EXO-12-041 Approval

E. Berry[1], S. Cooper[2], P. Rumerio[2], F. Santanastasio[3]

[1]Brown University

[2]University of Alabama

[3]Rome

Tuesday, June 24, 2014

Analysis documentation

- CADI:
  EXO-12-041
- Q/A twiki:
  LQ1-EXO-12-041-QuestionsBeforePreapproval
- Targets:
  1. Approval for ICHEP
  2. Combined paper with EXO-12-042, approved using same ntuples and similar methods

EXO-12-041

Available on CMS information server | **CMS AN -2013/109**

The Compact Muon Solenoid Experiment

Analysis Note

The content of this note is intended for CMS internal use and distribution only

01 April 2013 (v8, 30 March 2014)

Search for Pair-production of First Generation Scalar Leptoquarks in pp Collisions at $\sqrt{s} = 8$ TeV

E. Berry
Brown University, Providence, RI, USA
S. Cooper
University of Alabama, Tuscaloosa, AL, USA
P. Rumerio
University of Alabama, Tuscaloosa, AL, USA
F. Santanastasio
CERN, European Organization for Nuclear Research, Geneva, Switzerland

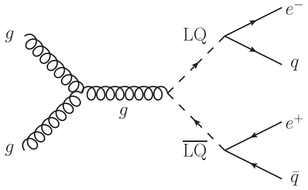
Abstract

A search for pair-production of first generation scalar leptoquarks is performed in the final states containing two electrons and at least two jets or an electron, a neutrino, and at least two jets using proton-proton collision data at $\sqrt{s} = 8$ TeV. The data were collected by the CMS detector at the LHC, corresponding to an integrated luminosity of 19.6 fb^{-1}.

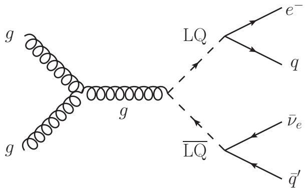
Theory

- Search for a scalar boson carrying both baryon and lepton number and fractional charge
- Leptoquark searches are traditionally grouped into generations
- This search is for pair-production of first generation leptoquarks
- $\beta = \mathrm{BR}(\mathrm{LQ} \rightarrow e^{\pm} q)$ is treated as a free parameter, leading to two separate analyses:
  - *eejj* : opt. for $\beta = 1.0$
  - *eνjj* : opt for $\beta = 0.5$

eejj final state



eνjj final state



Analysis strategy

- Define SM-dominated preselection for each analysis
- Optimize final selection using $S/\sqrt{S+B}$
  - Optimize a different selection for each LQ mass
- For *eejj* ($\beta = 1.0$) analysis, optimize cuts on:
  - $S_{\mathrm{T}} = p_{\mathrm{T}}(e_1) + p_{\mathrm{T}}(e_2) + p_{\mathrm{T}}(j_1) + p_{\mathrm{T}}(j_2)$
  - $m_{\mathrm{ej}}^{\mathrm{min}}$
  - m_{ee}
- For *eνjj* ($\beta = 0.5$) analysis, optimize cuts on:
  - $S_{\mathrm{T}} = p_{\mathrm{T}}(e) + \not{E}_{\mathrm{T}} + p_{\mathrm{T}}(j_1) + p_{\mathrm{T}}(j_2)$
  - m_{ej}
  - $m_{\mathrm{T},\ \mathrm{e}\nu}$
  - $\not{E}_{\mathrm{T}}$
- Set limit in plane of M_{LQ} vs. β

Datasets: all 8 TeV data

Run era	Run range	$\mathcal{L}_{int}(\mathrm{pb}^{-1})$
/Run2012A-recover-06Aug2012-v1/	190782 - 190949	82
/Run2012A-13Jul2012-v1/	190645 - 193621	808
/Run2012B-13Jul2012-v1/	193834 - 196531	4430
/Run2012C-24Aug2012-v1/	198049 - 198522	495
/Run2012C-EcalRecover_11Dec2012-v1/	201191	134
/Run2012C-PromptReco-v2/	198941 - 203002	6390
/Run2012D-PromptReco-v1/	203894 - 208686	7270
Total integrated luminosity ($\mathcal{L}_{int}$)		19.6 fb^{-1}

Primary datasets include:

- /ElectronHad/ for LQ search
- /SingleMu/ for $t\bar{t}$ bkgd in *eejj* analysis only
- /Photon/ + /SinglePhoton/ for QCD bkgd

Datasets: background Monte Carlo

Dataset name	cross section [pb]
/DY1JetsToLL_M-50_TuneZ2Star_8TeV-madgraph/	666.30
/DY2JetsToLL_M-50_TuneZ2Star_8TeV-madgraph/	214.97
/DY3JetsToLL_M-50_TuneZ2Star_8TeV-madgraph/	60.69
/DY4JetsToLL_M-50_TuneZ2Star_8TeV-madgraph/	27.36
/W1JetsToLNu_TuneZ2Star_8TeV-madgraph/	6663.
/W2JetsToLNu_TuneZ2Star_8TeV-madgraph/	2159.
/W3JetsToLNu_TuneZ2Star_8TeV-madgraph/	640.
/W4JetsToLNu_TuneZ2Star_8TeV-madgraph/	264.
/TTJets_FullLeptMGDecays_8TeV-madgraph/	26.18
/TTJets_SemiLeptMGDecays_8TeV-madgraph/	103.71
/TTJets_HadronicMGDecays_8TeV-madgraph/	104.10
/WW_TuneZ2star_8TeV_pythia6_tauola/	57.1
/WZ_TuneZ2star_8TeV_pythia6_tauola/	32.3
/ZZ_TuneZ2star_8TeV_pythia6_tauola/	8.26
/Tbar_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola/	11.1
/Tbar_t-channel_TuneZ2star_8TeV-powheg-tauola/	30.7
/Tbar_s-channel_TuneZ2star_8TeV-powheg-tauola/	1.76
/T_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola/	11.1
/T_t-channel_TuneZ2star_8TeV-powheg-tauola/	56.4
/T_s-channel_TuneZ2star_8TeV-powheg-tauola/	3.79
/G_Pt-XtoY_TuneZ2star_8TeV_pythia6/	Various

- From `Summer12` MC production campaign
- Reweighted to model `PU_S10`
- Various generators (see dataset name), `CTEQ6L1` PDFs

Datasets: signal Monte Carlo

M_{LQ} (GeV)	$\sigma(\mu = M_{\mathrm{LQ}})$ [pb]	$\delta(PDF)$ [pb]	$\sigma(\mu = M_{\mathrm{LQ}}/2)$ [pb]	$\sigma(\mu = M_{\mathrm{LQ}} \times 2)$ [pb]
300	1.89	0.214	1.63	2.13
350	0.77	0.102	0.663	0.866
400	0.342	0.052	0.295	0.385
450	0.163	0.0278	0.14	0.183
500	0.082	0.0155	0.0704	0.0922
550	0.0431	0.00893	0.037	0.0485
600	0.0235	0.0053	0.0201	0.0265
650	0.0132	0.00322	0.0113	0.0149
700	0.00761	0.002	0.00648	0.00858
750	0.00448	0.00126	0.00381	0.00506
800	0.00269	0.00081	0.00228	0.00304
850	0.00164	0.000527	0.00139	0.00186
900	0.00101	0.000347	0.000856	0.00115
950	0.000634	0.000231	0.000534	0.000722
1000	0.000401	0.000155	0.000337	0.000458
1050	0.000256	0.000105	0.000214	0.000293
1100	0.000165	7.18e-05	0.000138	0.000189
1150	0.000107	4.92e-05	8.88e-05	0.000123
1200	6.96e-05	3.4e-05	5.77e-05	8.04e-05

- From `Summer12` MC production campaign
- Reweighted to model `PU_S10`
- Generated with `Pythia`, `CTEQ6L1` PDFs, rescaled to NLO

Object selection

- Electrons:
  - HEEP v4.1 ID
- Muons:
  - Tight ID
- Jets:
  - Particle flow jets
  - Anti-k_T, $R = 0.5$
  - Particle flow loose ID
- $\not{E}_{\mathrm{T}}$:
  - Particle flow $\not{E}_{\mathrm{T}}$
  - Recommended filters
  - Corrections:
    - Type-0 correction
    - Type-1 correction
    - xy-shift correction

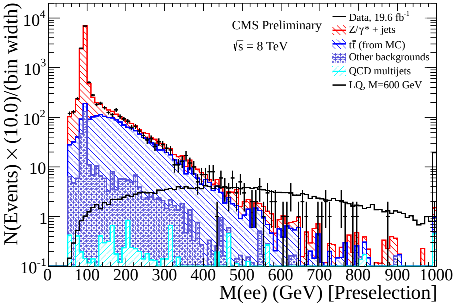
eejj preselection definition

- Exactly two electrons: $p_\mathrm{T} > 45$ GeV and $|\eta| < 2.5$
- At least two jets
- $p_\mathrm{T}(j_1) > 125$ GeV and $|\eta| < 2.4$
- $p_\mathrm{T}(j_2) > 45$ GeV and $|\eta| < 2.4$
- $m_{ee} > 50$ GeV
- $S_\mathrm{T} = p_\mathrm{T}(e_1) + p_\mathrm{T}(e_2) + p_\mathrm{T}(j_1) + p_\mathrm{T}(j_2) > 300$ GeV
- Muon veto
- Trigger (efficiency, below, applied as scale factor to signal):
  97.4 ± 0.56% (95.8 ± 1.35%) efficient on HEEP electrons in barrel (endcap)

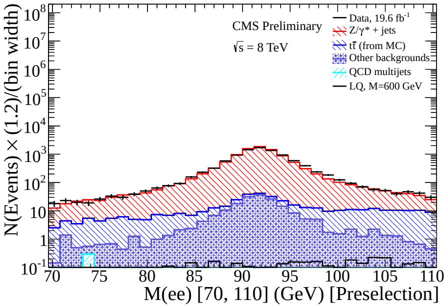
HLT path	Run range
HLT_Ele30_CaloIdVT_TrkIdT_PFJet100_PFJet25_v3	190456 - 190738
HLT_Ele30_CaloIdVT_TrkIdT_PFJet100_PFJet25_v4	190782 - 191419
HLT_Ele30_CaloIdVT_TrkIdT_PFNoPUJet100_PFNoPUJet25_v4	191691 - 194225
HLT_Ele30_CaloIdVT_TrkIdT_PFNoPUJet100_PFNoPUJet25_v5	194270 - 196531
HLT_Ele30_CaloIdVT_TrkIdT_PFNoPUJet100_PFNoPUJet25_v6	198022 - 199608
HLT_Ele30_CaloIdVT_TrkIdT_PFNoPUJet100_PFNoPUJet25_v7	199698 - 202504
HLT_Ele30_CaloIdVT_TrkIdT_PFNoPUJet100_PFNoPUJet25_v8	202970 - 208686

eejj preselection: m_{ee}

ee inv. mass, for approval

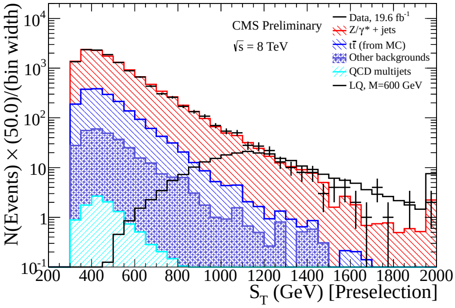


Electron pair inv. mass (zoomed)

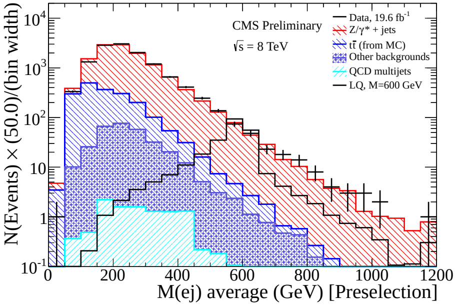


eejj preselection: S_T and m_{ej}

S_T, for approval



m_{ej} , for approval



eejj backgrounds

Backgrounds include:

- Z^0+jets : shape from MC, normalization from data (dominant background)
- $t\bar{t}$: shape and normalization from data
- QCD multijets: shape and normalization from data
- Other backgrounds: shape and normalization from MC

QCD background: overview

- Similar to method used by `EXO-12-061` ($Z' \to ee$)
- Events are selected within the `Photon` primary dataset
  - Prescaled single photon triggers select events online
  - *eejj* sample: two loose electrons, two jets
  - $e\nu jj$ sample: one loose electron, large $\not{E}_{\mathrm{T}}$, two jets
- Selected events are weighted to estimate QCD bkgd:

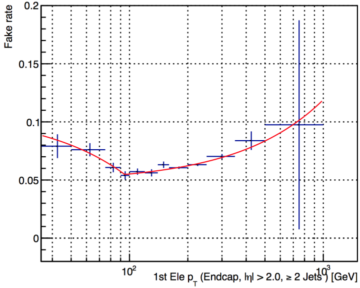
$$N^{QCD}_{eejj} = \sum_{\substack{\text{loose} \\ eejj \text{ events}}} P(e_{1,\text{ tight}} | e_{1,\text{ loose}} : p_{\mathrm{T}}, \eta) \cdot P(e_{2,\text{ tight}} | e_{2,\text{ loose}} : p_{\mathrm{T}}, \eta)$$

$$N^{QCD}_{enujj} = \sum_{\substack{\text{loose} \\ e\nu jj \text{ events}}} P(e_{1,\text{ tight}} | e_{1,\text{ loose}} : p_{\mathrm{T}}, \eta)$$

QCD background: fake rate calculation

- Define fake rate calculation sample:
  - Single photon trigger (see backup)
  - Exactly one loose electron
  - $N(\text{jets})$ with $p_T > 40$ GeV, where $N(\text{jets}) = \{0, 1, 2, 3\}$
- Fake rate = fraction of events with HEEP electron
  - Non-QCD events subtracted using MC
- Fake rate depends on: $p_T(e)$, $\eta(e)$, and $N(\text{jets})$
  - Bin results in $p_T(e)$ and fit (see plot at right)
  - Repeat study for $N(\text{jets}) = \{0, 1, 2, 3\}$
  - Repeat study for barrel electrons, inner endcap electrons ($|\eta| < 2.0$), and outer endcap electrons ($|\eta| > 2.0$)
- Closure test suggests uncertainty of 60% (30%) in the *eejj* ($e\nu jj$) analysis
- Contribution from QCD is 1% (3%) of total background in the *eejj* ($e\nu jj$) analysis

Fake rate for loose electrons in events with $N(\text{jets}) \geq 2$ and $|\eta(e)| > 2.0$



$t\bar{t}$ background in *eejj* analysis: overview

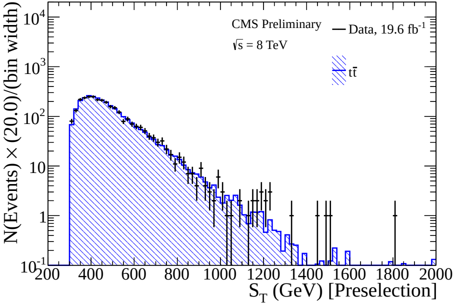
- $t\bar{t}$ background estimated using $e\mu jj$ events in data
- Selected using single muon trigger (see backup)
- Events are scaled:

$$N^{\text{data}}_{eejj} = \mathcal{C} \times N^{\text{data}}_{e\mu jj} = \frac{1}{2} \times \frac{\epsilon^{\text{trigger}}_{ee}}{\epsilon^{\text{trigger}}_{e\mu}} \times \frac{\epsilon^{\text{reco/ID/Iso}}_{e}}{\epsilon^{\text{reco/ID/Iso}}_{\mu}} \times N^{\text{data}}_{e\mu jj}$$

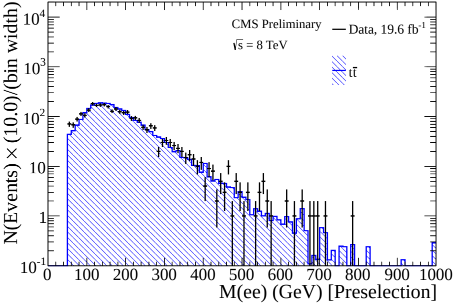
- $\epsilon^{\text{trigger}}_{ee} > 99.8\%$, taken as 1.0
- $\epsilon^{\text{trigger}}_{e\mu}$ varies with $|\eta(\mu)|$:
  - 0.94 for $0.0 < |\eta(\mu)| \leq 0.9$
  - 0.84 for $0.9 < |\eta(\mu)| \leq 1.2$
  - 0.82 for $1.2 < |\eta(\mu)| \leq 2.1$
- $\frac{\epsilon^{\text{reco/ID/Iso}}_{e}}{\epsilon^{\text{reco/ID/Iso}}_{\mu}} = 0.974 \pm 0.011$ (stat), taken from MC

$t\bar{t}$ background in *eejj* analysis: compare with MC

S_T , for approval



m_{ee} , for approval

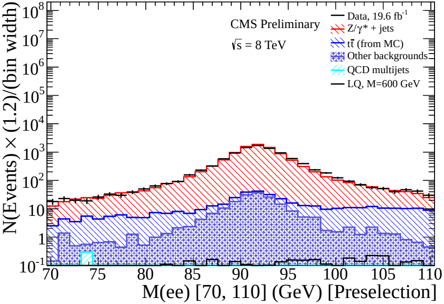


- *eμjj* data events predict 1579.6 ± 29.3 $t\bar{t}$ events at preselection
- *eejj* MC events predicts 1582.2 ± 13.8 $t\bar{t}$ events at preselection

Z^0+jets background in *eejj* analysis

- Z^0+jets MC rescaled to fit data
- Select events passing *eejj* preselection and $70 < m_{ee} < 110$
- Hold all backgrounds fixed, except Z^0+jets
- Rescale Z^0+jets MC so that N(data) and N(MC) agree:

Z^0+jets control region



$$\mathcal{R}_{Z^0} = \frac{N_{\text{data}} - (N_{\text{Others}} + N_{\text{QCD}})}{N_{Z^0}} = 0.97 \pm 0.01 \text{ (stat)}$$

eejj final selection optimization table

- Optimize S_T , m_{ej}^{min} , m_{ee} after *eejj* preselection
  - *e*-*j* pairs are chosen to minimize the difference between the mass of each pair
  - m_{ej}^{min} is the smallest of the two mass pairs
- Optimization figure of merit is $S/\sqrt{S+B}$
- Results:

	LQ mass (*eejj*)														
	300	350	400	450	500	550	600	650	700	750	800	850	900	950	$\geq$ 1000
S_T [GeV]	435	485	535	595	650	715	780	850	920	1000	1075	1160	1245	1330	1425
m_{ee} [GeV]	110	110	115	125	130	140	145	155	160	170	175	180	190	195	205
m_{ej}^{min} [GeV]	50	105	160	205	250	290	325	360	390	415	435	450	465	470	475

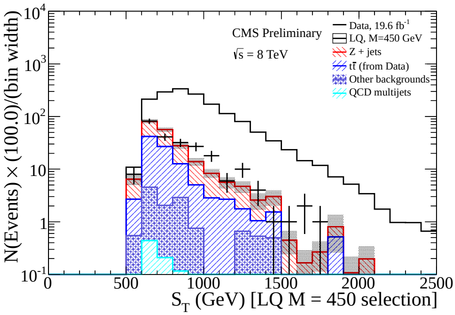
eejj final selection table

M_{LQ}	LQ Signal	Z^0+jets	$t\bar{t}$ (from data)	QCD (from data)	Other	Data	Total background
Presel	-	10538.4 ± 35.8	1566.6 ± 29.2	10.87 ± 0.10	303.8 ± 7.4	12442	12419.6 ± 46.8
300	13560.2 ± 80.1	462.2 ± 7.4	724.3 ± 19.8	5.282 ± 0.052	62.1 ± 4.6	1244	$1253.94 \pm 21.67 \pm 30.08$ (syst)
350	6473.9 ± 33.3	332.1 ± 6.2	352.0 ± 13.8	3.215 ± 0.036	37.7 ± 3.6	736	$725.10 \pm 15.57 \pm 24.99$ (syst)
400	3089.3 ± 15.0	203.2 ± 4.8	153.7 ± 9.1	1.696 ± 0.023	23.8 ± 2.9	389	$382.40 \pm 10.72 \pm 15.00$ (syst)
450	1508.1 ± 7.2	112.9 ± 3.5	86.9 ± 6.9	0.890 ± 0.016	11.8 ± 2.0	233	$212.44 \pm 7.99 \pm 13.33$ (syst)
500	767.4 ± 3.6	66.5 ± 2.7	47.2 ± 5.1	0.485 ± 0.011	7.4 ± 1.6	148	$121.61 \pm 5.96 \pm 6.03$ (syst)
550	410.5 ± 1.9	37.4 ± 2.1	25.8 ± 3.7	0.2758 ± 0.0084	3.7 ± 1.1	81	$67.24 \pm 4.40 \pm 3.39$ (syst)
600	225.7 ± 1.0	22.2 ± 1.6	14.2 ± 2.8	0.1527 ± 0.0065	3.12 ± 1.00	57	$39.66 \pm 3.35 \pm 2.42$ (syst)
650	125.85 ± 0.58	14.0 ± 1.2	5.4 ± 1.7	0.0760 ± 0.0040	1.05 ± 0.47	36	$20.49 \pm 2.14 \pm 2.45$ (syst)
700	72.88 ± 0.33	8.16 ± 0.93	4.3 ± 1.5	0.0448 ± 0.0029	0.21 ± 0.12	17	$12.74 \pm 1.80 \pm 2.15$ (syst)
750	43.10 ± 0.20	4.88 ± 0.69	1.55 ± 0.90	0.0258 ± 0.0023	0.078 ± 0.038	12	$6.53 \pm 1.13 \pm 1.09$ (syst)
800	26.17 ± 0.12	2.93 ± 0.52	1.04 ± 0.73	0.0193 ± 0.0022	0.078 ± 0.038	7	$4.06 \pm 0.90 \pm 0.89$ (syst)
850	15.978 ± 0.072	2.34 ± 0.48	0.52 ± 0.52	0.0111 ± 0.0015	0.042 ± 0.028	5	$2.91 \pm 0.71 \pm 0.71$ (syst)
900	9.813 ± 0.044	1.23 ± 0.36	0.52 ± 0.52	0.0069 ± 0.0012	0.022 ± 0.020	3	$1.77 \pm 0.63 \pm 0.37$ (syst)
950	6.086 ± 0.028	0.89 ± 0.29	$0.00000^{+1.14000}_{-0.00}$	0.00451 ± 0.00085	0.022 ± 0.020	1	$0.912^{+1.178}_{-0.295} \pm 0.27$ (syst)
1000	3.860 ± 0.018	0.56 ± 0.22	$0.00000^{+1.14000}_{-0.00}$	0.00374 ± 0.00082	0.0025 ± 0.0025	1	$0.567^{+1.162}_{-0.223} \pm 0.17$ (syst)
1050	2.576 ± 0.011	0.56 ± 0.22	$0.00000^{+1.14000}_{-0.00}$	0.00374 ± 0.00082	0.0025 ± 0.0025	1	$0.567^{+1.162}_{-0.223} \pm 0.17$ (syst)
1100	1.6936 ± 0.0072	0.56 ± 0.22	$0.00000^{+1.14000}_{-0.00}$	0.00374 ± 0.00082	0.0025 ± 0.0025	1	$0.567^{+1.162}_{-0.223} \pm 0.17$ (syst)
1150	1.1272 ± 0.0047	0.56 ± 0.22	$0.00000^{+1.14000}_{-0.00}$	0.00374 ± 0.00082	0.0025 ± 0.0025	1	$0.567^{+1.162}_{-0.223} \pm 0.17$ (syst)
1200	0.7498 ± 0.0030	0.56 ± 0.22	$0.00000^{+1.14000}_{-0.00}$	0.00374 ± 0.00082	0.0025 ± 0.0025	1	$0.567^{+1.162}_{-0.223} \pm 0.17$ (syst)

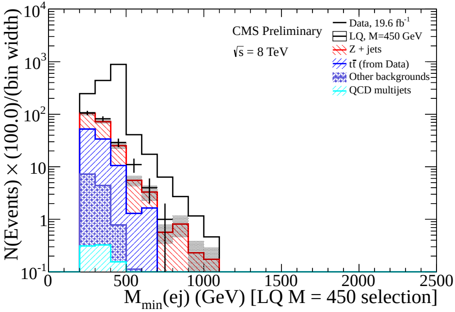
- Broad excess of data w.r.t. total background
- Most significant for $M_{\mathrm{LQ}} = 650$ GeV selection

eejj final selection (450): S_T and m_{ej}^{min} ($\beta = 1.0$)

S_T, for approval

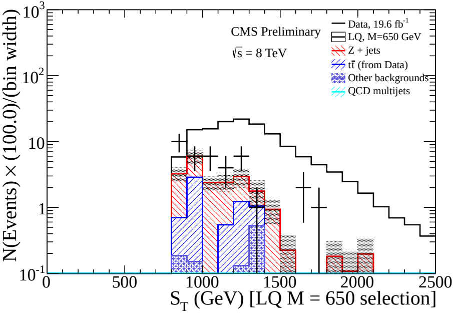


m_{ej}^{min}, for approval

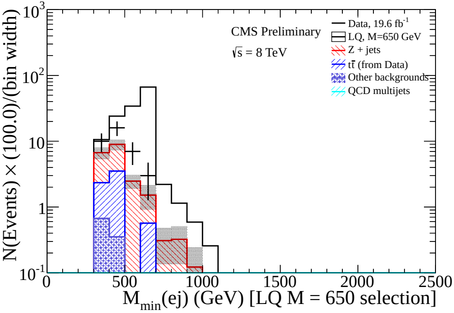


eejj final selection (650): S_T and m_{ej}^{min} ($\beta = 1.0$)

S_T, for approval



m_{ej}^{min} , for approval

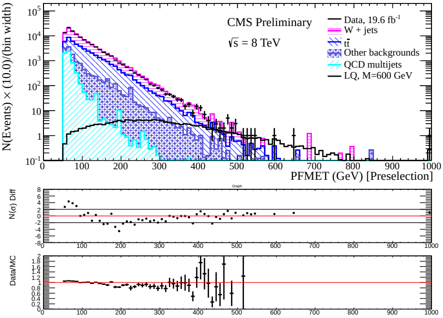


$e\nu jj$ preselection definition

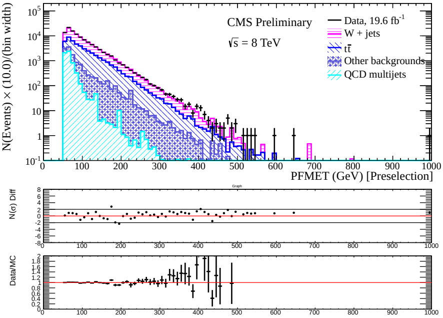
- Exactly one electron: $p_{\mathrm{T}} > 45$ GeV and $|\eta| < 2.2$
- $\not{E}_{\mathrm{T}} > 55$ GeV
- At least two jets
- $p_{\mathrm{T}}(j_1) > 125$ GeV and $|\eta| < 2.4$
- $p_{\mathrm{T}}(j_2) > 45$ GeV and $|\eta| < 2.4$
- $|\Delta\phi(e, \not{E}_{\mathrm{T}})| > 0.5$
- $|\Delta\phi(j_1, \not{E}_{\mathrm{T}})| > 0.5$
- $m_{\mathrm{T},\, e\nu} > 50$ GeV
- $S_{\mathrm{T}} = p_{\mathrm{T}}(e_1) + \not{E}_{\mathrm{T}} + p_{\mathrm{T}}(j_1) + p_{\mathrm{T}}(j_2) > 300$ GeV
- Muon veto
- Same trigger as *eejj* analysis

eνjj preselection: $\not\!\!E_T$

$\not\!\!E_T$
(as in analysis, app. plot in PAS)



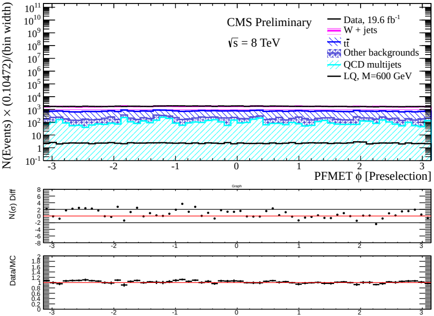
$\not\!\!E_T$
(after reweighting)

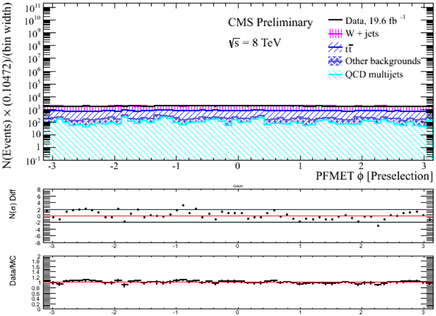


Reweighting investigated but not used in main analysis (backup)

$e\nu jj$ preselection: $\phi(\not{E}_T)$

$\phi(\not{E}_T)$ (as in analysis, app. plot in PAS)	$\phi(\not{E}_T)$ (after reweighting)

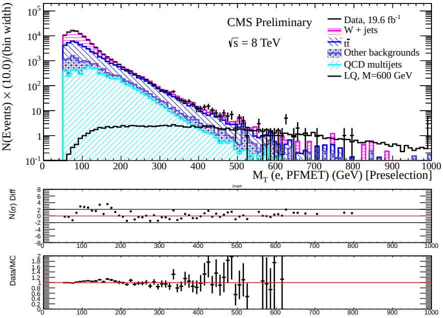




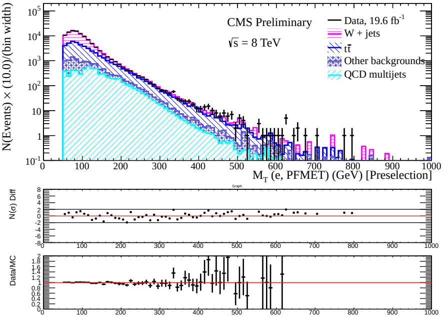
Reweighting investigated but not used in main analysis (backup)

$e\nu jj$ preselection: $m_{T,\,e\nu}$

Electron-$\not\!\!E_T$ transverse mass (as in analysis, app. plot in PAS)



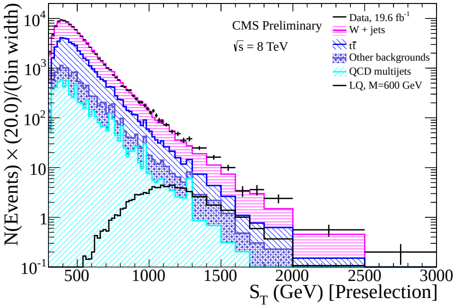
Electron-$\not\!\!E_T$ transverse mass (after reweighting)



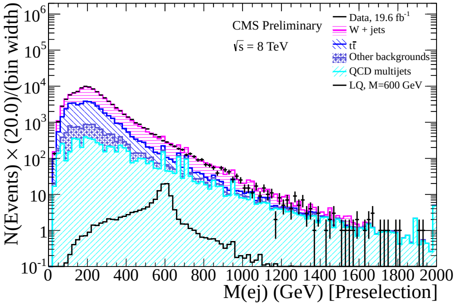
Reweighting investigated but not used in main analysis (backup)

$e\nu jj$ preselection: S_T and m_{ej}

S_T, for approval



m_{ej} , for approval



$e\nu jj$ backgrounds

Backgrounds include:

- $t\bar{t}$: shape from MC, normalization from data (dominant background)
- $W^{\pm}$+jets : shape from MC, normalization from data
- QCD multijets: shape and normalization from data (same as $eejj$)
- Other backgrounds: shape and normalization from MC

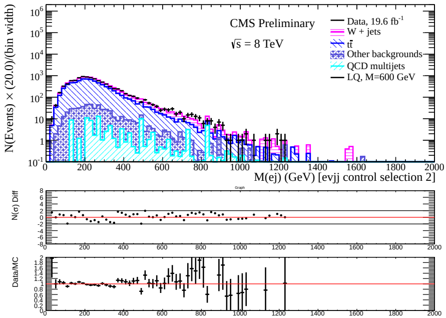
$W^{\pm}$+jets and $t\bar{t}$ backgrounds in $e\nu jj$ analysis

- MC is rescaled to fit data
- Two selections:
  - Sel. 1: $W^{\pm}$+jets dominates
    - $e\nu jj$ preselection
    - $50 < m_{\mathrm{T},\, e\nu} < 110$ GeV
    - N(jets) < 4
  - Sel. 2: $t\bar{t}$ dominates
    - $e\nu jj$ preselection
    - $50 < m_{\mathrm{T},\, e\nu} < 110$ GeV
    - N(jets) ≥ 4
- Solve system of equations:

$$N^1_{\mathrm{data}} = \mathcal{R}_{t\bar{t}} N^1_{t\bar{t}} + \mathcal{R}_W N^1_W + N^1_{\mathrm{QCD}} + N^1_{\mathrm{Others}}$$
$$N^2_{\mathrm{data}} = \mathcal{R}_{t\bar{t}} N^2_{t\bar{t}} + \mathcal{R}_W N^2_W + N^2_{\mathrm{QCD}} + N^2_{\mathrm{Others}}$$

$$\mathcal{R}_{t\bar{t}} = 0.97 \pm 0.02\ (\mathrm{stat}) \pm 0.01\ (\mathrm{syst})$$
$$\mathcal{R}_{\mathrm{W}} = 0.85 \pm 0.01\ (\mathrm{stat}) \pm 0.01\ (\mathrm{syst})$$

m_{ej} in selection 2



$e\nu jj$ final selection optimization table

- Optimize S_{T} , m_{ej} , $m_{\mathrm{T,\, e}\nu}$, and $\not{E}_{\mathrm{T}}$ after *eejj* preselection
  - e-j and $\not{E}_{\mathrm{T}}$-j pairs are chosen to minimize the difference between the transverse mass of each pair
  - m_{ej} is the mass of the e-j pair
  - $\not{E}_{\mathrm{T}}$ is optimized to reduce QCD background
- Optimization figure of merit is $S/\sqrt{S+B}$
- Results:

	LQ Mass (evjj)													
	300	350	400	450	500	550	600	650	700	750	800	850	900	$\geq$ 950
S_{T} [GeV]	495	570	645	720	800	880	960	1040	1120	1205	1290	1375	1460	1545
$\not{E}_{\mathrm{T}}$ [GeV]	90	95	100	110	115	125	135	145	155	170	180	195	210	220
m_{ej} [GeV]	195	250	300	355	405	455	505	555	600	645	695	740	780	825
$m_{\mathrm{T,\, e}\nu}$ [GeV]	125	150	175	200	220	240	255	270	280	290	295	300	300	300

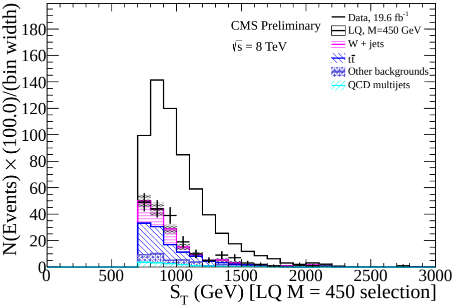
$e\nu jj$ final selection table

M_{LQ}	LQ Signal	$W^{\pm}$+jets	$t\bar{t}$	QCD	Other	Data	Total background
Presel	-	58284.8 ± 197.0	32196.7 ± 69.8	5950.5 ± 20.1	6590.8 ± 231.6	105164	103022.8 ± 312.6
300	4765.5 ± 51.1	822.1 ± 22.4	1191.3 ± 12.0	117.9 ± 1.5	210.5 ± 7.7	2455	$2341.90 \pm 26.58 \pm 329.79$ (syst)
350	2168.4 ± 21.6	275.9 ± 14.5	441.4 ± 7.2	59.11 ± 0.97	102.1 ± 5.4	908	$878.55 \pm 17.08 \pm 122.13$ (syst)
400	971.1 ± 9.6	110.4 ± 7.8	184.2 ± 4.7	32.88 ± 0.69	51.5 ± 3.8	413	$378.98 \pm 9.91 \pm 51.38$ (syst)
450	469.7 ± 4.6	53.1 ± 5.8	74.7 ± 3.0	14.13 ± 0.42	25.7 ± 2.7	192	$167.64 \pm 7.06 \pm 21.33$ (syst)
500	232.7 ± 2.3	20.5 ± 3.3	34.4 ± 2.0	7.76 ± 0.30	15.3 ± 2.1	83	$77.99 \pm 4.41 \pm 9.77$ (syst)
550	121.4 ± 1.2	8.6 ± 1.8	14.9 ± 1.4	3.89 ± 0.21	7.8 ± 1.6	44	$35.24 \pm 2.76 \pm 4.31$ (syst)
600	66.37 ± 0.66	2.3 ± 1.0	7.08 ± 0.93	2.29 ± 0.17	4.6 ± 1.2	28	$16.27 \pm 1.84 \pm 2.03$ (syst)
650	37.22 ± 0.37	0.41 ± 0.29	3.82 ± 0.70	1.18 ± 0.12	2.13 ± 0.92	18	$7.54 \pm 1.20 \pm 1.07$ (syst)
700	21.74 ± 0.21	0.41 ± 0.29	2.61 ± 0.60	0.85 ± 0.10	0.58 ± 0.24	6	$4.45 \pm 0.71 \pm 0.74$ (syst)
750	12.90 ± 0.13	$0.00^{+0.94}_{-0.00}$	1.75 ± 0.47	0.514 ± 0.091	0.27 ± 0.15	4	$2.535^{+1.062}_{-0.504} \pm 0.49$ (syst)
800	7.610 ± 0.075	$0.00^{+0.94}_{-0.00}$	1.10 ± 0.37	0.317 ± 0.067	0.27 ± 0.15	3	$1.696^{+1.019}_{-0.404} \pm 0.31$ (syst)
850	4.713 ± 0.046	$0.00^{+0.94}_{-0.00}$	0.90 ± 0.34	0.117 ± 0.029	0.140 ± 0.087	2	$1.153^{+0.999}_{-0.353} \pm 0.24$ (syst)
900	2.929 ± 0.028	$0.00^{+0.94}_{-0.00}$	0.37 ± 0.21	0.076 ± 0.024	0.084 ± 0.069	1	$0.530^{+0.962}_{-0.226} \pm 0.10$ (syst)
950	1.839 ± 0.018	$0.00^{+0.94}_{-0.00}$	0.37 ± 0.21	0.069 ± 0.023	0.084 ± 0.069	1	$0.524^{+0.962}_{-0.226} \pm 0.10$ (syst)
1000	1.306 ± 0.012	$0.00^{+0.94}_{-0.00}$	0.37 ± 0.21	0.069 ± 0.023	0.084 ± 0.069	1	$0.524^{+0.962}_{-0.226} \pm 0.10$ (syst)
1050	0.9022 ± 0.0076	$0.00^{+0.94}_{-0.00}$	0.37 ± 0.21	0.069 ± 0.023	0.084 ± 0.069	1	$0.524^{+0.962}_{-0.226} \pm 0.10$ (syst)
1100	0.6225 ± 0.0050	$0.00^{+0.94}_{-0.00}$	0.37 ± 0.21	0.069 ± 0.023	0.084 ± 0.069	1	$0.524^{+0.962}_{-0.226} \pm 0.10$ (syst)
1150	0.4308 ± 0.0032	$0.00^{+0.94}_{-0.00}$	0.37 ± 0.21	0.069 ± 0.023	0.084 ± 0.069	1	$0.524^{+0.962}_{-0.226} \pm 0.10$ (syst)
1200	0.2971 ± 0.0022	$0.00^{+0.94}_{-0.00}$	0.37 ± 0.21	0.069 ± 0.023	0.084 ± 0.069	1	$0.524^{+0.962}_{-0.226} \pm 0.10$ (syst)

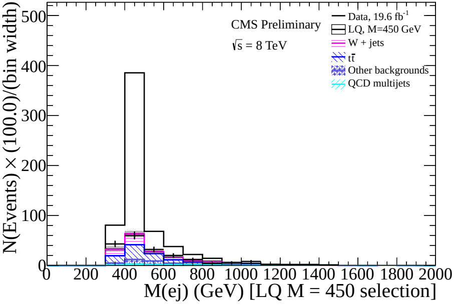
- Broad excess of data w.r.t. total background (as in *eejj*)
- Most significant for $M_{\mathrm{LQ}} = 650$ GeV selection (as in *eejj*)

$e\nu jj$ final selection (450): S_T and m_{ej} ($\beta = 0.5$)

S_T , for approval

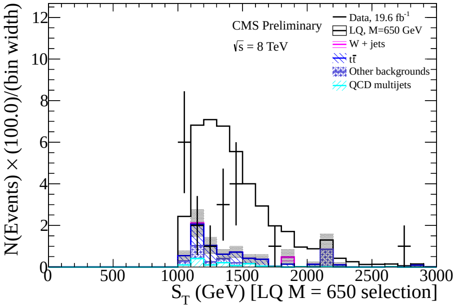


m_{ej} , for approval

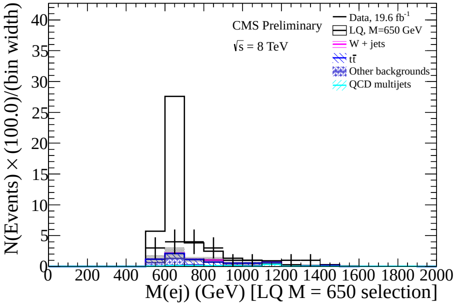


$e\nu jj$ final selection (650): S_T and m_{ej} ($\beta = 0.5$)

S_T , for approval



m_{ej} , for approval



Systematic uncertainties

- Background MC shape (varies):
  - $W^{\pm}$+jets and $t\bar{t}$ in $e\nu jj$
  - Z^0+jets in *eejj*
- PDF (varies)
- Jet energy scale:
  taken from GlobalTag
- Jet energy resolution:
  eta-dependent, 5-30%
- Electron energy scale:
  0.4% barrel, 4.1% endcap
- Electron energy resolution:
  0.6% barrel, 1.5% endcap
- Background MC normalization:
  - $W^{\pm}$+jets (2%) in $e\nu jj$
  - $t\bar{t}$ (2%) in $e\nu jj$
  - Z^0+jets (1%) in *eejj*
- QCD normalization:
  60% (30%) in *eejj* ($e\nu jj$)
- $t\bar{t}$ normalization in *eejj* : 2%
- Electron reco/ID/Iso effi:
  4% (2%) in *eejj* ($e\nu jj$) signal
- Pileup
- Luminosity: 2.6%
- MC statistics: Dominates

Systematic uncertainties: *eejj* for $M_{LQ} = 650$ GeV

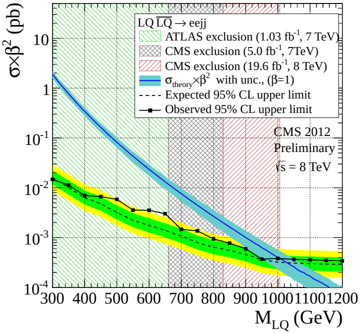
Systematic	Signal (%)	Background (%)
Electron efficiency	4.00%	0.00%
Electron energy scale	0.33%	1.45%
Electron energy resolution	0.02%	0.04%
Jet energy scale	0.30%	0.52%
Jet energy resolution	0.01%	0.23%
Pileup	0.04%	0.38%
Luminosity	2.60%	0.10%
Z normalization	0.00%	0.75%
Z shape	0.00%	11.62%
$t\bar{t}$ estimate	0.00%	0.52%
QCD multijet estimate	0.00%	0.11%
PDF uncertainty	2.00%	2.05%
Total	5.19%	11.94%

Systematic uncertainties: $e\nu jj$ for $M_{LQ} = 650$ GeV

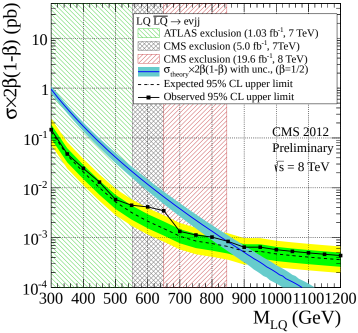
Systematic	Signal (%)	Background (%)
Electron efficiency	2.00%	0.00%
Electron energy scale	1.09%	1.38%
Electron energy resolution	0.08%	0.68%
Jet energy scale	1.56%	2.15%
Jet energy resolution	0.09%	0.46%
Pileup	0.14%	1.18%
Luminosity	2.60%	0.47%
W normalization	0.00%	0.12%
W shape	0.00%	0.87%
$t\bar{t}$ normalization	0.00%	1.50%
$t\bar{t}$ shape	0.00%	3.00%
QCD multijet estimate	0.00%	4.71%
PDF uncertainty	3.00%	12.65%
Total	4.84%	14.25%

Results: standalone limits, including systematics

$\beta = 1.0$, for approval



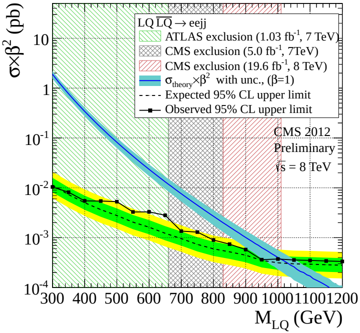
$\beta = 0.5$, for approval



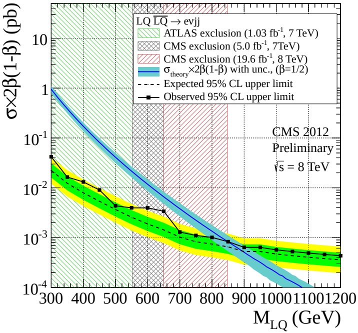
- Expected limits: $M_{LQ} < 1030$ (890) GeV for *eejj* (*eνjj*)
- Observed limits: $M_{LQ} < 1005$ (845) GeV for *eejj* (*eνjj*)

Results: standalone limits, without systematics

$\beta = 1.0$: *eejj* analysis, no syst.



$\beta = 0.5$: *eνjj* analysis, no syst.

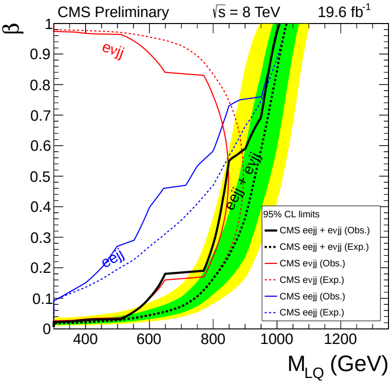


- Expected limits: $M_{LQ} < 1030$ (895) GeV for *eejj* (*eνjj*)
- Observed limits: $M_{LQ} < 1010$ (850) GeV for *eejj* (*eνjj*)

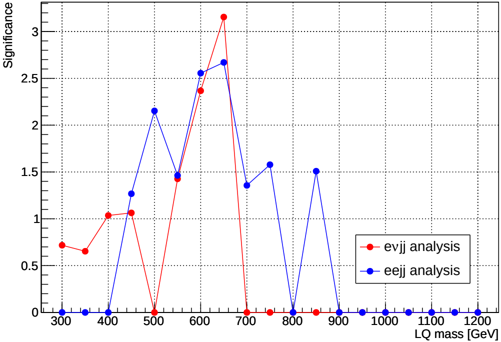
Results: combined limits, including systematics

- Made with asymptotic CLs
- Obs. limits unchanged
- $e\nu jj$ excess has strongest effect on combined limit discrepancy
- Limits at $\beta = 0.15$:
  - Exp.: $M_{LQ} < 790$ GeV
  - Obs.: $M_{LQ} < 635$ GeV

for approval



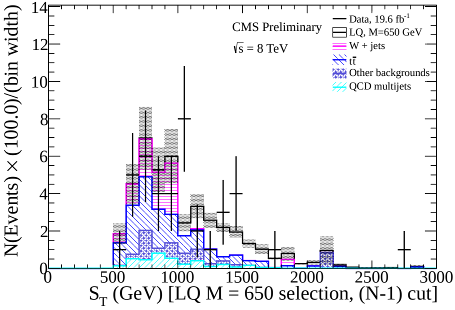
Results: significance (no look-elsewhere applied)



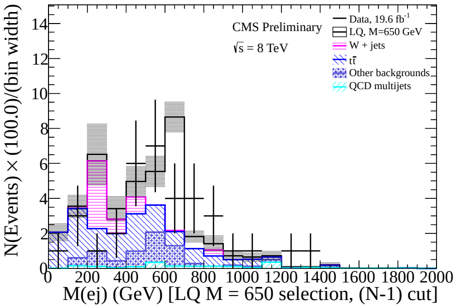
- Currently in PAS
- Considering removing and putting numbers in table

Results: $\beta = 0.15$, $M_{LQ} = 650$ (1/3)

S_T

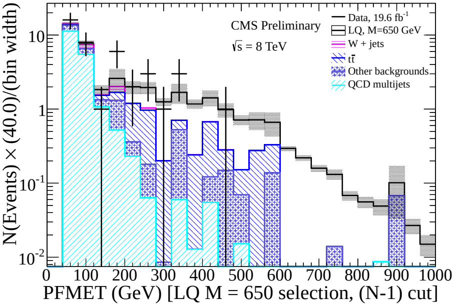


m_{ej}

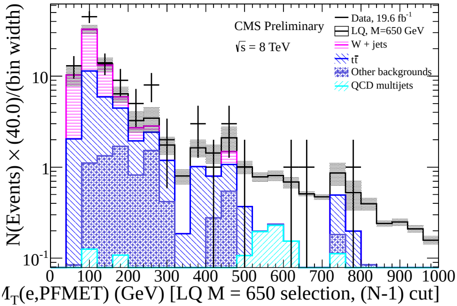


Results: $\beta = 0.15$, $M_{LQ} = 650$ (2/3)

$\not{E}_T$

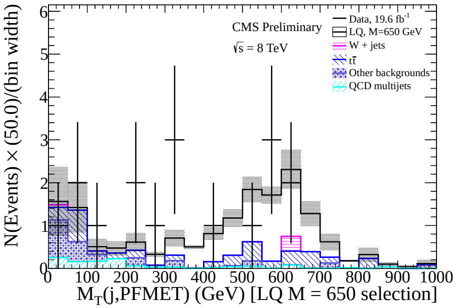


$m_{T,\,e\nu}$



Results: $\beta = 0.15$, $M_{LQ} = 650$ (3/3)

$m_{T,\, j\nu}$



Overview of checks

- **Problem with analysis code?** No
  W_R analysis (*eejj* final state) reproduced the excess (J. Pastika, B. Dahmes)
- **Problem with ECAL?** No
  ECAL DPG says these events are ok. Electrons are spread in η and ϕ. See backup.
- **Problem with unstable running conditions?** No
  Excesses are flat vs run period. See backup.
- **Problem with signal trigger?** No
  eejj excess persists with `HLT_DoubleEle33_CaloIdL_GsfTrkIdVL`.
- **Problem with single object mis-measurement (eejj analysis only)?** No
  Events in *eejj* excess do not have an excess of single objects (electrons, jets) aligned with $\not{E}_T$.
- **Problem modeling $\not{E}_T$ and $m_{T,\,e\nu}$ ($e\nu jj$ analysis only)?** ...
  Discrepancy between data and MC in $\not{E}_T$ and $m_{T,\,e\nu}$ distributions at $e\nu jj$ preselection, but reweighting $m_{T,\,e\nu}$ and $\not{E}_T$ at preselection increases the final selection discrepancy. See backup.
- **Problem with electrons from pileup?** No
  Electrons in excess have low d_Z w.r.t. primary vertex
- **Problem with data-driven $t\bar{t}$ background estimate?** No
  Results with $t\bar{t} \rightarrow$ *eejj* MC agree within statistics
- **Problem with your data-driven QCD background estimate?** No
  Excess is almost entirely OS electron pairs. Contribution from QCD is predicted to be « 1 event.
- **Problem with your various MC background estimates?** No
  Background for final selection optimized for $M_{LQ} = 650$ GeV is cross-checked using only data. See backup.

Conclusion

- A search was carried out for first generation LQs in two channels:
  - $\mathrm{LQ}\overline{\mathrm{LQ}} \to eejj$ (optimized for $\beta = 1.0$)
  - $\mathrm{LQ}\overline{\mathrm{LQ}} \to e\nu jj$ (optimized for $\beta = 0.5$)
- Combination of the channels sets world's best limits on leptoquarks at 95% CL:
  - Exp. limits: $M_{LQ} < 1030$ (890) GeV for $\beta = 1.0$ (0.5)
  - Obs. limits: $M_{LQ} < 1005$ (845) GeV for $\beta = 1.0$ (0.5)
- With current data:
  - We observe an excess of 3σ
  - We cannot exclude an LQ of mass 650 GeV with $\beta = 0.15$
- Results have been extensively cross checked
- We ask for the approval of this analysis