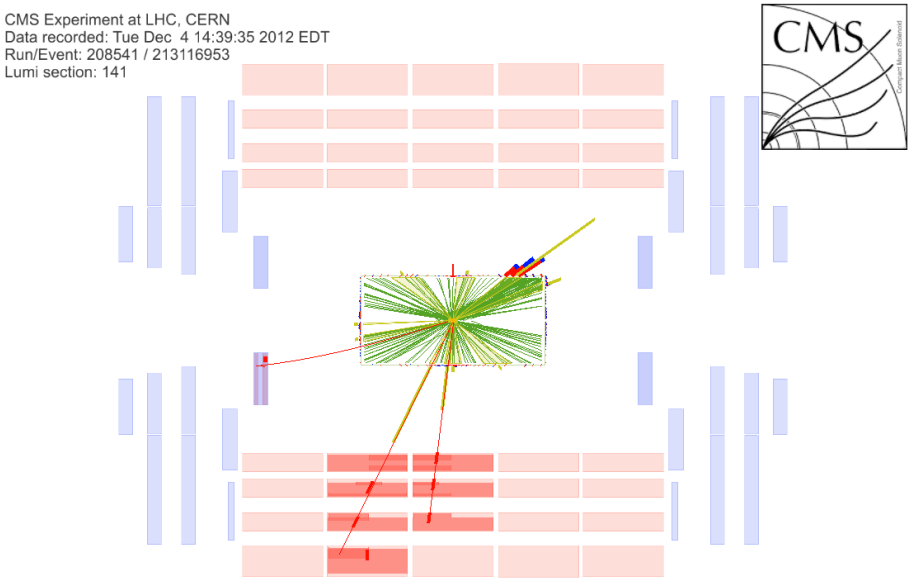


m(μ,jet) = 1450 GeV

[CMS-PAS-EXO-12-042]

LQ_2LQ_2 → μμjj Event Display





$m_{min}(\mu,jet) = 662$ GeV