



SEARCH FOR HEAVY RESONANCES WITH LEPTONS AND JETS AT CMS

**PRINCETON
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Outline

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- Introduction
- Three analyses with full 8 TeV dataset:
 - ▣ CMS-PAS-EXO-12-060: $W' \rightarrow l\nu$
 - ▣ CMS-PAS-EXO-12-061: $Z' \rightarrow l^+l^-$
 - ▣ CMS-PAS-EXO-12-042: $LQ_2\overline{LQ_2} \rightarrow \mu\mu jj/\mu\nu jj$
- One analysis with partial 8 TeV dataset (in backup)
 - ▣ CMS-PAS-EXO-12-017: $W_R \rightarrow lljj$
- Conclusion

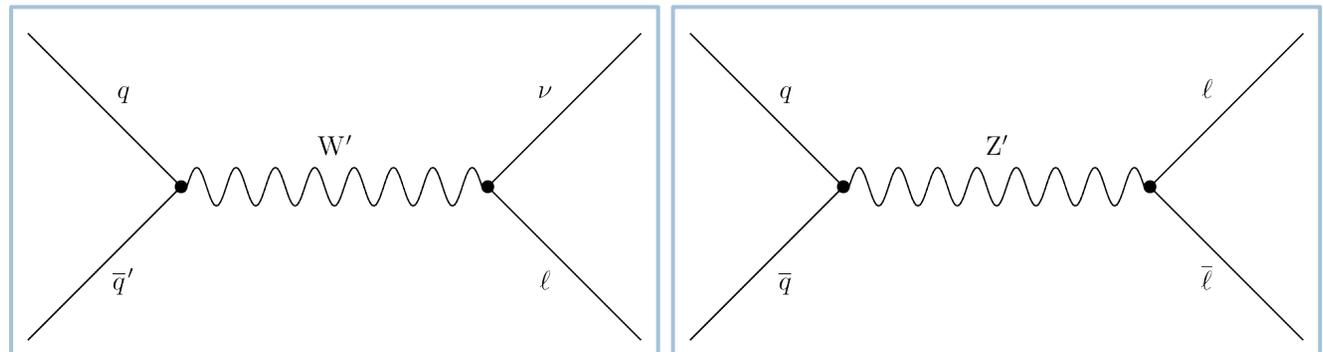
Note other EPS talks with CMS results on resonances with leptons and jets:

- “Search for $t\bar{t}$ resonances below 1 TeV in the semileptonic final state”
- “Search for heavy resonances decaying to top quarks”

Introduction

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- Classic motivations for new (BSM) heavy resonances:
 - Extension of SM symmetry group:
 - $SU(3)_C \times SU(2)_L \times U(1)_Y \times \mathbf{U(1)'} \rightarrow$ Provides for gauge boson ($\mathbf{Z'}$)
 - $SU(3)_C \times SU(2)_L \times U(1)_Y \times \mathbf{SU(2)'} \rightarrow$ Provides for gauge bosons ($\mathbf{Z'}$, $\mathbf{W'}$)
 - Larger symmetry that includes SM:
 - Leptons and quarks in an **additional multiplet** \rightarrow Provides for **leptoquarks**
- Plenty of other theories predict heavy resonances decaying to leptons and/or jets:
 - Z' from GUT-inspired theories [E_6 , $SU(6)$, $SO(10)$,...]
 - Extra-dimensions
 - RPV SUSY
 - Many more



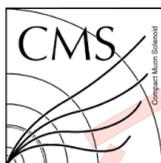
Introduction

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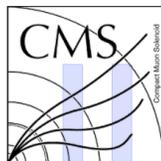
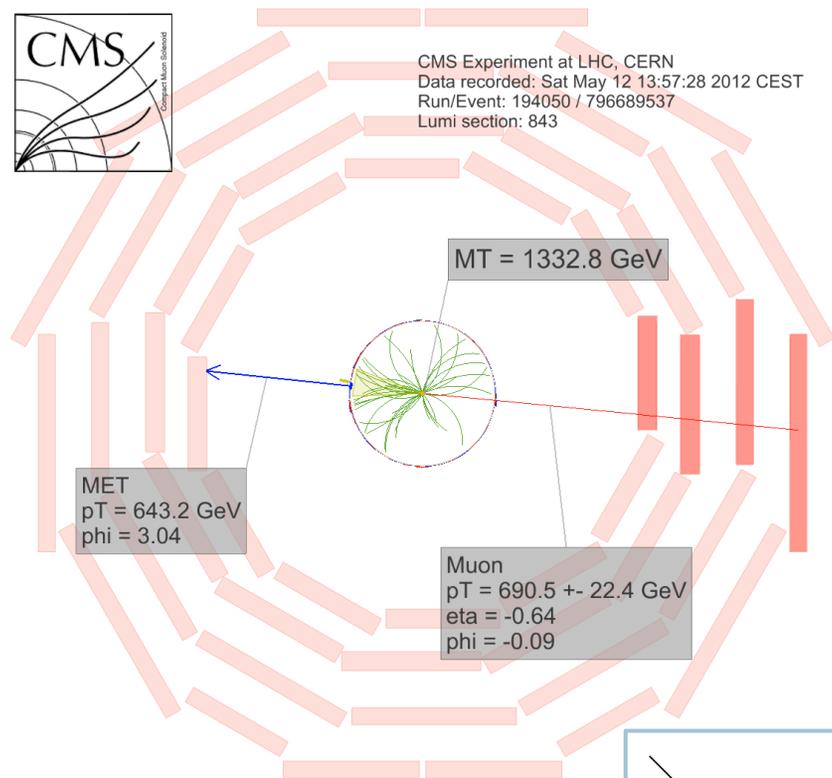
- Experimental strategy
 - ▣ Probing for results at the highest available energies
 - ▣ **Advantage:** high- p_T , isolated leptons in final states allow for clean signature and small backgrounds
 - ▣ **Challenge:** understanding efficiencies and uncertainties of reconstructed objects in high- p_T tails of SM background
- All analyses in this talk use data taken by CMS during the 2012 run period
 - ▣ $\sqrt{s} = 8 \text{ TeV}$, $\int \mathcal{L} \approx 20 \text{ fb}^{-1}$

$$W' \rightarrow \ell \nu$$

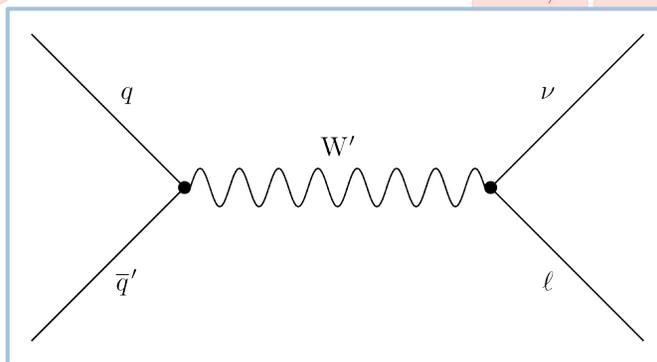
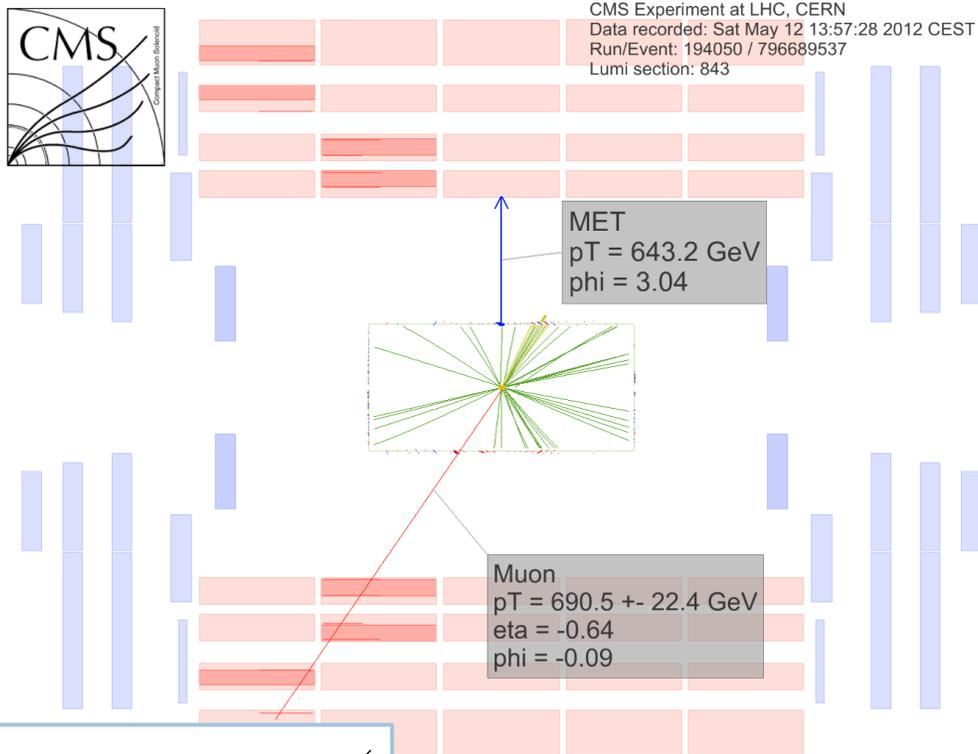
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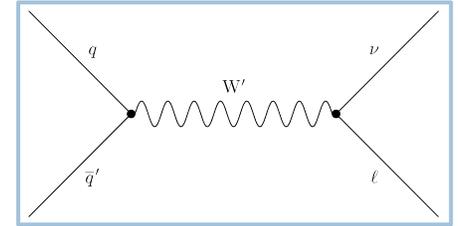
CMS Experiment at LHC, CERN
Data recorded: Sat May 12 13:57:28 2012 CEST
Run/Event: 194050 / 796689537
Lumi section: 843



CMS Experiment at LHC, CERN
Data recorded: Sat May 12 13:57:28 2012 CEST
Run/Event: 194050 / 796689537
Lumi section: 843



$$W' \rightarrow \ell \nu$$



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- Search for peak in the SM m_T tail

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

- Event selection

- 1 isolated lepton (electron, muon)
 - electron $p_T > 100$ GeV
 - muon $p_T > 45$ GeV
- $0.4 < [\text{lepton } p_T / \text{MET}] < 1.5$
- $\Delta\phi(\text{lepton}, \text{MET}) > 2.5$

- Signal modeling

- Pythia, normalized to NNLO
- Models:
 - Sequential Standard Model
 - Constructive interference with SM
 - Destructive interference with SM
 - Kaluza-Klein excitations of W in split-UED
 - Helicity Non-Conserved Contact Interaction

- Background modeling

- All modeled with MC normalized to NNLO, unless indicated
- W (dominant):
 - Pythia
 - NLO k-factors, binned in m_T
 - Finally normalized to NNLO
- Drell-Yan:
 - POWHEG for electrons, muons
 - Pythia for taus
- Top:
 - Pair production: MadGraph
 - Single production: POWHEG
- Others:
 - Pythia
 - Diboson (WW, WZ, ZZ) (NNLO)
 - photon + jets, QCD (LO only)

- Background estimate from MC fit

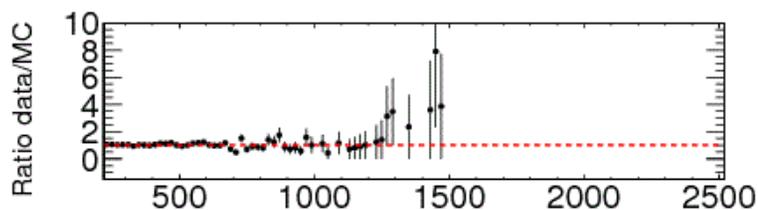
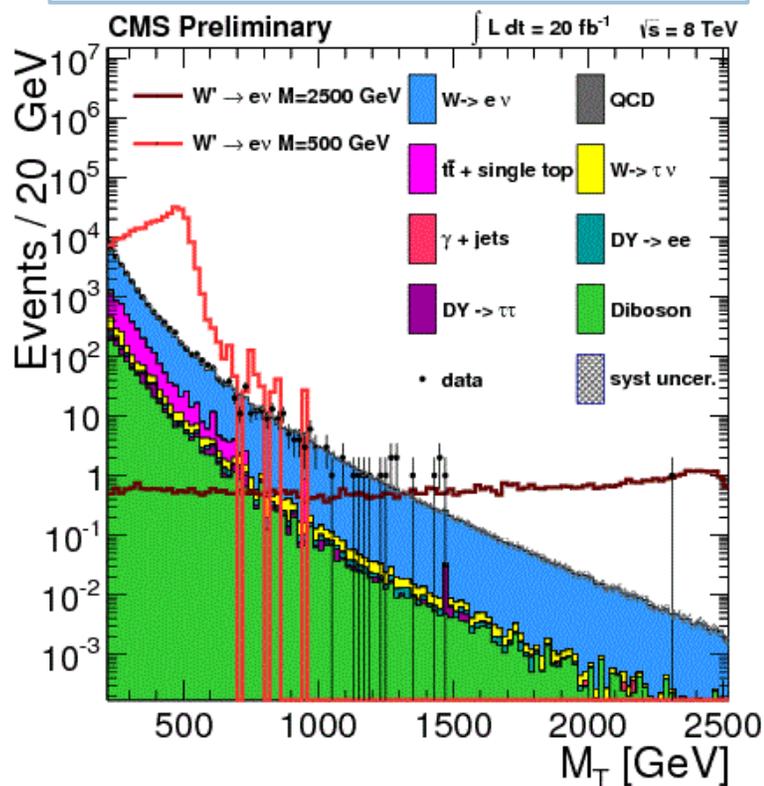
- Fit range: $250 < m_T < 3000$ GeV

$$M_T \cdot e^{a + b \cdot M_T + c \cdot M_T^2}$$

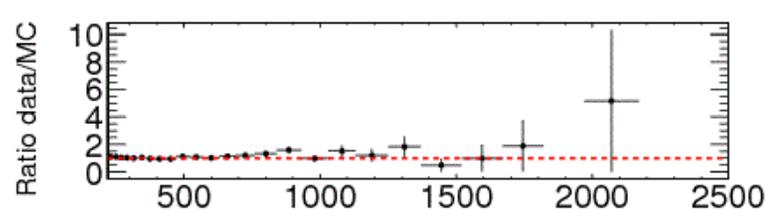
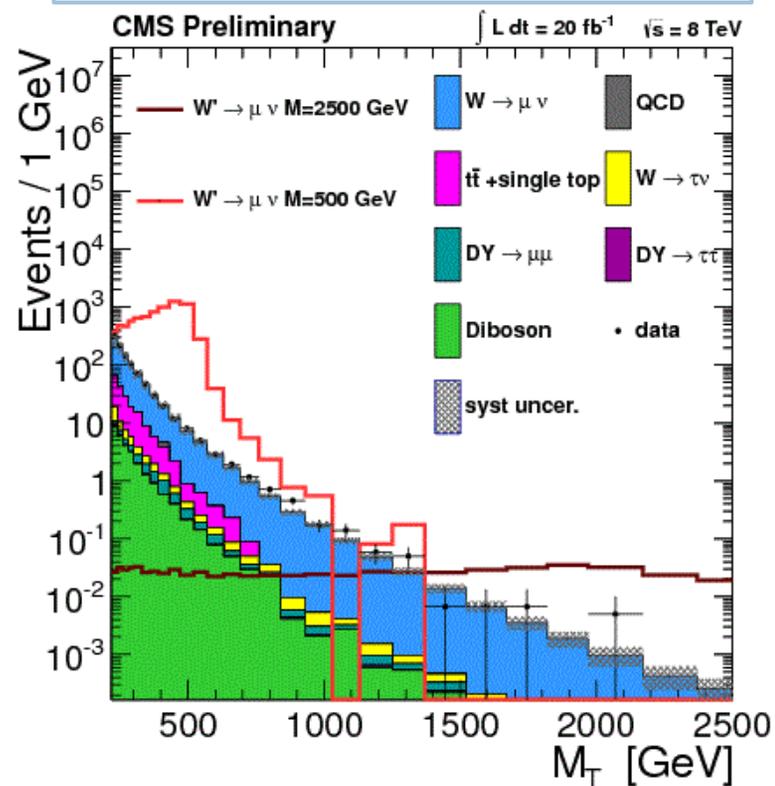
$W' \rightarrow \ell\nu$ Results

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Electron channel

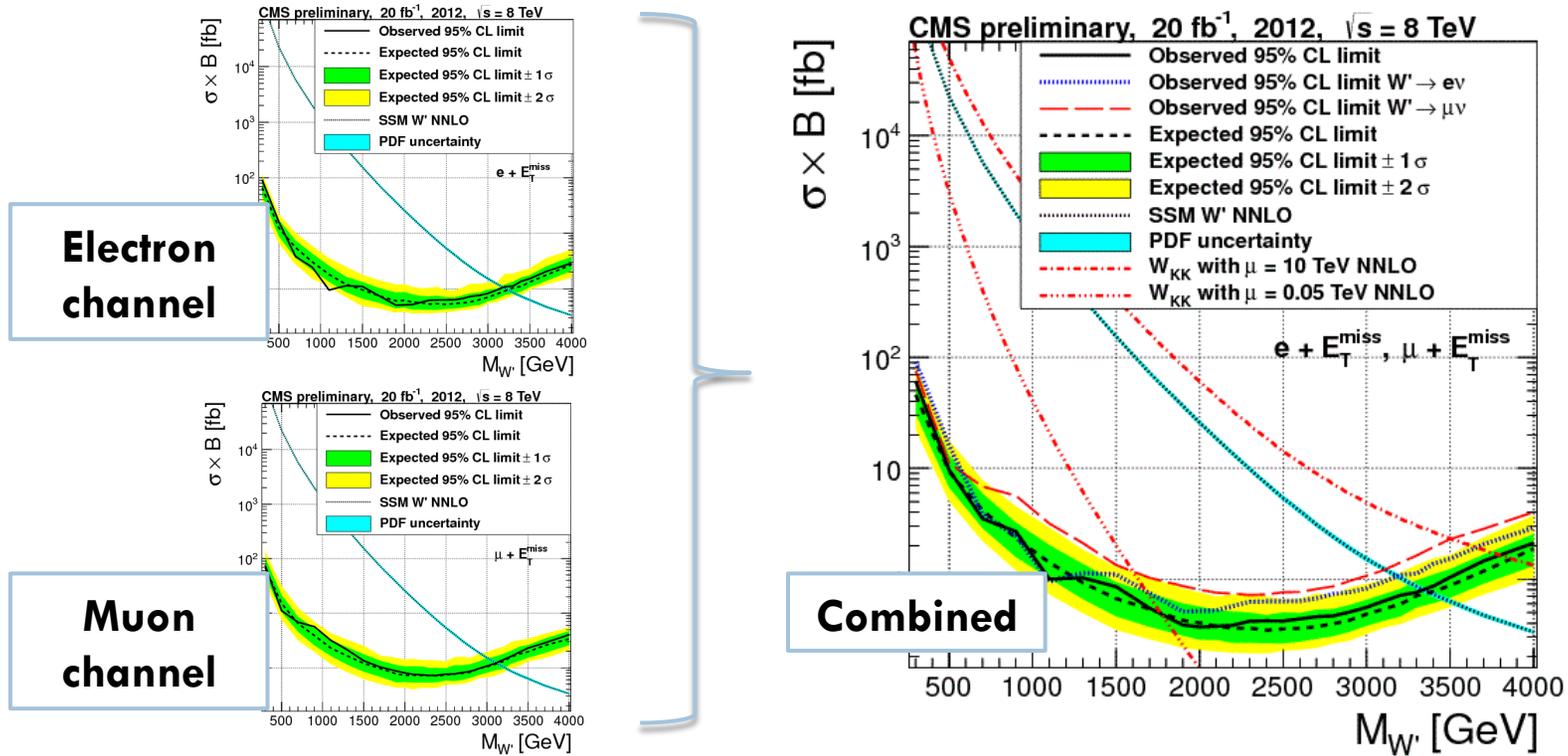


Muon channel



$W' \rightarrow \ell\nu$ Limits

SSM: Sequential Standard Model
 SSMO: Constructive interference with SM
 SSMS: Destructive interference with SM
 KK: Kaluza-Klein excitations of W in split-UED
 HNC CI: Helicity Non-Cons. Contact Interaction

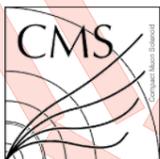
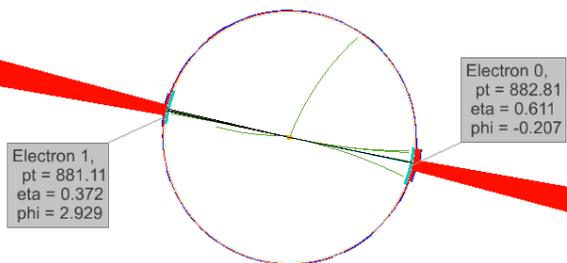


Channel	Obs. W'_{SSM} limit	Obs. W'_{SSMO} limit	Obs. W'_{SSMS} limit	Obs. W'_{KK} limit		Obs. $W'_{HNC CI}$ limit
				$\mu = 0.05$ TeV	$\mu = 10.0$ TeV	
e^\pm	3.20 TeV	3.60 TeV	3.00 TeV	-	-	13.0 TeV
μ^\pm	3.15 TeV	3.05 TeV	2.80 TeV	-	-	10.9 TeV
combined	3.35 TeV	3.60 TeV	3.10 TeV	1.7 TeV	3.7 TeV	-

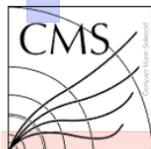
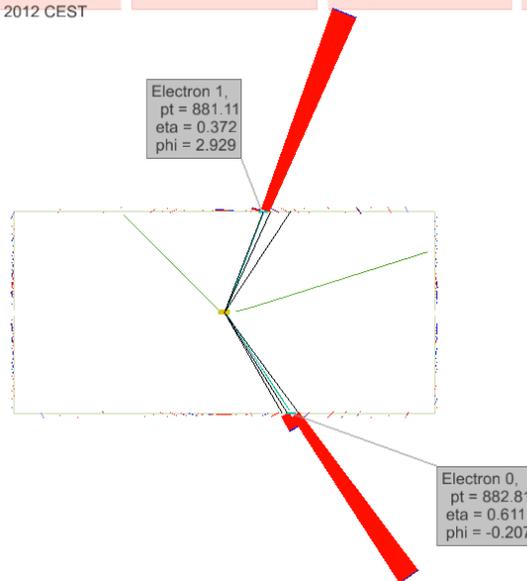
$$Z' \rightarrow l^+ l^-$$

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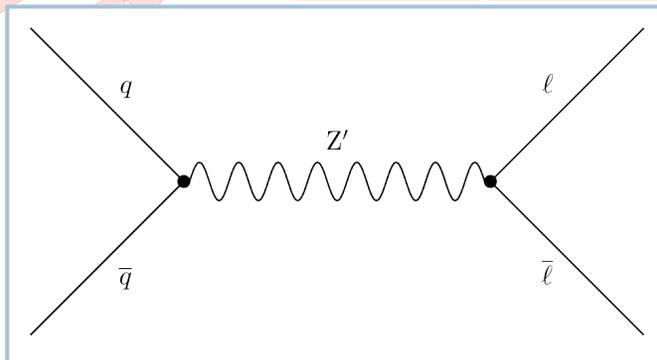
CMS Experiment at LHC, CERN
Data recorded: Sun Jul 15 03:34:01 2012 CEST
Run/Event: 198969 / 1188478742
Lumi section: 1021



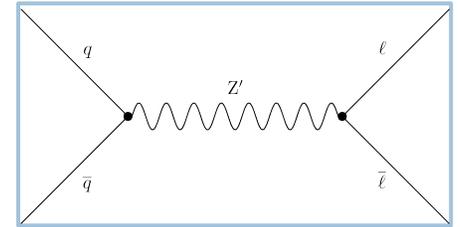
CMS Experiment at LHC, CERN
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Run/Event: 198969 / 1188478742
Lumi section: 1021



$M(ee) = 1.78 \text{ TeV}$



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



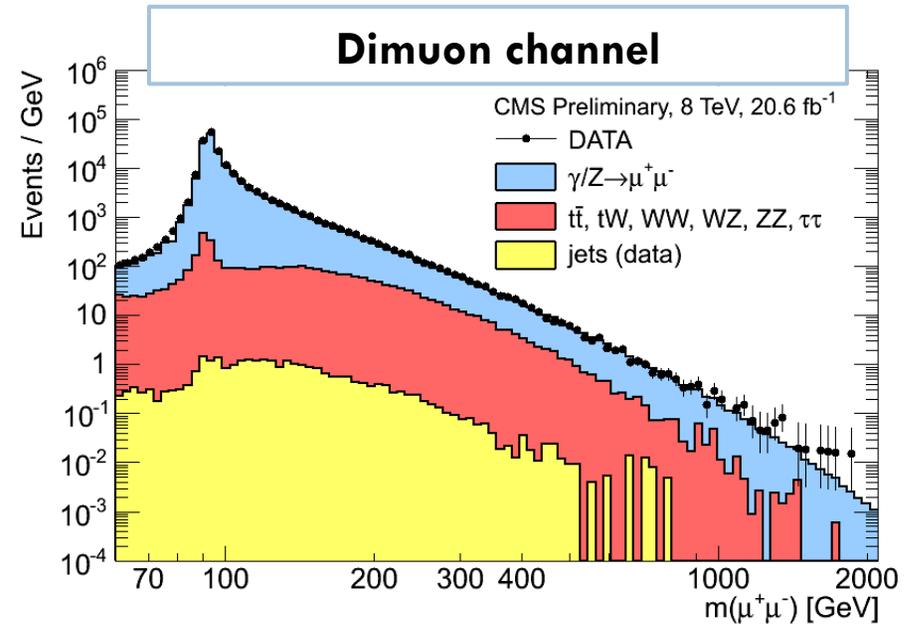
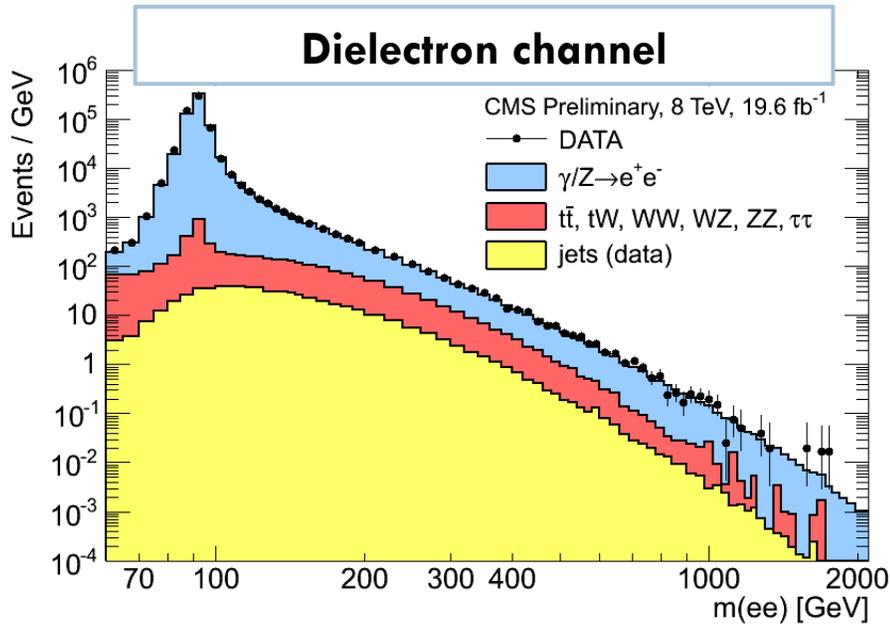
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- Event selection
 - 2 isolated leptons (electron, muon)
 - electron $p_T > 35$ GeV
 - muon $p_T > 40$ GeV
 - Muons are OS, from the same vertex
- Signal modeling
 - Pythia
 - NNLO k-factor (mass-binned)
 - Models:
 - Sequential Standard Model
 - Superstring-inspired Z_ψ'
- For electron channel only, separate events into two categories:
 - ECAL barrel-barrel
 - ECAL endcap-barrel
- Background modeling
 - All modeled with MC normalized to NNLO, unless indicated
 - Drell-Yan (dominant): POWHEG
 - W: MadGraph
 - Top:
 - Pair production: Modeled using electron + muon events **from data**
 - Single production: POWHEG
 - QCD:
 - Electron channel: modeled using fake rate **on data**
 - Muon channel: Pythia (LO, and small)
 - All other backgrounds: Pythia
 - Diboson (WW, WZ, ZZ) (NNLO)
 - Electron channel: photon + jets (LO)
- Background estimate from MC fit:

$$m^\kappa e^{\alpha m + \beta m^2}$$

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

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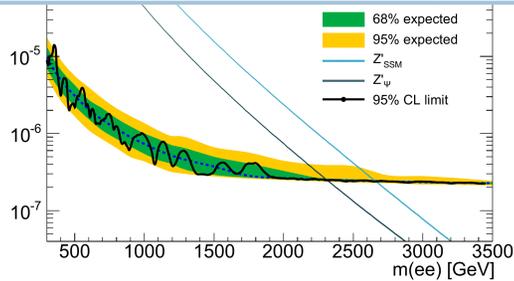
	Dielectron (barrel+barrel)		Dielectron (barrel+endcap)		Dimuon	
$m(\ell^+\ell^-)$	120 – 200	> 200	120 – 200	> 200	120 – 200	> 200
Data	41953	8947	28523	7995	78100	20000
Total Bkg.	42700 ± 1900	8900 ± 400	28600 ± 1400	7800 ± 400	78400 ± 3500	20100 ± 800
Z/γ^*	37800 ± 1900	7000 ± 400	25200 ± 1300	5600 ± 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

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

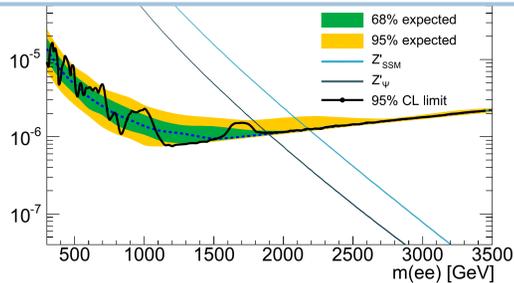
$$R_\sigma = \frac{\sigma(pp \rightarrow Z' + X \rightarrow \ell\ell + X)}{\sigma(pp \rightarrow Z + X \rightarrow \ell\ell + X)}$$

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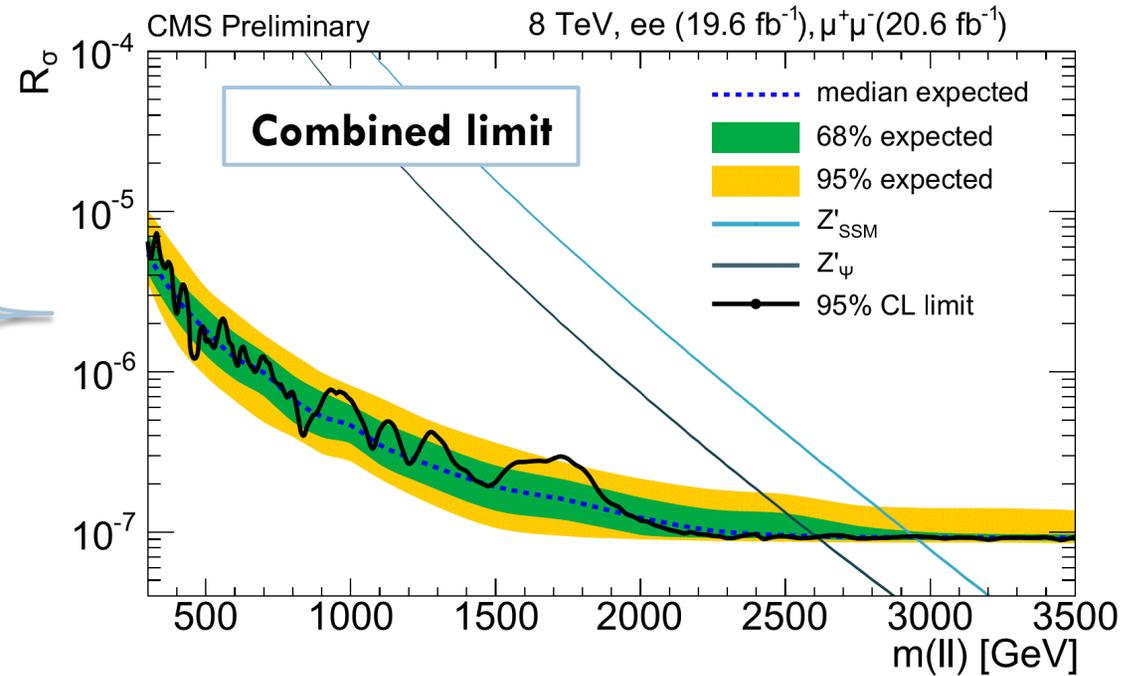
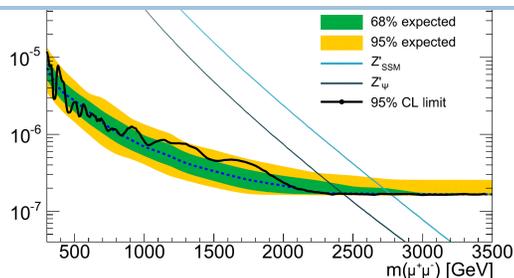
Dielectron (barrel+barrel)



Dielectron (barrel+endcap)



Dimuon

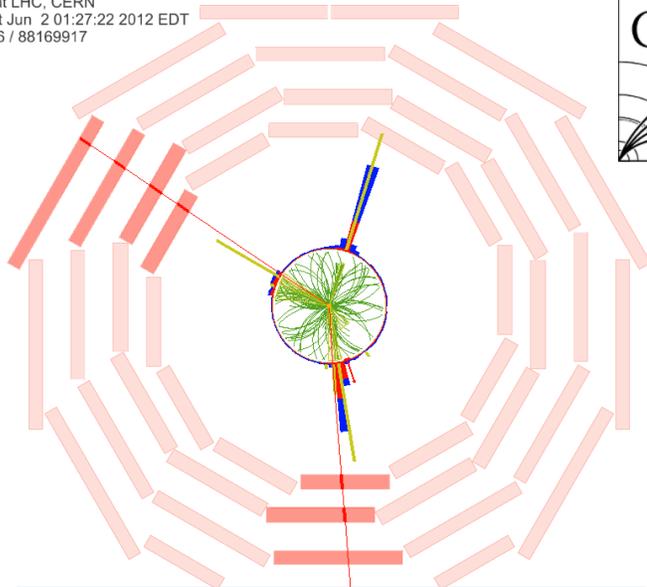
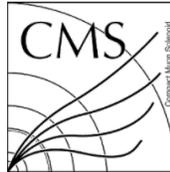


Channel	Obs. Z'_{SSM} limit	Obs. Z'_{Ψ} limit
ee (barrel-barrel)	2.65 TeV	2.31 TeV
ee (barrel-endcap)	2.18 TeV	1.90 TeV
$\mu\mu$	2.77 TeV	2.43 TeV
Combination	2.96 TeV	2.60 TeV

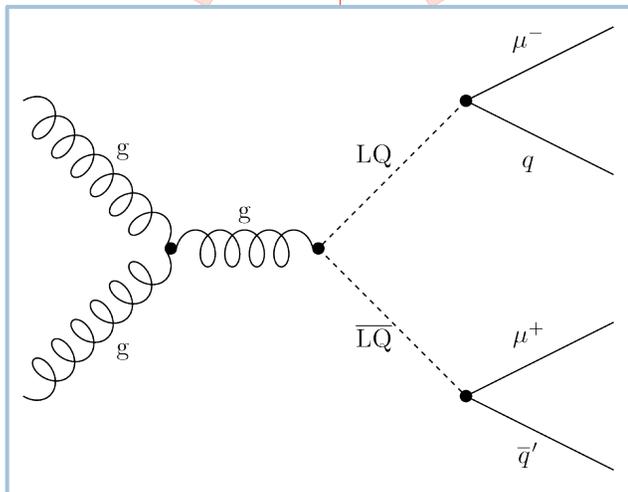
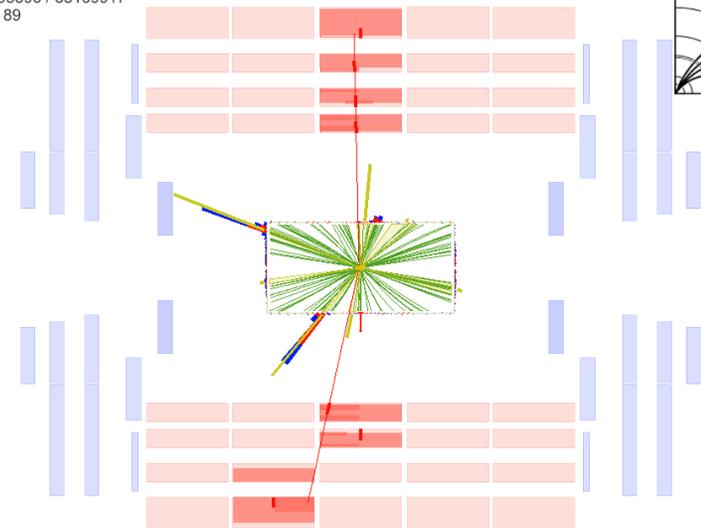
$$LQ_2 \overline{LQ_2} \rightarrow \mu\mu jj / \mu\nu jj$$

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CMS Experiment at LHC, CERN
 Data recorded: Sat Jun 2 01:27:22 2012 EDT
 Run/Event: 195396 / 88169917
 Lumi section: 89



CMS Experiment at LHC, CERN
 Data recorded: Sat Jun 2 01:27:22 2012 EDT
 Run/Event: 195396 / 88169917
 Lumi section: 89



- Search for a scalar boson carrying both baryon and lepton number and fractional charge
- Leptoquark searches are grouped into generations
- This search is for pair-production of **second** generation leptoquarks: decay to **muons + quarks**
- $\beta = BR(LQ \rightarrow l^\pm q)$ is treated as a free parameter (like LQ mass), leading to two separate analyses:
 - $\beta = 1.0$: $\mu\mu jj$ final state
 - $\beta = 0.5$: $\mu\nu jj$ final state

$LQ_2 \overline{LQ_2} \rightarrow \mu\mu jj / \mu\nu jj$

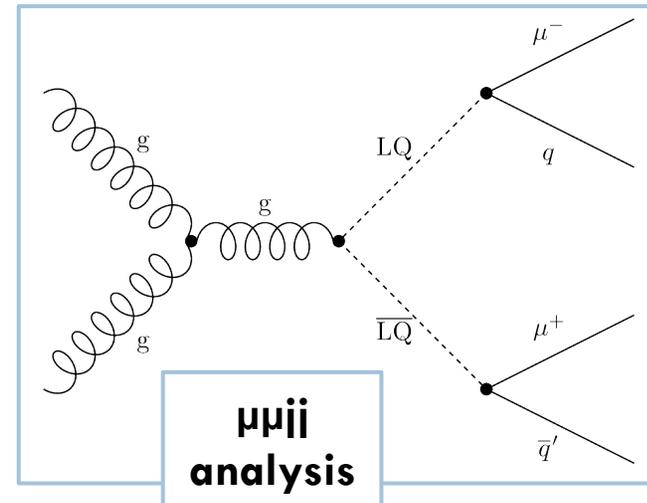
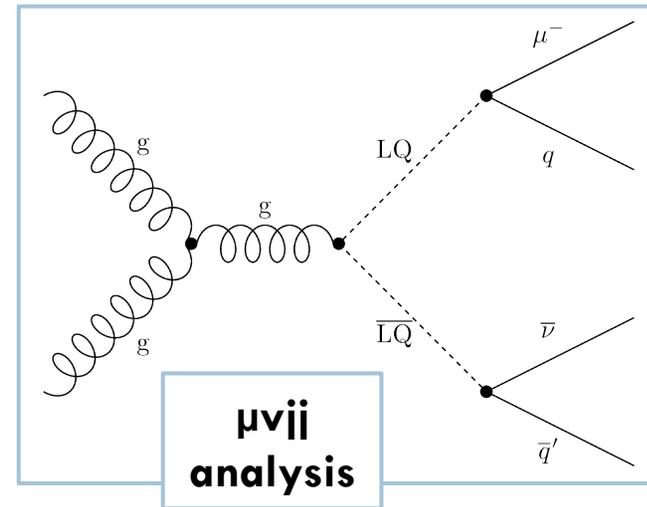
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Event preselection:

- At least 2 jets
 - ▣ 1st jet $p_T > 125$ GeV
 - ▣ 2nd jet $p_T > 45$ GeV
- electron veto
- $\mu\nu jj$ analysis:
 - ▣ $S_T > 300$

$$S_T \equiv p_T(\mu_1) + E_T^{\text{miss}} + p_T(j_1) + p_T(j_2)$$
 - ▣ Exactly 1 isolated muon
 - ▣ $m_T(\text{MET}, 1^{\text{st}} \text{ muon}) > 50$ GeV
 - ▣ $\text{MET} > 55$ GeV
 - ▣ $\Delta\phi(\text{MET}, 1^{\text{st}} \text{ jet}) > 0.5$
 - ▣ $\Delta\phi(\text{MET}, 1^{\text{st}} \text{ muon}) > 0.5$
- $\mu\mu jj$ analysis:
 - ▣ $S_T > 300$

$$S_T \equiv p_T(\mu_1) + p_T(\mu_2) + p_T(j_1) + p_T(j_2)$$
 - ▣ Exactly 2 isolated muons
 - ▣ $m(\mu\mu) > 50$ GeV



$$LQ_2 \overline{LQ_2} \rightarrow \mu\mu jj / \mu\nu jj$$

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□ Background modeling

□ $\mu\mu jj$ analysis:

- Drell-Yan + jets
 - Shape from MadGraph
 - Rescaled within Z mass peak
- top pair production:
 - Modeled using electron + muon events **from data**

□ $\mu\nu jj$ analysis

- W+jets & ttbar
 - Shape from MadGraph
 - Rescaled within W transverse mass peak

□ Final selection

□ Cut variables:

- $\mu\nu jj$: $S_T, m_T, m_{\min}(\mu j)$
- $\mu\mu jj$: $S_T, m(\mu\mu), m(\mu j)$

□ Cuts optimized using $S/\sqrt{S+B}$

for each mass hypothesis

□ Cuts optimized for mass hypotheses from $M(LQ) = 300$ to 1200

□ Final selection results **below**

**$\mu\nu jj$
analysis**

M_{LQ}	Signal	W+jets	$t\bar{t}$	Other BG	All BG	Data
300	5032 ± 69	990 ± 21	1741 ± 14	362 ± 11	$3093 \pm 27 \pm 383$ (syst)	3276
500	257.6 ± 2.7	59.3 ± 5.0	53.9 ± 2.4	23.6 ± 2.1	$136.8 \pm 5.9 \pm 15$ (syst)	158
750	14.63 ± 0.15	5.3 ± 1.5	2.87 ± 0.55	$1.87^{+0.76}_{-0.42}$	$10^{+1.7}_{-1.6} \pm 2.3$ (syst)	16

**$\mu\mu jj$
analysis**

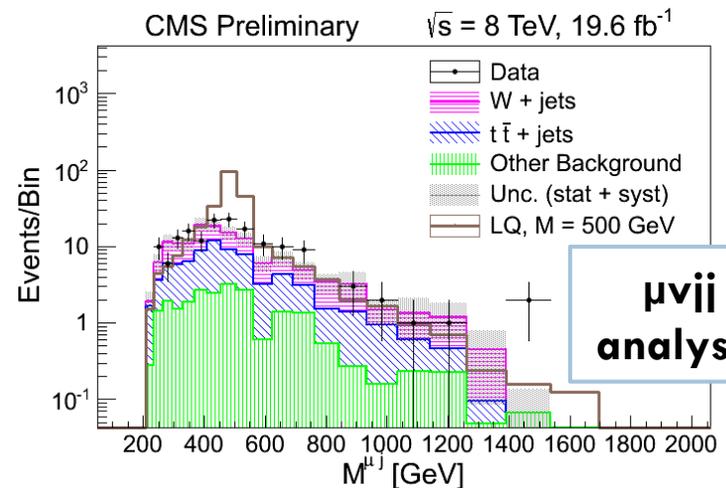
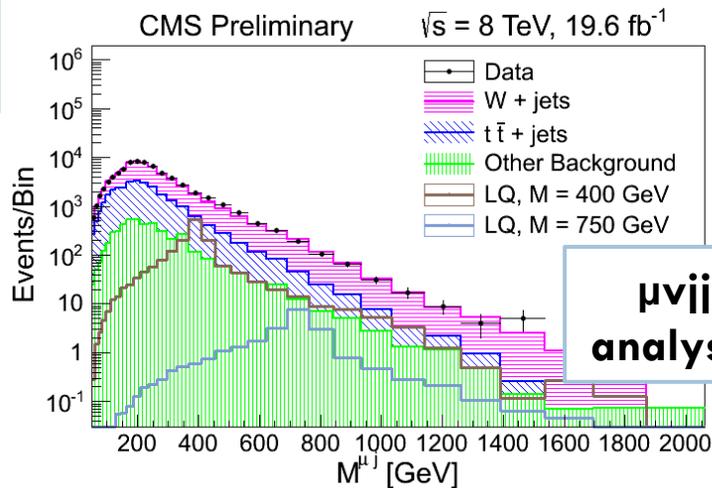
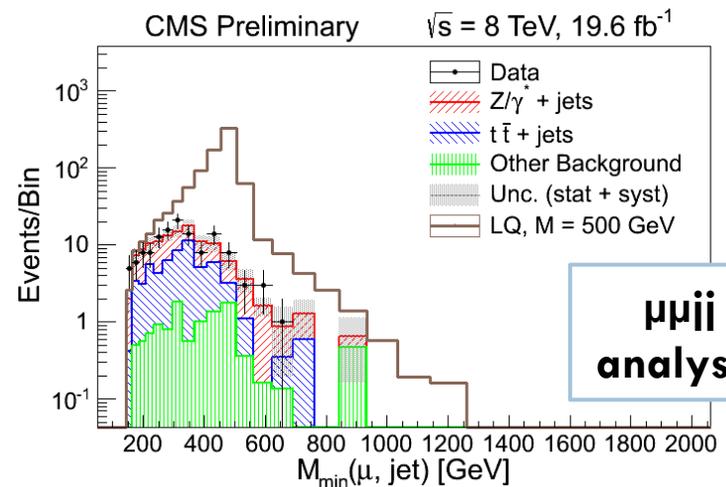
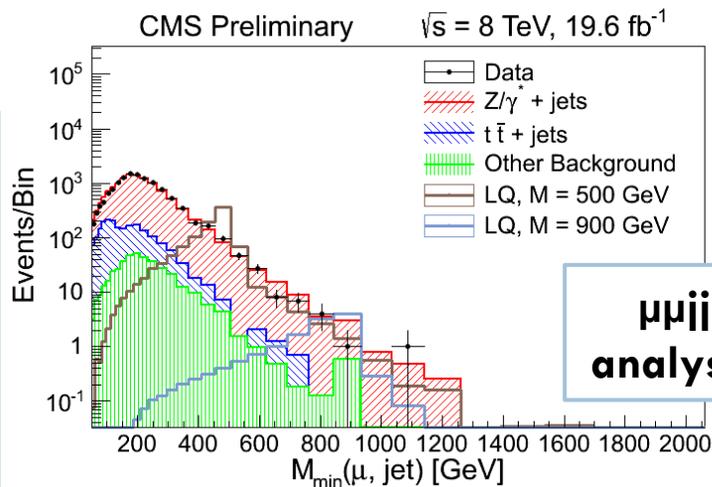
M_{LQ}	Signal	Z+jets	$t\bar{t}$	Other BG	All BG	Data
300	14980 ± 110	716.2 ± 8.4	612 ± 18	86.7 ± 5.0	$1415 \pm 20 \pm 45$ (syst)	1461
500	859.4 ± 5.2	61.9 ± 2.4	48.5 ± 4.8	11.2 ± 1.9	$121.6 \pm 5.7 \pm 4.8$ (syst)	128
1000	3.845 ± 0.025	0.383 ± 0.171	$0.0^{+0.59}_{-0.0}$	$0.0^{+0.65}_{-0.0}$	$0.383^{+0.894}_{-0.171} \pm 0.031$ (syst)	0

$LQ_2 \overline{LQ_2} \rightarrow \mu\mu jj / \mu\nu jj$ Results

Preselection

Final selection: $M(LQ) = 500$ GeV

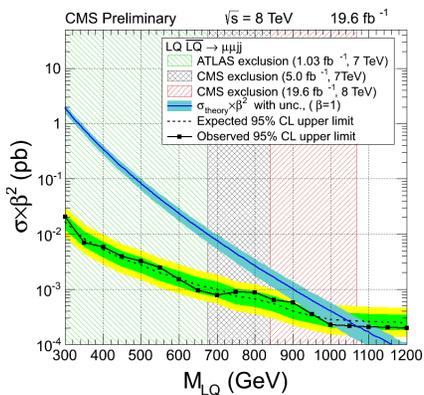
$M(\mu j)$ distributions



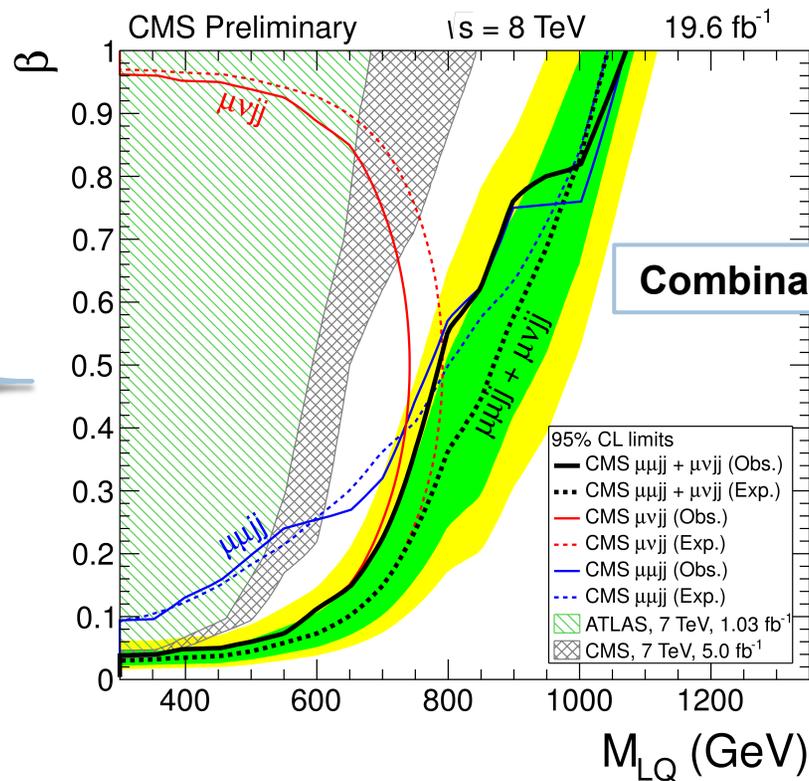
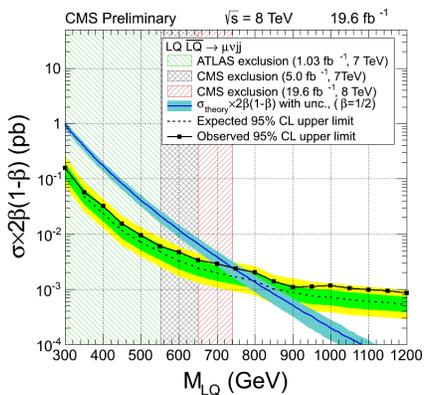
$LQ_2\overline{LQ_2} \rightarrow \mu\mu jj / \mu\nu jj$ Limits

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$\mu\mu jj$ ($\beta=1$)
analysis



$\mu\nu jj$ ($\beta=0.5$)
analysis



Combination

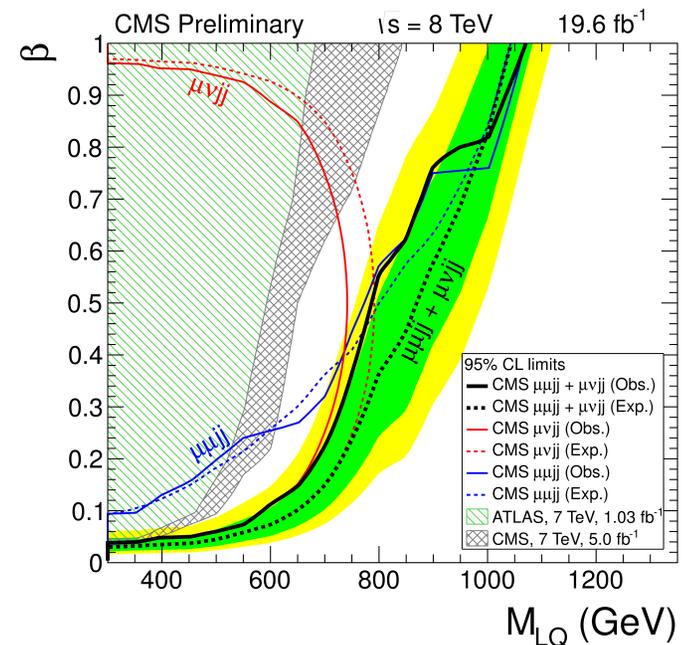
Channel (β)	Obs. Limit
$\mu\mu jj$ (1.0)	1070 GeV
$\mu\nu jj$ (0.5)	740 GeV
Combination (0.5)	785 GeV

Conclusion

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- CMS is exploring a variety of final states for heavy resonances at the energy frontier
- Many of these searches are setting multi-TeV limits (shown at right)
- Generally good agreement between data and SM background predictions
 - ▣ CMS is in a very good position to continue to explore the high energy frontier
 - ▣ CMS has the means to make discoveries if new physics exists at the LHC energy scale
 - ▣ So far, no discoveries
- More information is available, here:
 - ▣ <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>

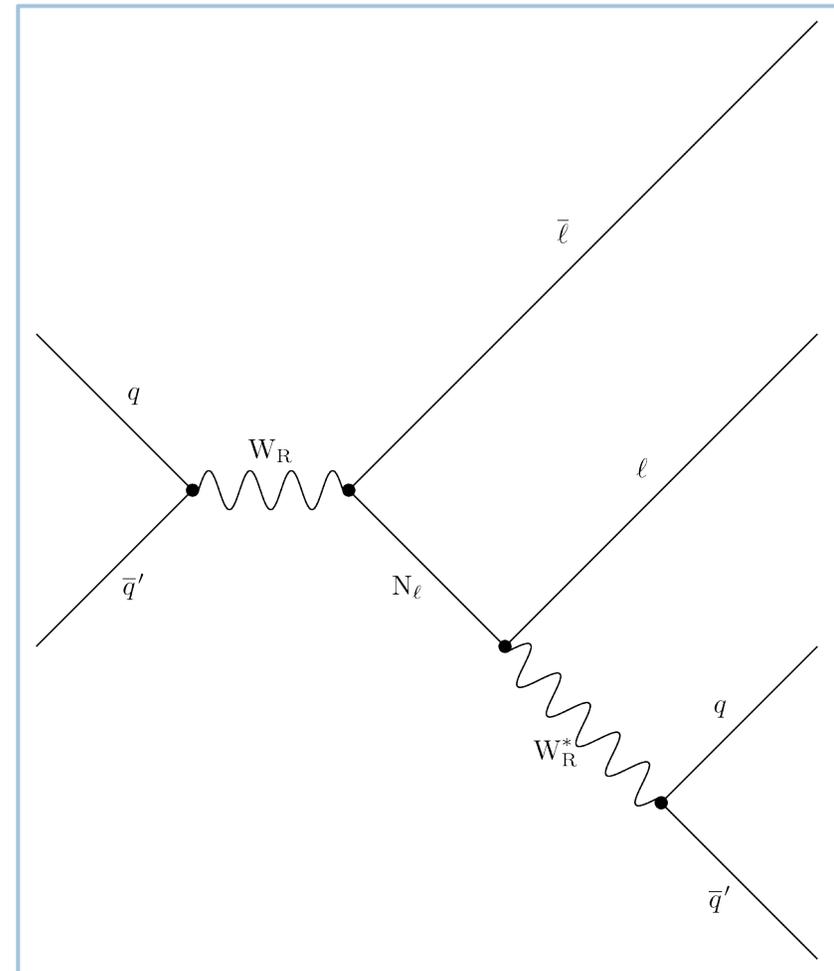
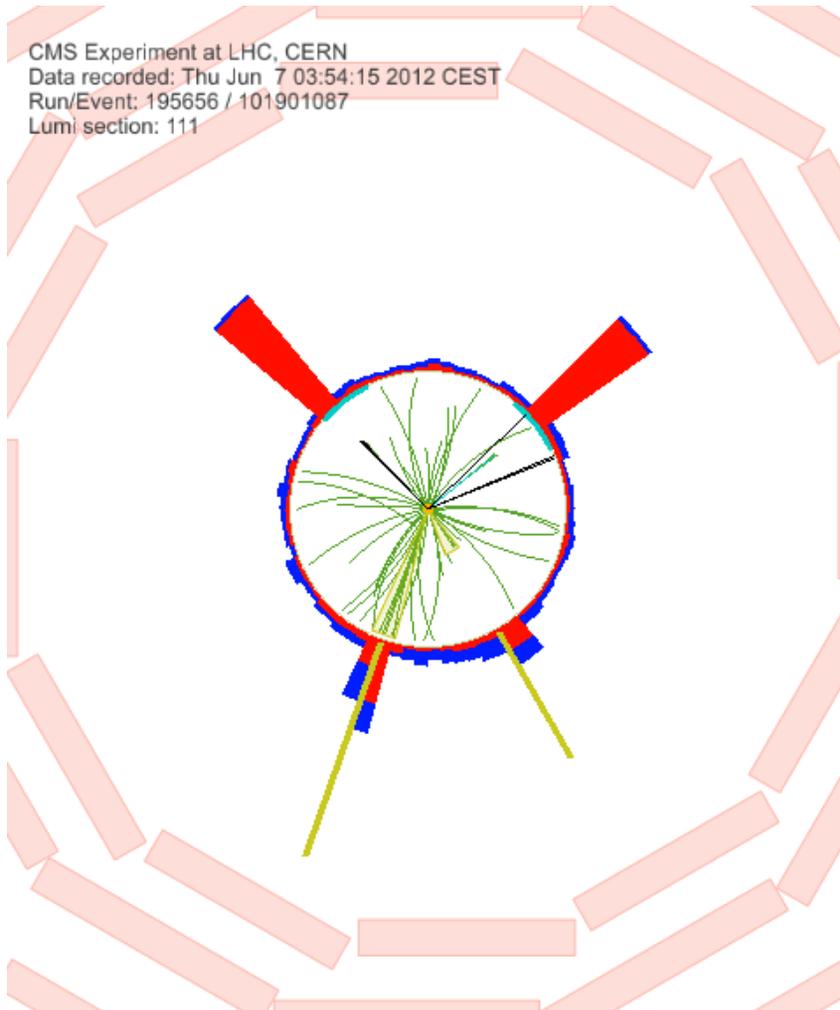
Model		Observed Limit [TeV]
Z'	SSM	2.96
	GUT	2.60
W'	SSM	3.55
	SSMO	3.6
	SSMS	3.1
W_{KK}^2	$\mu = 0.05$ TeV	1.7
	$\mu = 10$ TeV	3.7
W' HNC CI	e	13
	μ	10.9



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Backup: W_R

$$W_R \rightarrow \ell\ell jj$$



$W_R \rightarrow \ell\ell jj$

Event selection

- At least 2 isolated leptons (electron, muon)
 - 1st lepton $p_T > 60$ GeV
 - 2nd lepton $p_T > 40$ GeV
- At least 2 jets
 - $p_T > 40$ GeV
- $m(\ell\ell) > 200$ GeV
- $m(\ell\ell jj) > 600$ GeV

Background modeling

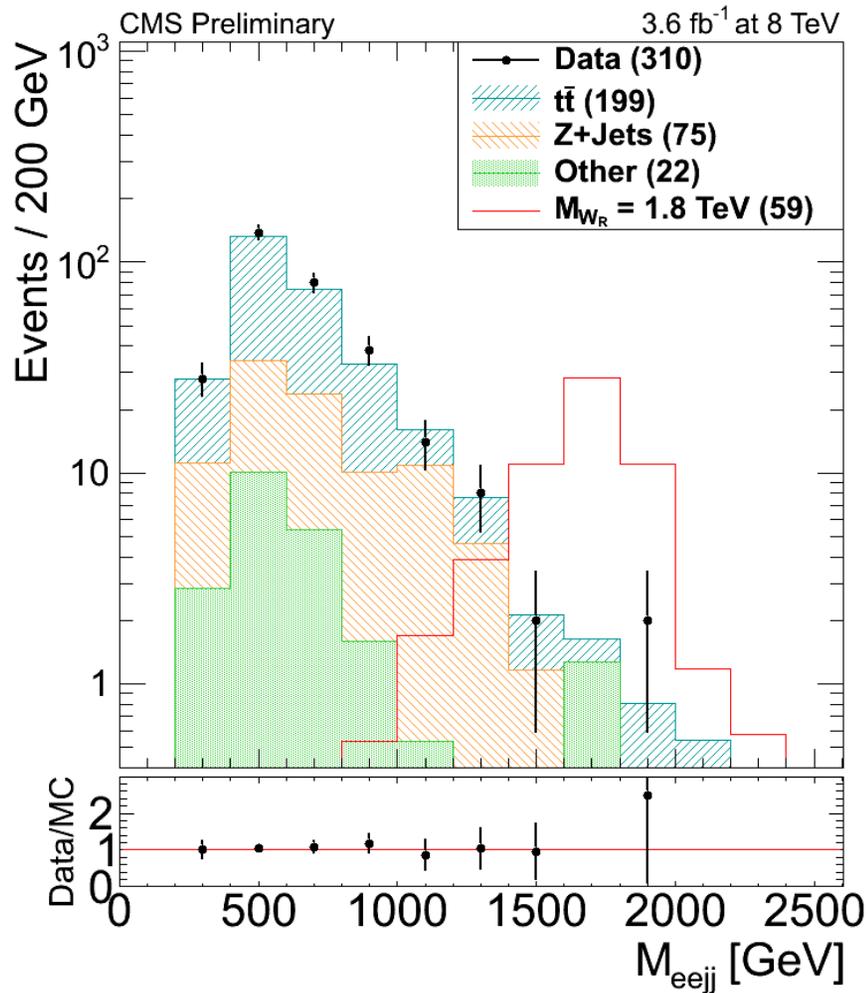
- DY+jets
 - Shape from MadGraph
 - Rescaled within Z mass peak
- top pair production:
 - Modeled using electron + muon events **from data**
- Other backgrounds
 - Modeled with MC

		Selection	Data	Signal	Total background	$t\bar{t}$	Z+jets	QCD	Other
eejj analysis	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	130	83	35	0.7	11
		Selection	Data	Signal	Total background	$t\bar{t}$	Z+jets	QCD	Other
$\mu\mu jj$ analysis	Two electrons, 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	135	83	43	2	7

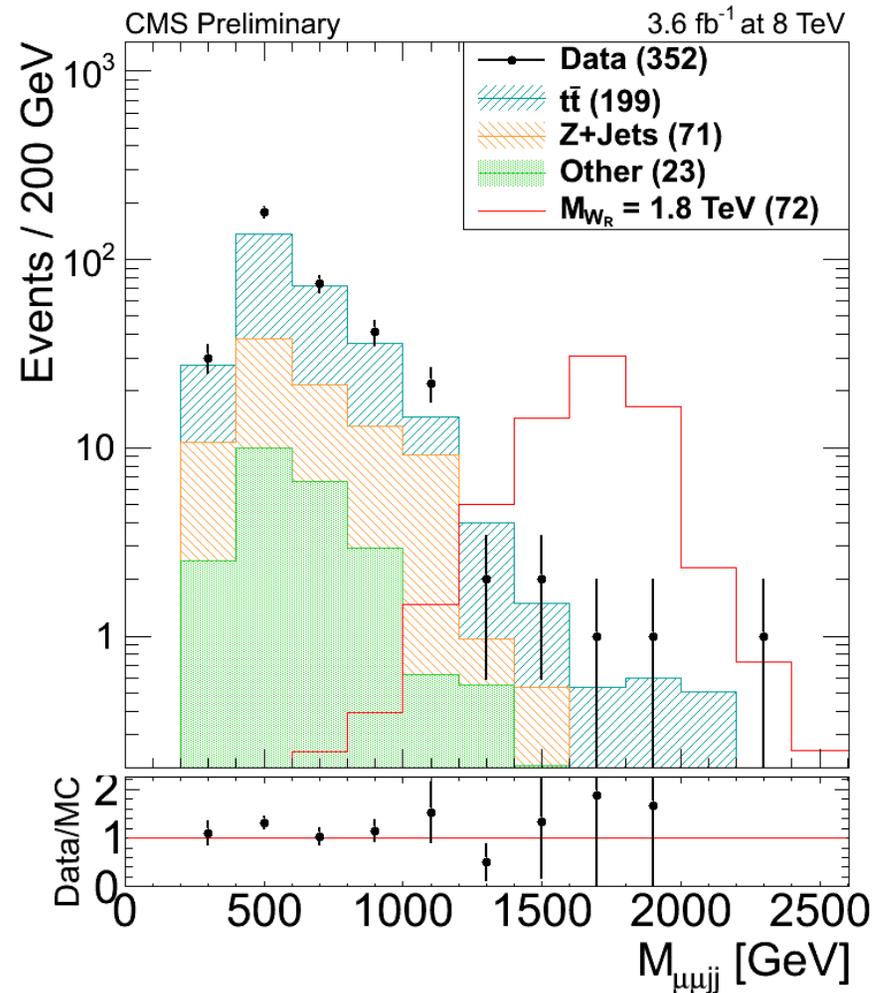
$W_R \rightarrow \ell\ell jj$ Results

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eejj analysis



$\mu\mu jj$ analysis

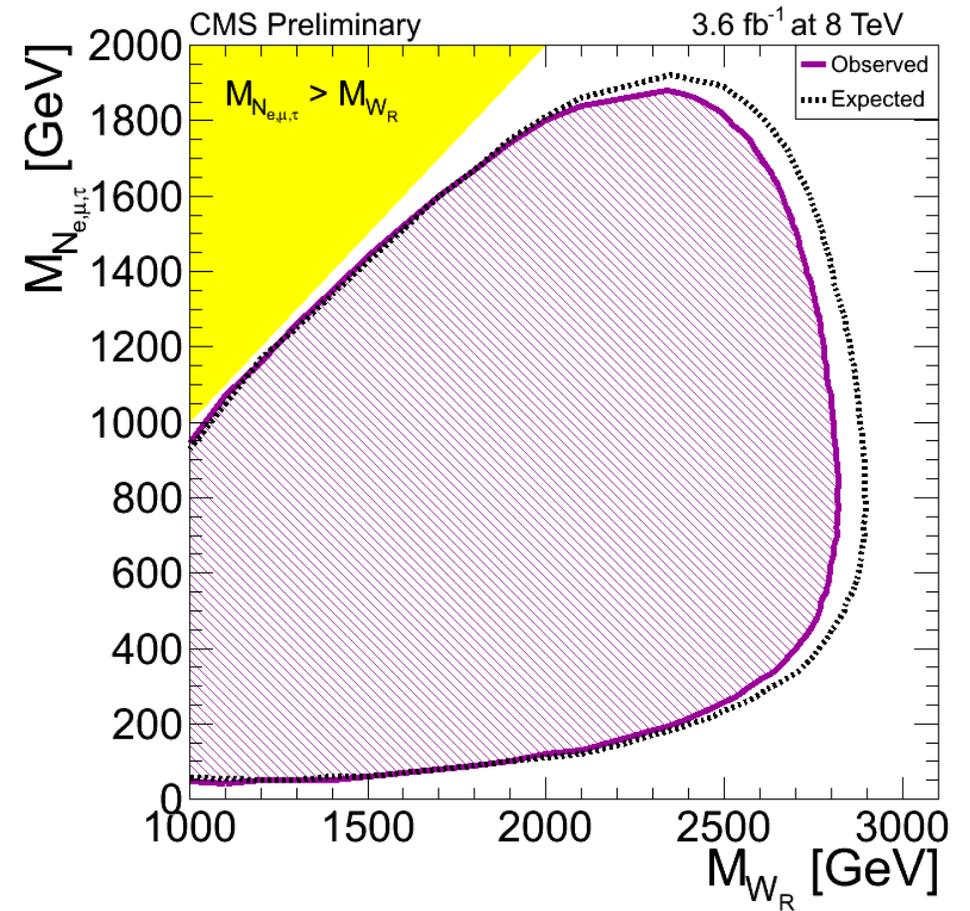
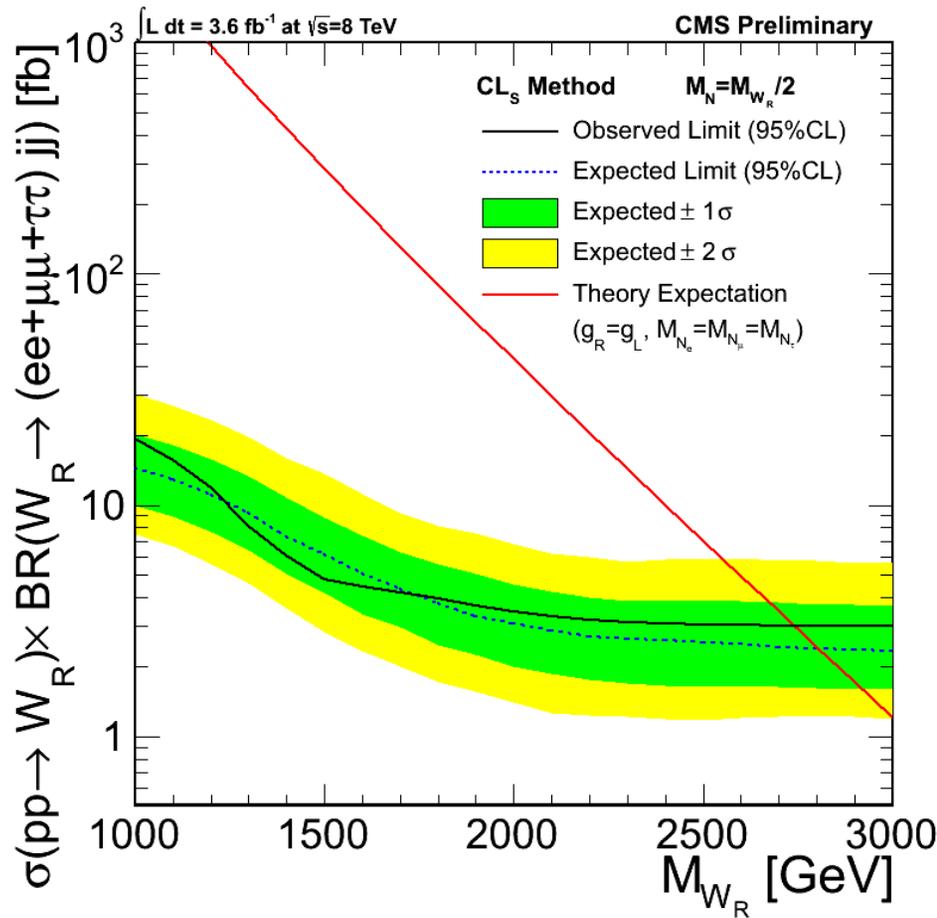


$W_R \rightarrow \ell\ell jj$ Limits

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Combined limit if $m(N) = 1/2 m(W_R)$

Exclusion in $m(N)$ vs $m(W_R)$ plane



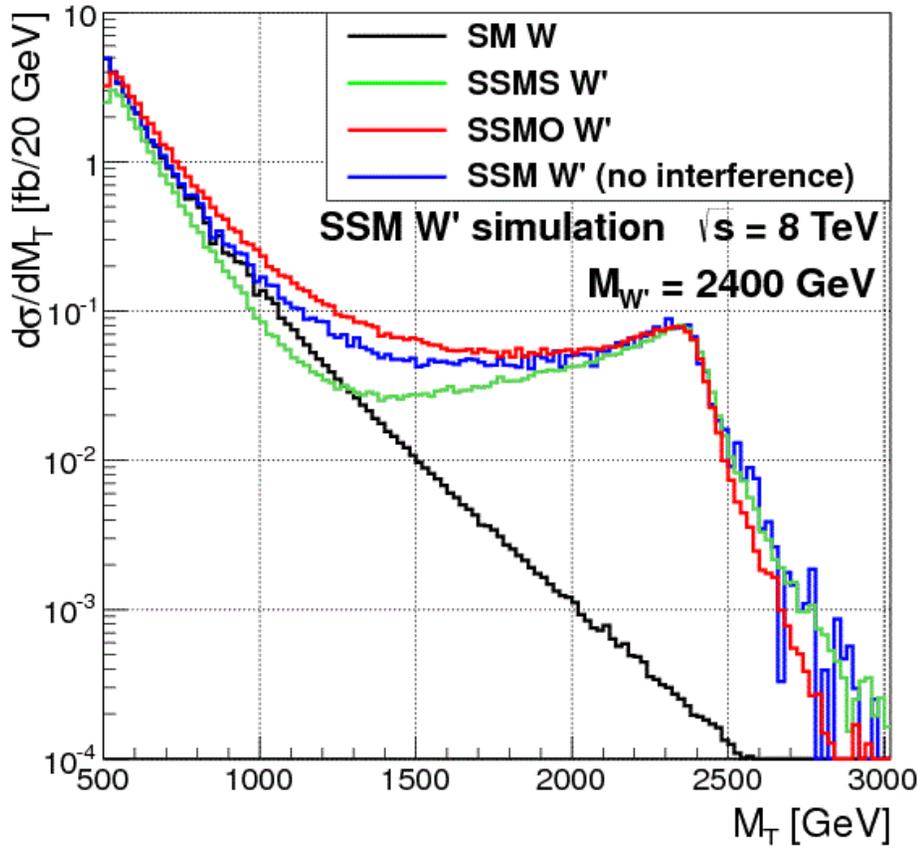
24

Backup: W'

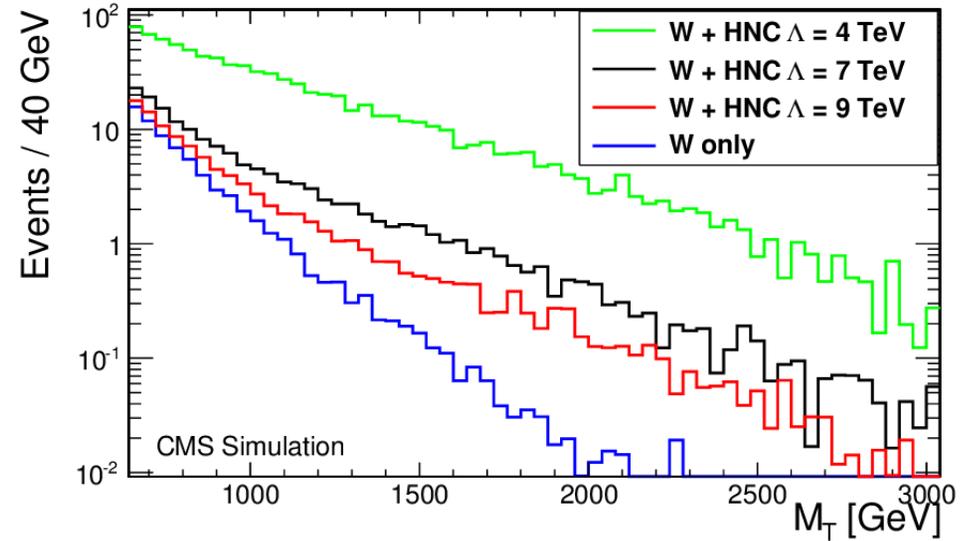
$W' \rightarrow \ell\nu$: signal m_T

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m_T distribution for different interference models



m_T distribution for HNC contact interaction model

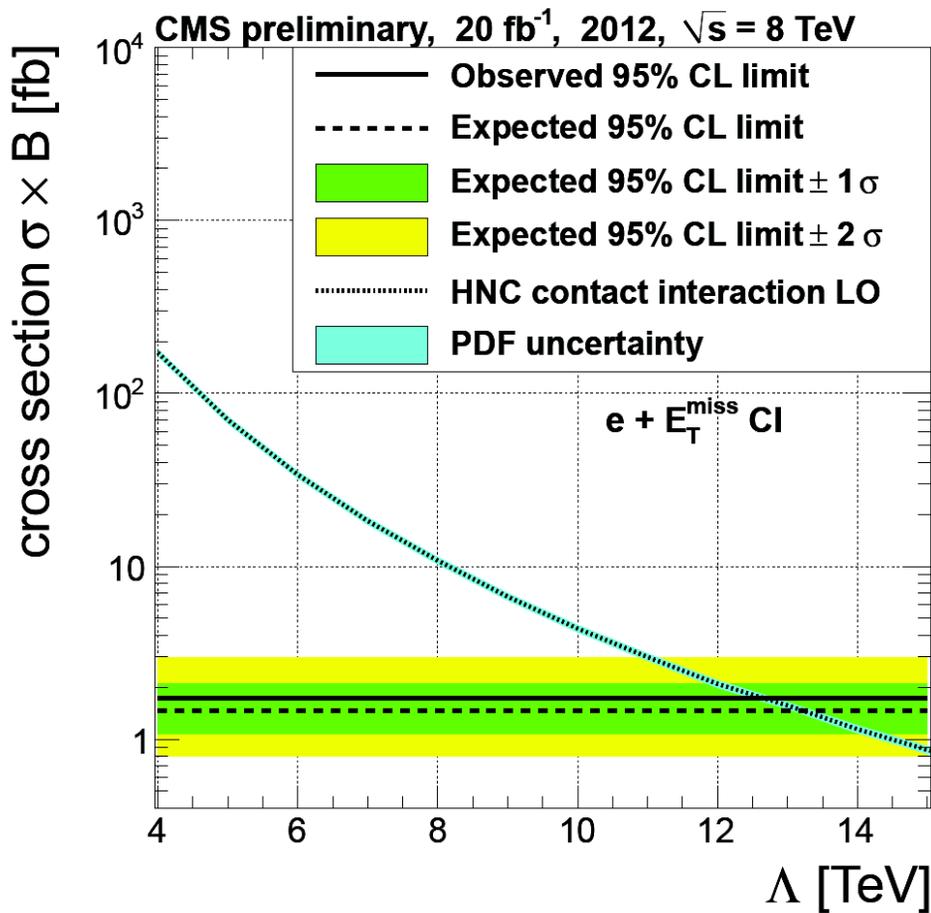


$W' \rightarrow \ell\nu$: HNC CI limits

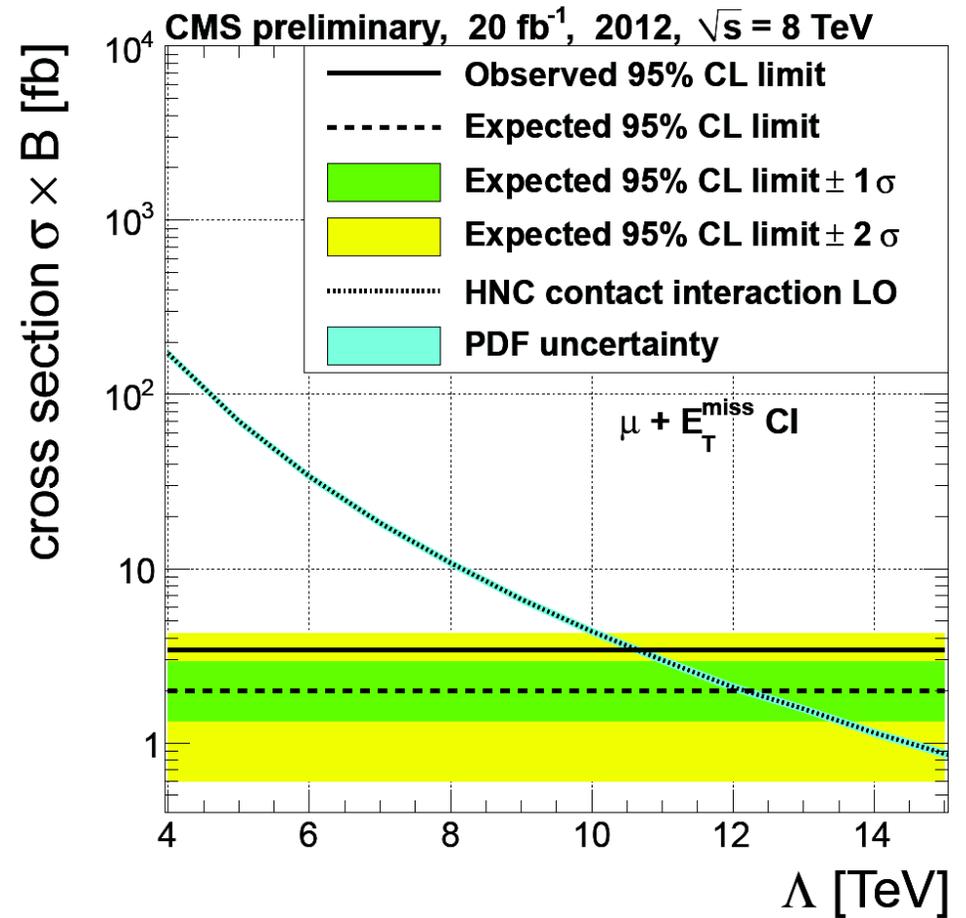
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First muon limits

HNC CI limit: electron channel

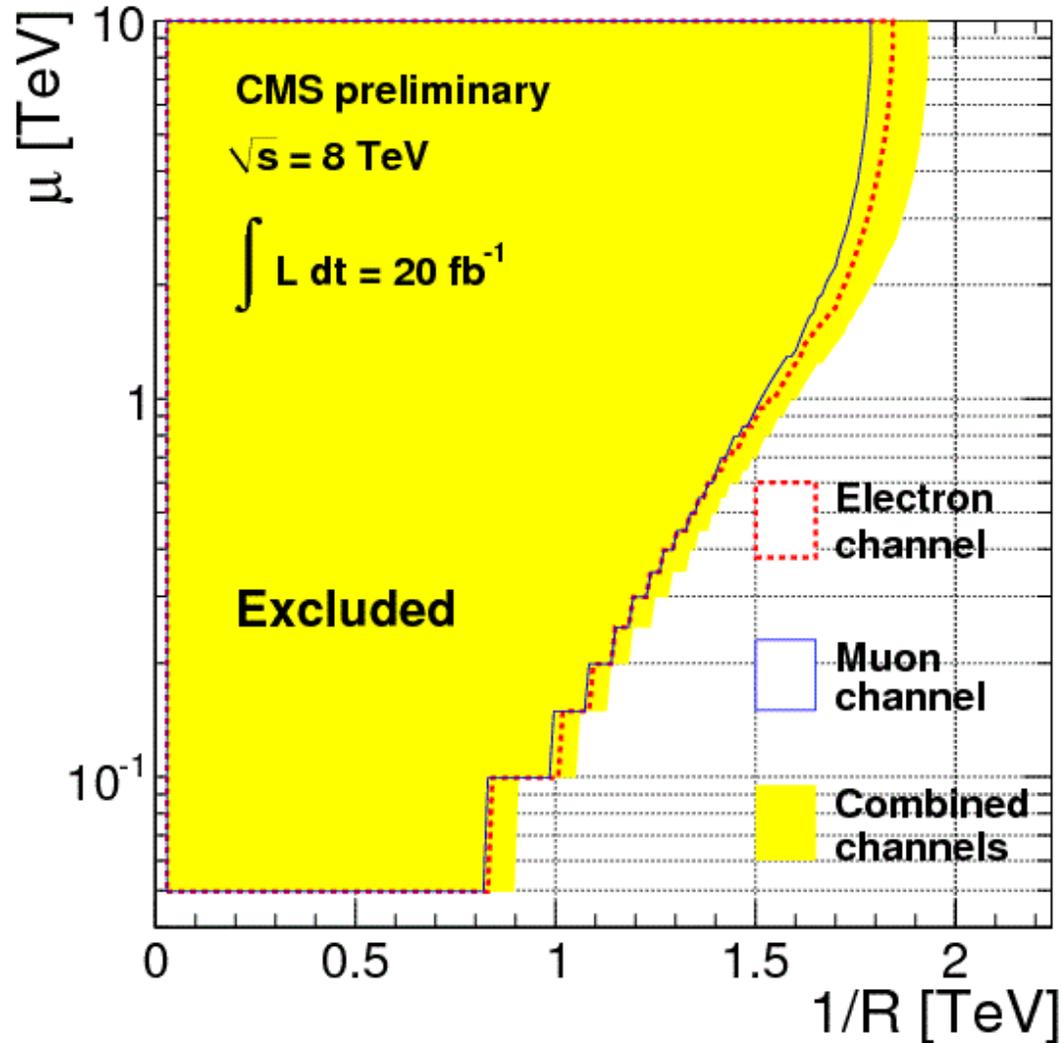


HNC CI limit: muon channel



$W' \rightarrow \ell\nu$: KK limit

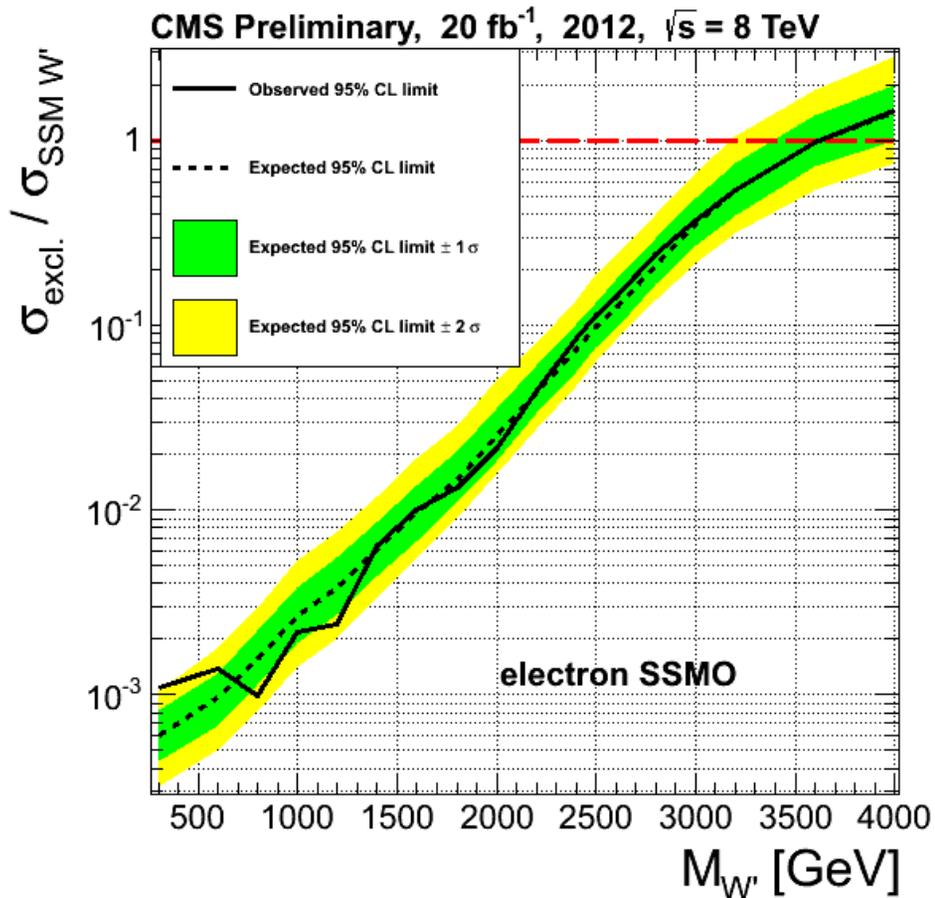
27



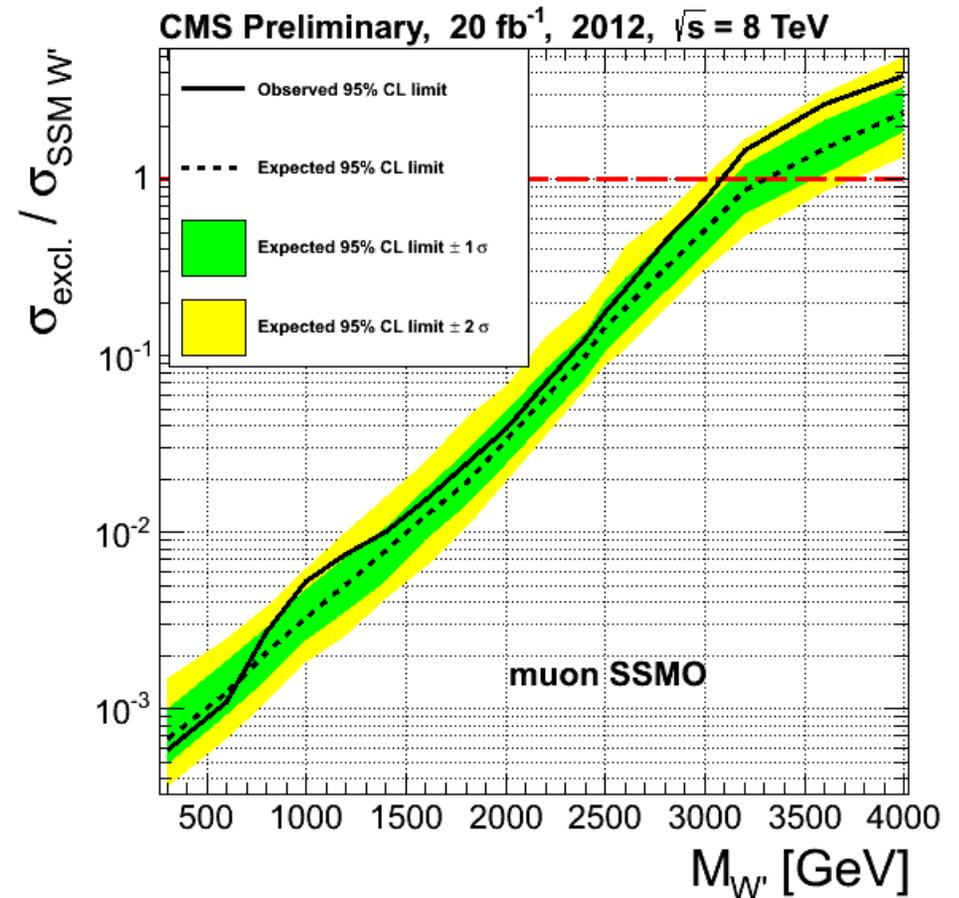
$W' \rightarrow \ell\nu$: SSMO separate limits

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SSMO limit: electron channel



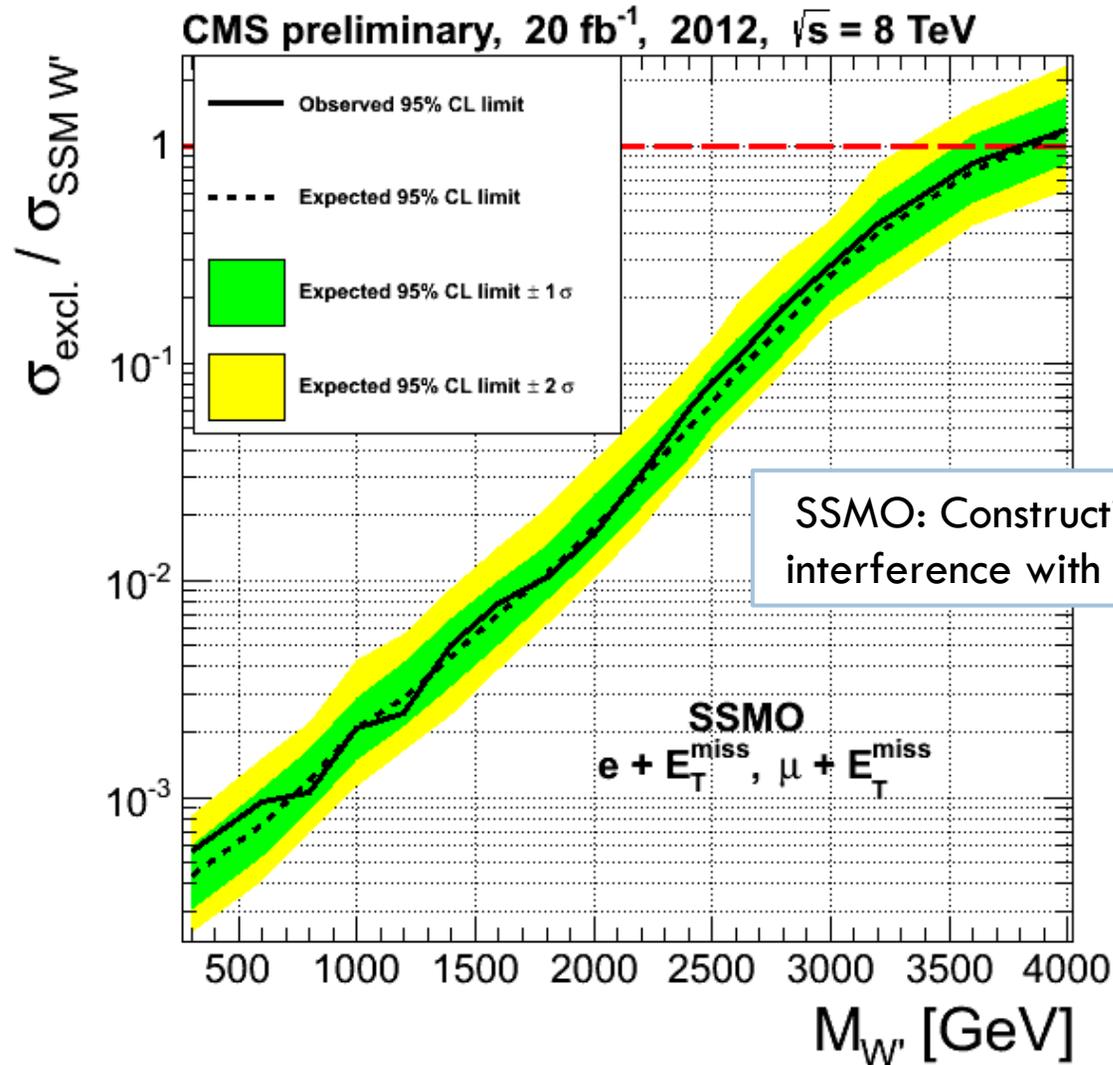
SSMO limit: muon channel



SSMO: Constructive interference with SM

$W' \rightarrow \ell\nu$: SSMO combined limit

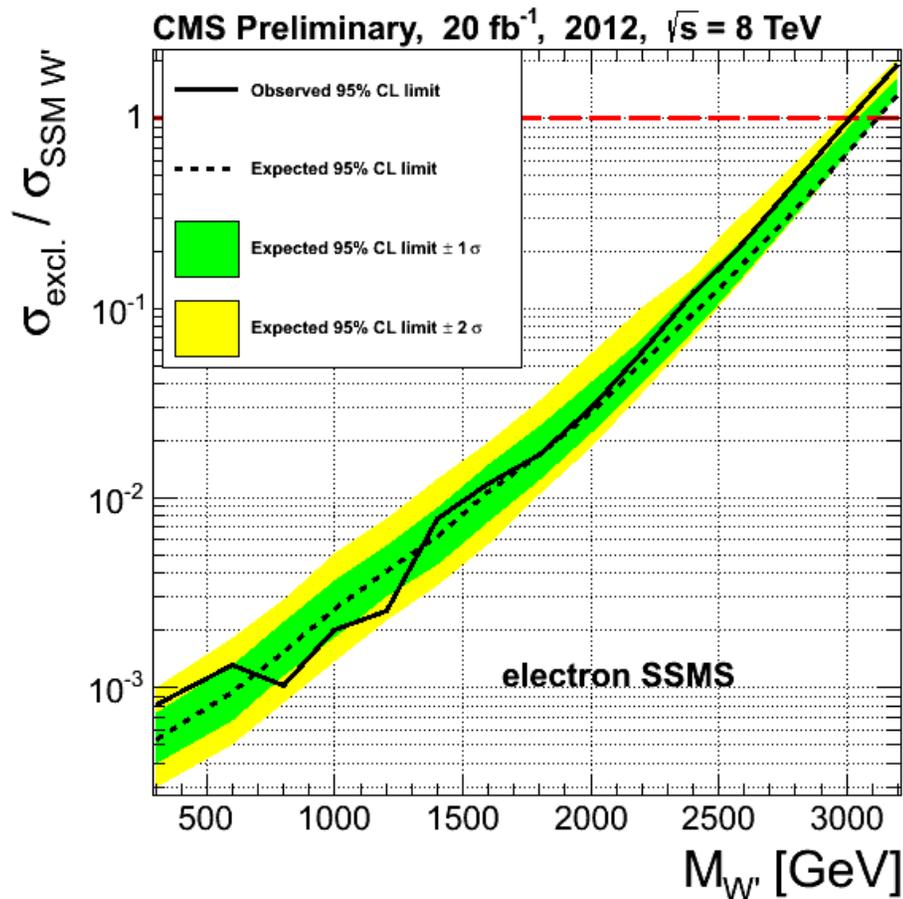
29



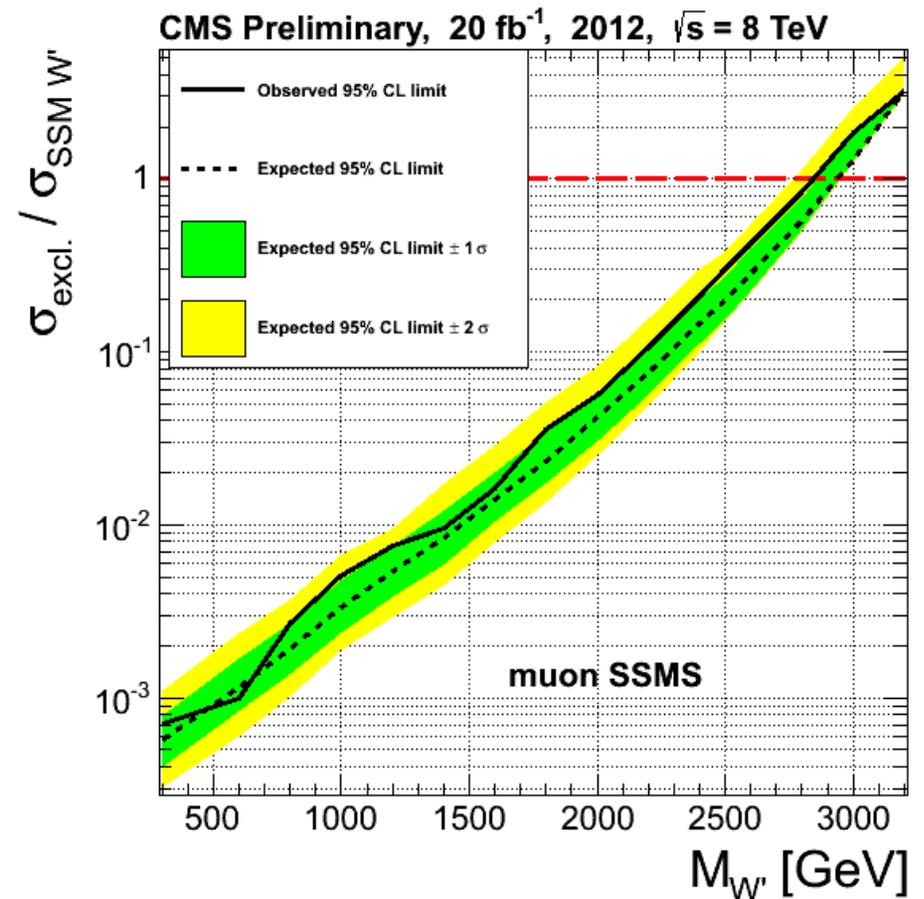
$W' \rightarrow \ell\nu$: SSMS separate limits

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SSMS limit: electron channel



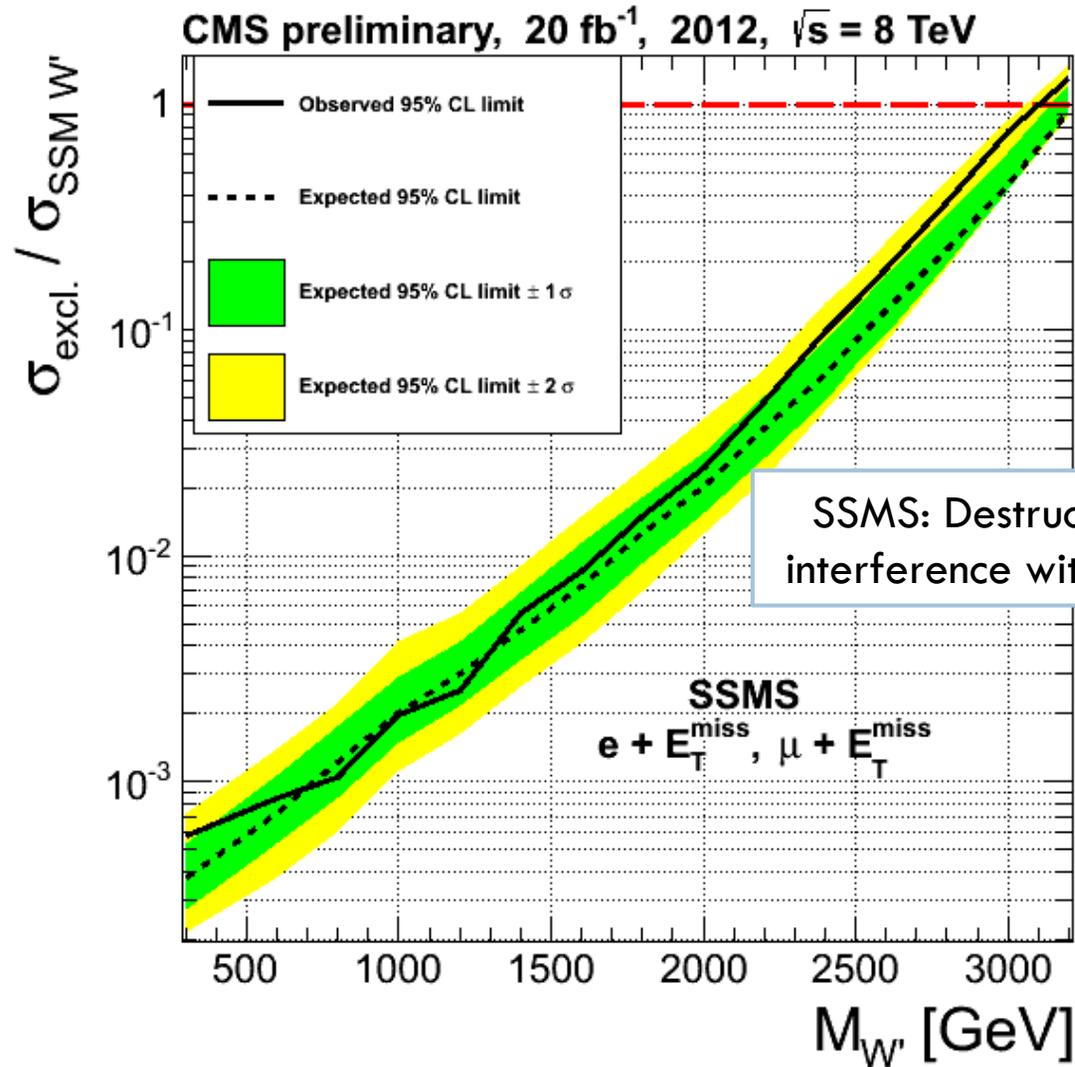
SSMS limit: muon channel



SSMS: Destructive interference with SM

$W' \rightarrow \ell\nu$: SSMS combined limit

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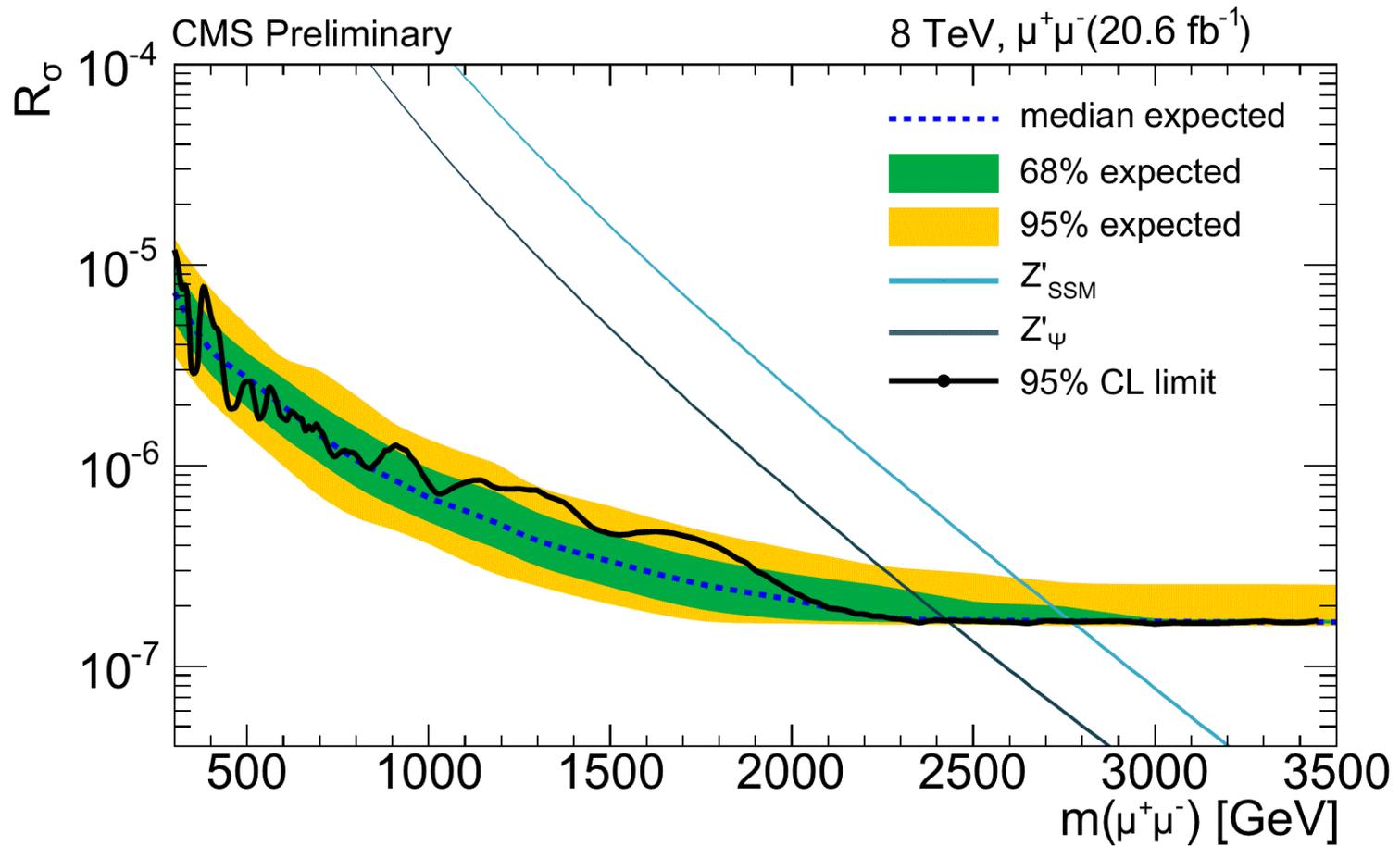


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Backup: Z'

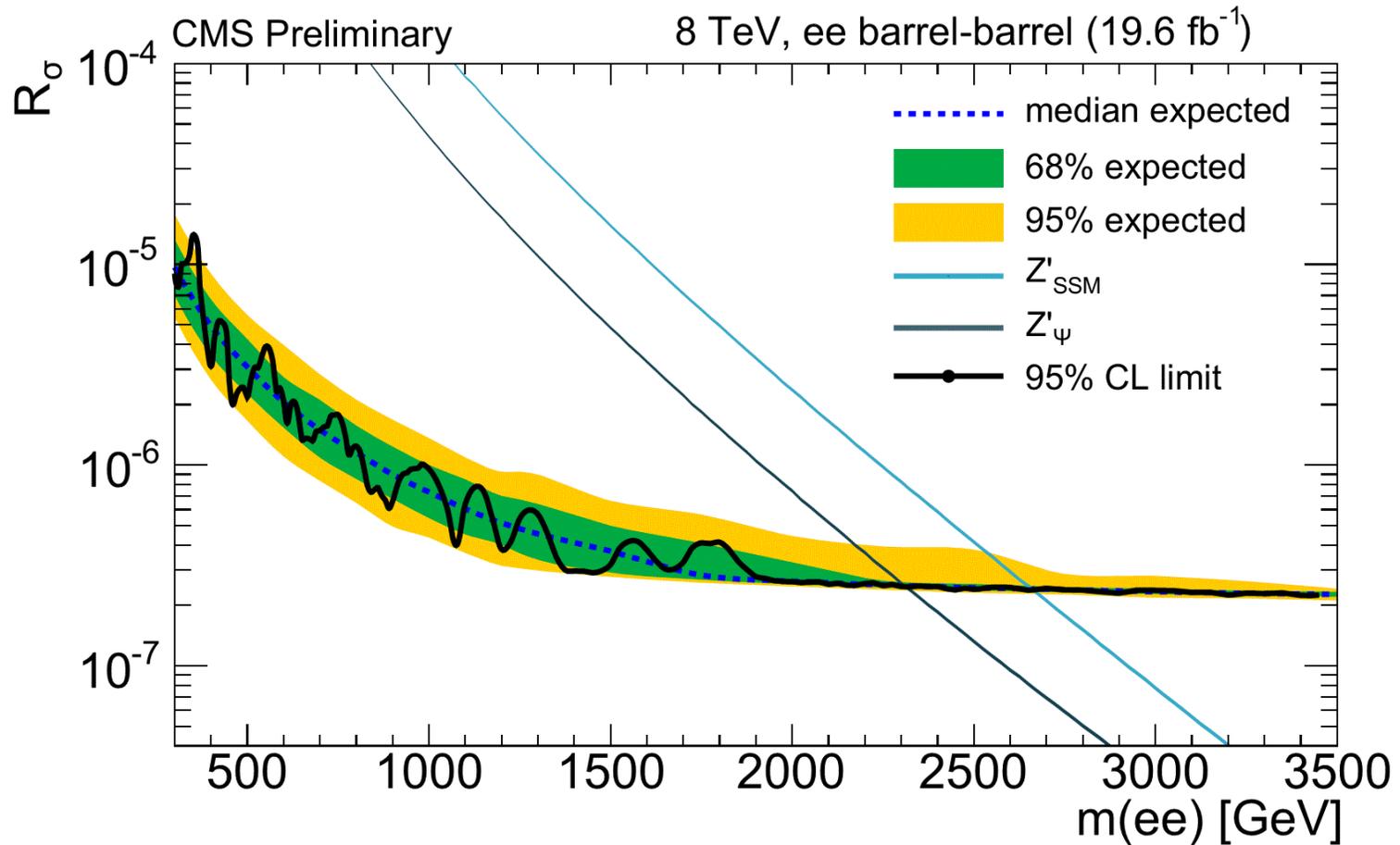
$Z' \rightarrow \ell^+ \ell^-$: muon limit

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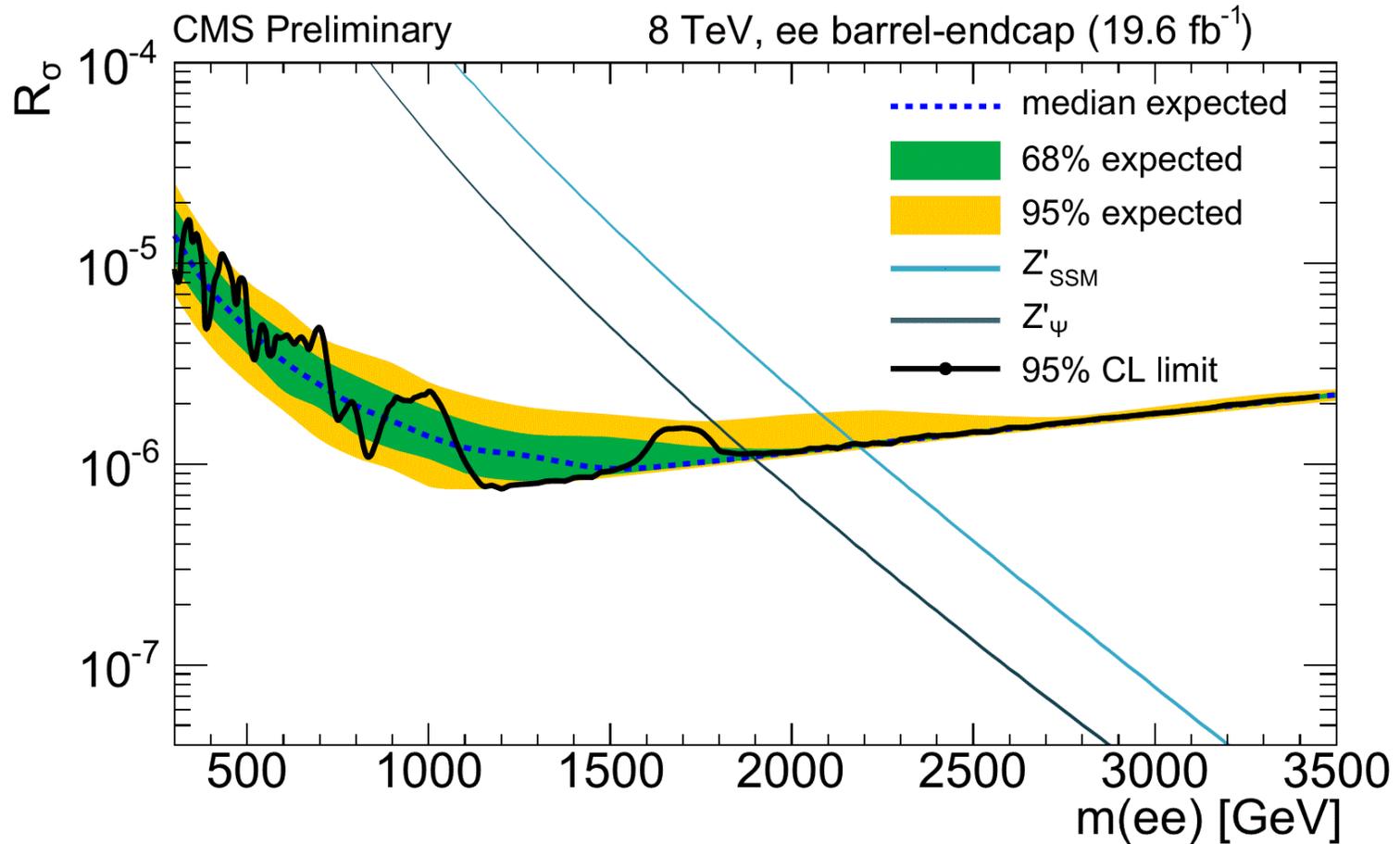
$Z' \rightarrow \ell^+ \ell^-$: e (EB-EB) limit

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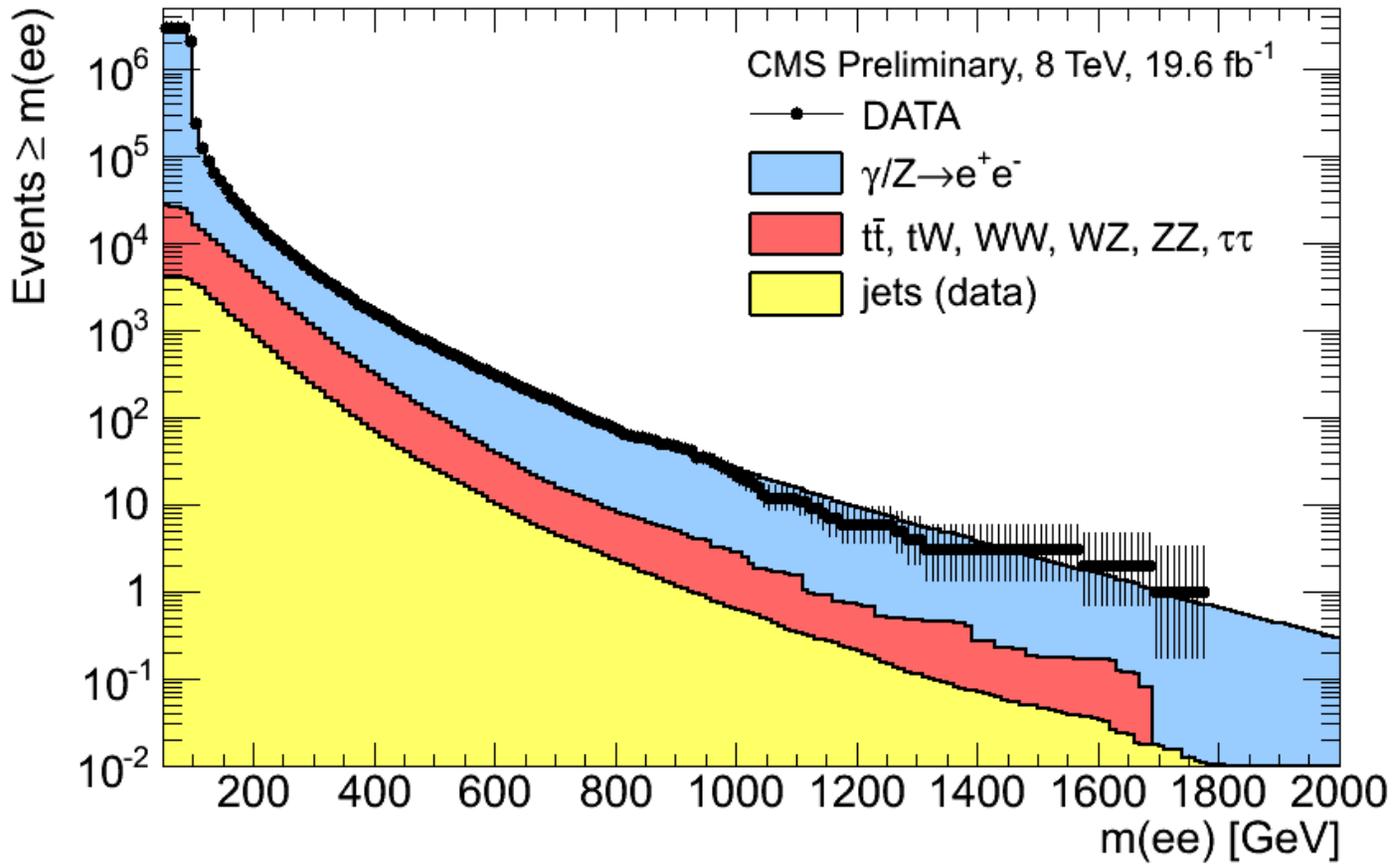
$Z' \rightarrow \ell^+ \ell^-$: e (EB-EE) limit

35



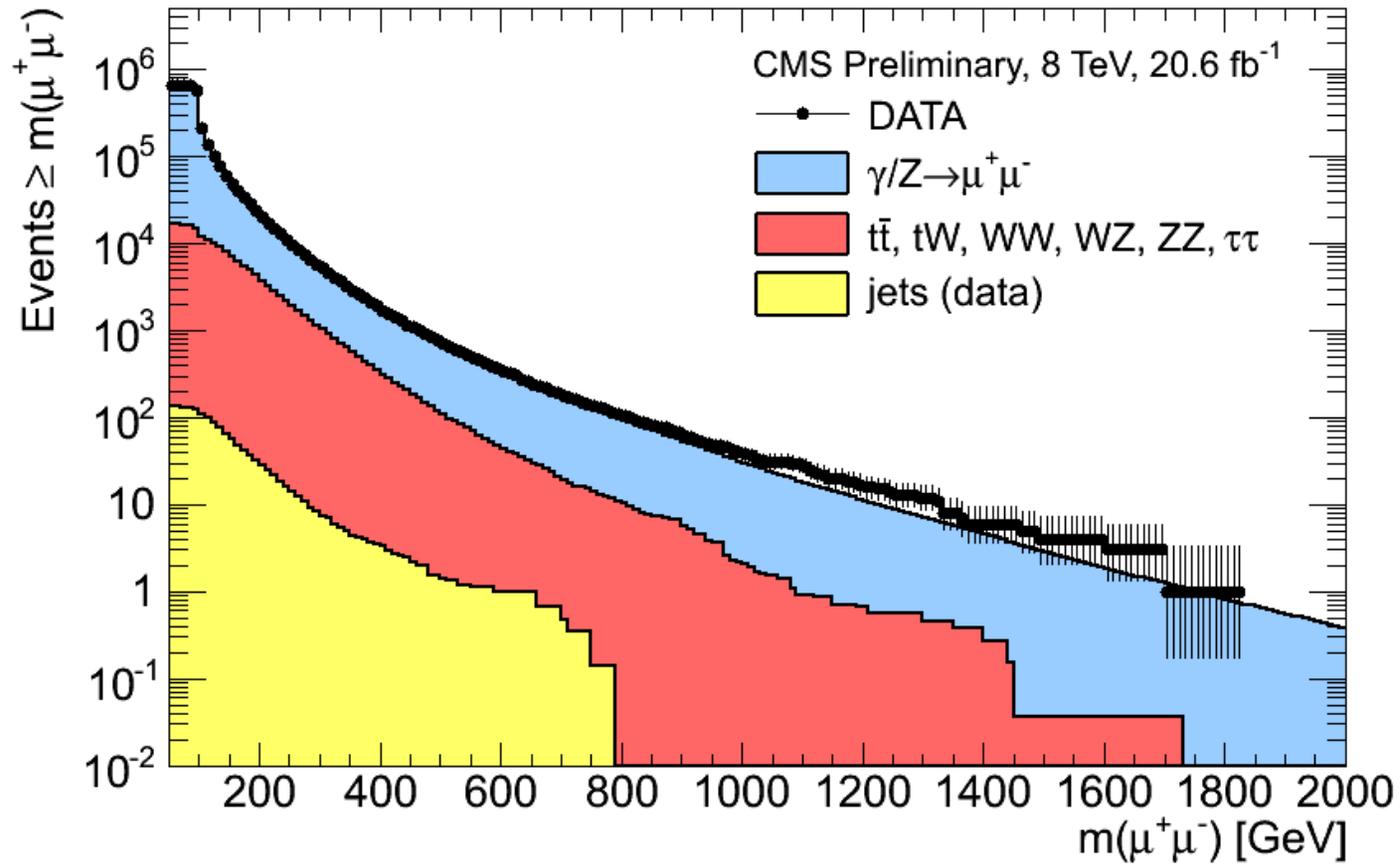
$Z' \rightarrow \ell^+ \ell^-$: e cum. plot

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$Z' \rightarrow \ell^+ \ell^-$: muon cum. plot

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Backup: LQ_2

$LQ_2 \overline{LQ_2} \rightarrow \mu\mu jj / \mu\nu jj$ Results

Preselection

Final selection: $M(LQ) = 500$ GeV

S_T distributions

