Search for Heavy Neutrinos in di-lepton and di-jet events

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Outline

- Many models Beyond the SM with a di-lep+di-jet signature:
  - LeptoQuark of the three generations;
  - Heavy Neutrinos arising in different scenarios.
- The last CMS results show an excess in di-ele+di-jet:
  - search for scalar LeptoQuarks of first generation;
  - search for Heavy Neutrinos within the LR-symmetry extension.
- A new Heavy Neutrino's search analysis based on an original model:
  - composite fermions;
  - contact interactions;
  - a benchmark process;
  - discovery/exclusion potential.

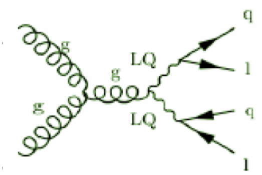
Perugia's group: Livio Fano', Francesco Romeo, Alunni Solestizi Luisa (experimental view) Orlando Panella, Roberto Leonardi (phenomenological view).

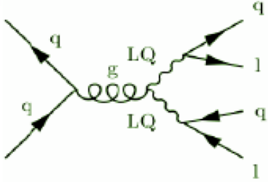
LeptoQuark

Many models beyond the SM (GUTs, Composite models, Technicolor) predict scalar or vector bosons carrying no-zero lepton and baryon numbers and fractional charge, called LeptoQuarks (LQ).

Their production and decay depend on: LQ mass (M_{LQ}), coupling constant LQ-quark-lepton (λ), BR decay in charge lepton+quark (β).

Only coupling with same family lepton and quark is accessible by LHC.
Looking for $LQ + \overline{LQ}$ production.
$BR(LQ \rightarrow \ell + q) = \beta$ with $\ell = e, \mu, \tau$;
$BR(LQ \rightarrow \nu + q) = 1 - \beta$.





$LQ + \overline{LQ}$	β^2	$\beta(1-\beta)$	$(1-\beta)^2$
LQ1	ee + jj	$e\nu$ + jj	-
LQ2	$\mu\mu$ + jj	$\mu\nu$ + jj	-
LQ3	$\tau\tau$ + bb(tt)	-	$\nu\nu$ + bb(tt)

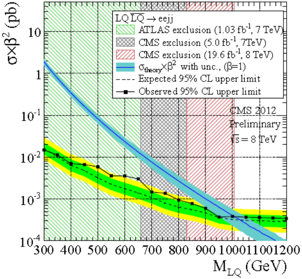
LQ - 1st generation

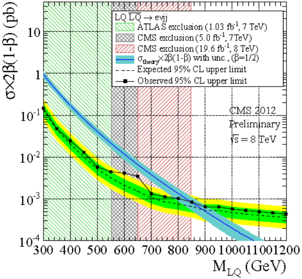
EXO-12-041 - FINAL STATE: eejj or $e\nu jj$ - L $=19,6\ fb^{-1}$, $\sqrt{s}=8\ TeV$

SELECTION (eejj channel): HLT single electron di-jet,
exactly 2 electrons with $p_T > 45$ GeV and $|\eta| < 2.5$,
at least 1 jet with $p_T > 125$ GeV and $|\eta| < 2.4$,
at least 2 jets with $p_T > 45$ GeV and $|\eta| < 2.4$,
$M_{ee} > 50$ GeV, $S_T = p_T(e_1) + p_T(e_2) + p_T(jet_1) + p_T(jet_2) > 300$ GeV.

excluded $M_{LQ1} < 950(845)$ GeV with $\beta = 1(0.5)$
excess at $M_{LQ1} \sim 650$ GeV, 2.4 (2.8) σ in $eejj(e\nu jj)$

BACKGROUND:
Z+jets, simulation normalized on data in a control region.
$t\bar{t}$ from data using an $e\mu jj$ sample.
QCD, VV, W+jets.





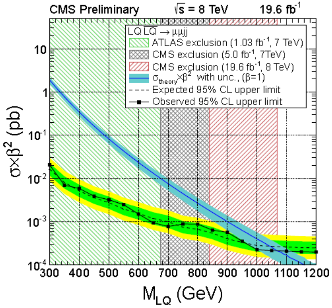
LQ - 2nd generation

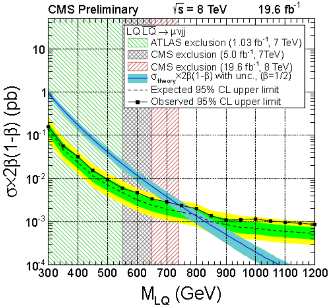
EXO-12-042 - FINAL STATE: $\mu\mu jj$ or $\mu\nu jj$ - L=19.6 fb^{-1}, $\sqrt{s}$ = 8 TeV

SELECTION ($\mu\mu jj$ channel): at least 2 muons and two jets,
muons: $p_T > 45$ GeV and $|\eta| < 2.1$,
jets: $p_T(jet_1) > 125$ GeV and $p_T(jet_2) > 45$ GeV, $|\eta| < 2.4$,
$\Delta R > 0.3$ between jets and muons,
$M_{\mu\mu} > 50$ GeV, $S_T = p_T(\mu_1) + p_T(\mu_2) + p_T(jet_1) + p_T(jet_2) > 300$ GeV

BACKGROUND:
Z+jets MC normalized in a control region around Z peak.
$t\bar{t}$ with an enriched $t\bar{t}$ data sample of $e\mu jj$.
VV, W+jets, QCD.

$M_{LQ2} < 1070(785)$ GeV excluded for $\beta = 1(0.5)$



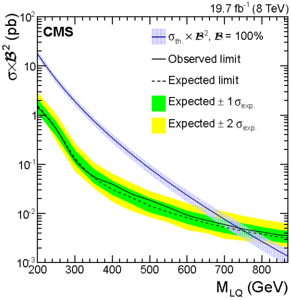


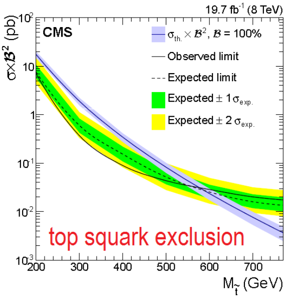
LQ - 3rd generation

EXO-12-032 - FINAL STATE: $\tau_h \tau_{lep} jj$ bb(tt) - L = 19.7 fb^{-1}, $\sqrt{s}$ = 8 TeV

SELECTION (for LQ3 search):

HLT an electron (muon) with $p_T >$27 (24) GeV,
electron (muon): $p_T > 30\ GeV$ and $|\eta| < 2.1$,
τ_h: $p_T > 50\ GeV$ and $|\eta| < 2.3$,
jets: $p_T > 30\ GeV$ and $|\eta| < 2.4$, b-tagging,
Leptons and jets separated by $\Delta R > 0.5$,
$M_{\tau_h,jet} > 250$ GeV.





BACKGROUND:
$t\bar{t}$ unreducible, data driven method used;
$W + jets$, $Z + jets$.

$M_{LQ3} < 740\ GeV$ excluded at 95% CL.

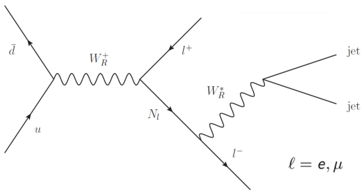
$M_{top\ squark} < 580\ GeV$ excluded at 95% CL.

Heavy Neutrinos - LR-symmetry extension

The extension of the LR-symmetry explains the parity violation in the SM as a consequence of spontaneous breaking symmetry of a larger gauge group and the mass of neutrinos within the seesaw mechanism.

It includes naturally: heavy W_R and Z_R gauge bosons and heavy right handed heavy Majorana neutrinos N_e, N_μ, N_τ.

EXO-13-008, FINAL STATE: $\mu\mu jj$ or $eejj$ - L= $19,7\ fb^{-1}$, $\sqrt{s} = 8$ TeV

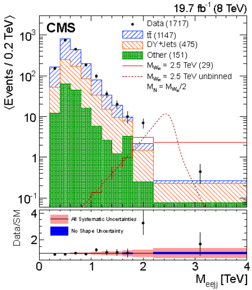


SELECTION: 2 jet e 2 same flavour leptons (N Majorana).
$p_T\ lep_1\ (lep_2) > 60(40)\ GeV$,
$|\eta|(lep) < 2.4$,
p_T jets $> 40\ GeV$, merged jets,
no charge requirement for leptons.
$M_{\ell\ell jj} > 600\ GeV$, $M_{\ell\ell} > 200\ GeV$.

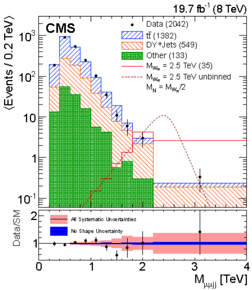
BACKGROUND: $t\bar{t}$ using an $e\mu jj$ control sample from data, DY+jets from $Z \to \ell\ell$, MC normalized around Z peak in data.

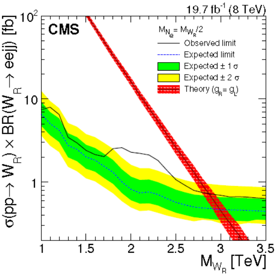
Heavy Neutrinos - LR-symmetry extension

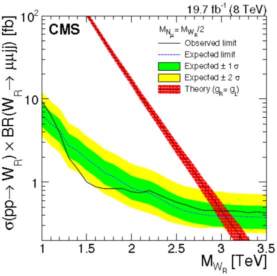
eejj



$\mu\mu jj$







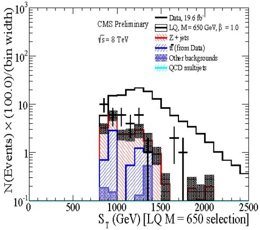
Shape analysis:
$M_{W_R} = M(\ell, \ell, j, j)$.

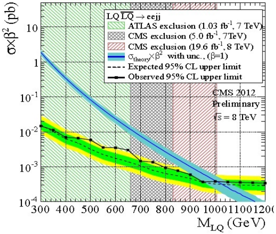
Exclusion at 95% CL extended to $M_{W_R} < 3.0$ *TeV*

Excess of 2.8σ in *eejj* channel at around 2.2 TeV;
No excess in $\mu\mu jj$ channel.

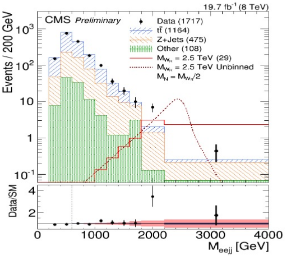
Experimental motivations

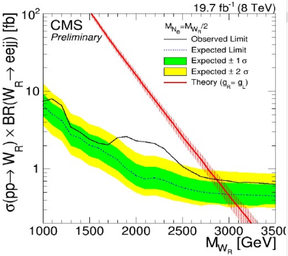
eejj - 1st generation LeptoQuark





eejj - Heavy Neutrinos and W_R boson





Excess in eejj channel in two indipendent analysis:

- Heavy Neutrinos search;
- 1st generation LeptoQuark search.

No excesses in $\mu\mu jj$;

No searches for Heavy Neutrinos in $\tau\tau jj$, (only in $\tau\tau tt$ and $\tau\tau bb$ optimized for 3rd generation LeptoQuarks)

Aim to do a **Heavy Neutrinos search** at $\sqrt{s} = 13$ *TeV* in **di-lep+di-jet**.

Compositness scenario

The proliferation of SM fermion families suggests a further compositness (original model developed by Perugia's group: **arXiv:hep-ph/9903253v2**, **arXiv:1405.3911v1,**
Eichten, Lane, Peskin PRL 50 811 (1983) (Contact Interactions)
Cabibbo, Maiani, Srivastava , PLB 139, 459 (1984) (Gauge Interactions)
Hagiwara, Komamiya, Zeppenfeld: Phys. C 29, 115 (195), (GI+CI)):

- excited leptons and quarks, substructure visible at high scale Λ;
- composite fermions interact via contact interactions, a residual force among their contituents.

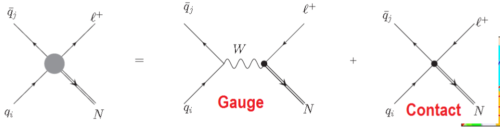
These excited fermions can couple with SM fermions through both gauge and contact vertices. Heavy Majorana excited neutrinos for the three generation are included in the model: N_e, N_μ and N_τ.

Gauge current:

$$L_G = \frac{g \cdot f}{\sqrt{2}\Lambda} \bar{N} \sigma_{\mu\nu} \ell_L \partial^\nu W^\mu + h.c.$$

Contact Interactions current:

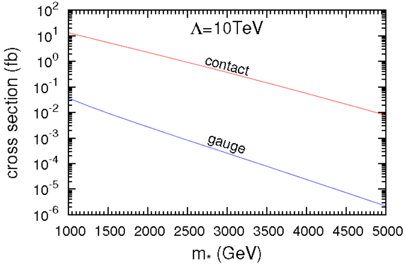
$$L_{CI} = \frac{g_*^2}{\Lambda^2} \bar{q}_L \gamma^\mu q'_L \bar{N}_L \gamma_\mu \ell_L$$

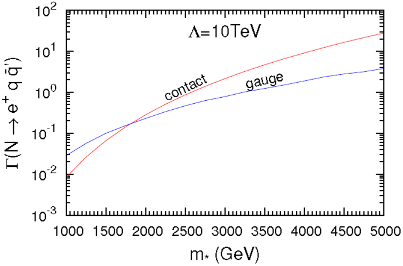


N production and decay

$$\sigma = \sum_{ij} \int_{\frac{m_+^2}{s}}^{1} d\tau \int_{\tau}^{1} \frac{dx}{x} f_i(x, Q^2) f_j(\tfrac{\tau}{x}, Q^2)\hat{\sigma}$$

$\hat{\sigma}$ is the partonic cross section, performed simulation with CalcHEP, CTEQ6m parton distributions, $\sqrt{s} = 13$ TeV.

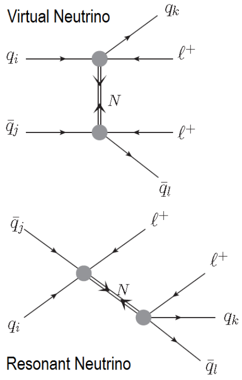


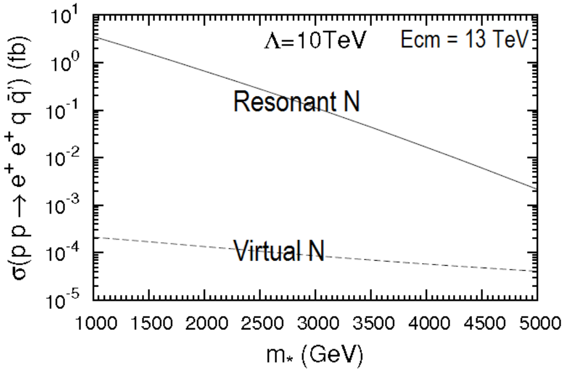


$pp \to N$
The dominant production mechanism is via contact interactions (from 2 to 3 order of size).

$N \to \ell q \bar{q}'$ favourite channel
The 2 interactions are more balanced in the decay.
Other decays:
$N \to \ell^+ \ell^- \nu(\bar{\nu})$, $N \to \nu(\bar{\nu}) q \bar{q}'$

Benchmark process



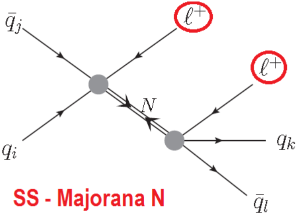


Two processes: s-channel resonantly produced neutrino and the t-channel exchange of a virtual neutrino;
the grey blobs at vertices include both gauge and contact interactions;
the resonant channel dominates from 4 to 2 order of size increasing the neutrino's mass.

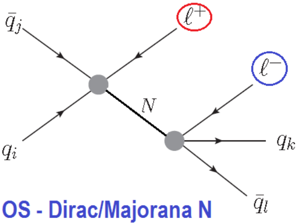
$$\sigma(pp \to \ell\ell jj) = \sigma(pp \to \ell N) BR(N \to \ell jj).$$

Di-lepton sign

Same sign leptons possible only if you assume a Majorana neutrino:

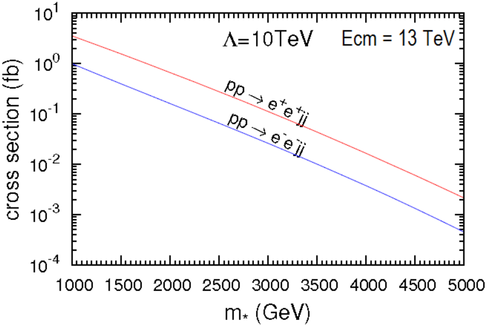


SS - Majorana N



OS - Dirac/Majorana N

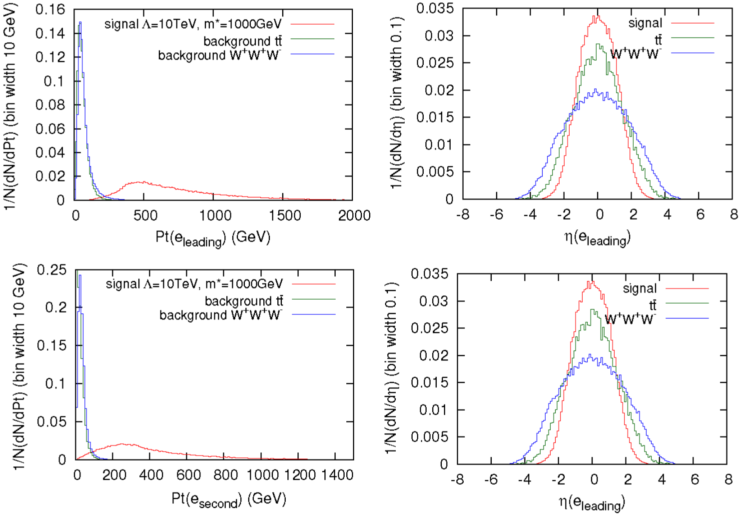
The sea-quark PDF lower then valence-quark at high 4-momenta, $u\bar{d} \to W^+$ prevails on $d\bar{u} \to W^-$:



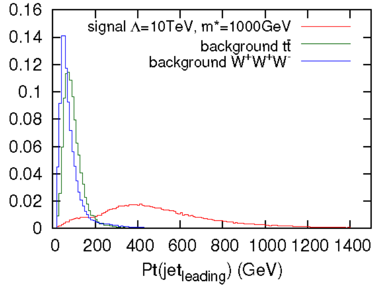
Both possibilities open in our analysis:
no charge requirements for leptons.

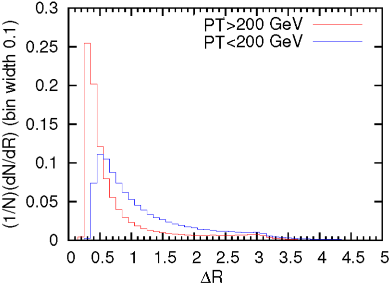
Kinematics - leptons

CalchHEP simulations, signal leptons have a harder p_T specrum compared with the BG leptons (considered only $t\bar{t}$, $W^+W^+W^-$).



Kinematics - merged jets





Observed a discontinuity at 200 GeV in the p_T distribution of the leading jet.

The angular separation ΔR between the 2 jets is shown for:

$p_T(\textit{lead jet}) > 200$ GeV $\rightarrow$ high boost rate of N and merged jets;

$p_T(\textit{lead jet}) < 200$ GeV $\rightarrow$ low boost rate of N and separate jets.

At $p_T > 200$ GeV the p_T of two overlapped jet can be summed up, causing the discontinuity.

Needed specific techniques in the analysis to deal with merged jets in the final state.

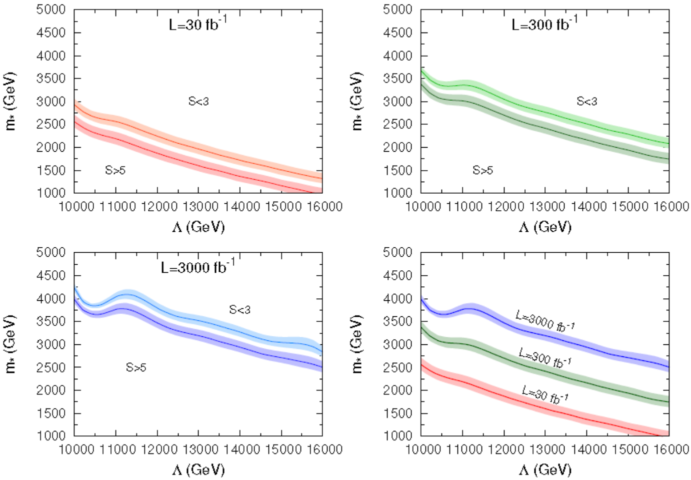
Significance

Delphes simulates detector's response: acceptance and reco.;
Preliminar cuts: $p_T(lep_1) > 200\ GeV$ and $p_T(lep_2) > 100\ GeV$;

Signal yield:
$N_s = L\sigma_s\epsilon_s$;

BG ($t\bar{t}$ and WWW) yield:
$N_b = L\sigma_b\epsilon_b$.

Significance:
$S = \frac{N_s}{\sqrt{N_b}}$.



Summary

- Recent excesses measured by CMS in *eejj* final state have aroused great interest;
- Perugia's group has developed a new compositness model including the contact interaction;
- looking forward to searching for Heavy Neutrinos in di-lepton+di-jet signature within this model;
- discovery/exclusion range $(M_N, \Lambda) = (1 - 4\ TeV, 10 - 16\ TeV)$ at 3'000 fb^{-1}.

Thanks for your attention!

Backup slides

Yields

Estimated signal yields at 3 luminosity stages of Run2 (1, 4, 13 fb^{-1});
Contact interactions significantly help to be sensistive to the signal.

$$pp \rightarrow N\ell \rightarrow (\ell jj)\ell \text{ with } \ell = e, \mu, \tau$$

Signal (→l+,l+, dijet)	σ [fb]	Nevn = σ · Lint (1 fb^{-1})	Nevn = σ · Lint (4 fb^{-1})	Nevn = σ · Lint (13 fb^{-1})
		Contact interaction:		
Nm = 1 TeV	7,65	7,65	30,6	99,45
Nm = 3 TeV	0,22	0,22	0,88	2,86
Nm = 4,5 TeV	0,01	0,01	0,04	0,13
		Gauge interaction:		
Nm = 1 TeV	0,021813	0,021813	0,087552	0,283569
Nm = 3 TeV	0,000157	0,000157	0,000628	0,002041
Nm = 4,5 TeV	0,000004	0,000004	0,000016	0,000052

$pp \rightarrow N\tau \rightarrow (\tau jj)\tau$ the 6 di-τ channels yields in the best scenario:

Contact interactions (Nm = 1 TeV → σ = 7,65 fb)				
ττ decay channels:	σ x BR (fb)	Nevn = σBR · Lint (1 fb^{-1})	Nevn = σBR · Lint (4 fb^{-1})	Nevn = σBR · Lint (13 fb^{-1})
di-mu	σ x 3% = 0,2295	0,2295	0,918	2,9835
di-ele	σ x 3% = 0,2295	0,2295	0,918	2,9835
di-had	σ x 42% = 3,213	3,213	12,852	41,769
mu + ele	σ x 6% = 0,4590	0,4590	1,836	5,967
mu + had	σ x 23% = 1,7595	1,7595	7,038	22,874
ele + had	σ x 23% = 1,7595	1,7595	7,038	22,874

$\tau_h \tau_{lep}$ decay: a compromise between BR and reconstruction capability.

Analysis strategy - Trigger

Tested paths:

di-mu + di-jet channel	di_ele + di-jet channel
HLT_Mu24_v17	HLT_Ele17_CaloIdL_CaloIsoVL_v18
HLT_Mu24_eta2p1_v6	HLT_Ele17_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL_v7
HLT_IsoMu24_eta2p1_v16	HLT_Ele22_CaloIdL_CaloIsoVL_v7
HLT_Mu30_v17	HLT_Ele32_CaloIdL_CaloIsoVL_TrkIdVL_TrkIsoVL_v12
HLT_Mu30_eta2p1_v6	HLT_DoubleEle8_CaloIdT_TrkIdVL_v13
HLT_IsoMu30_eta2p1_v16	HLT_Ele17_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL_Ele8(samesel)_v20
HLT_Mu22_TkMu8_v10	HLT_DoubleEle33_CaloIdL_v15
HLT_Mu22_TkMu22_v10	

The single lepton paths *HLT_Mu24*(*HLT_Ele17_CaloIdL_CaloIsoVL*) for $\mu\mu jj$ (ee jj) give the best performances in terms of trigger efficiency.

Analysis strategy - Selection

OBJECTS: POG reccomandations for high p_T objects.
Electrons: HEEP or EG selection; Muons: POG, Tight or High-pT.
Jets: PF, $antik_T$, R=0.5. Two final jets may tend to overlap, more sophisticated techniques for jet reconstruction.

SELECTION ($e(\mu)e(\mu) + jj$ channel or $\tau_h\tau_\ell + jj$ channel):
Single lepton HLT paths: Mu24 and Ele17-CaloIdL-CaloIsoVL.
Exactly 2 leptons; 2 or 1 jet, depending on the rate of boosted N.
No b jets to reduce $t\bar{t}$ background. No charge requests for lepton.
$E_T < 40$ GeV to reduce W+jets);
$E_T > 40$ GeV to reduce multi-jets bkg;
$m(\ell, \ell) > 110$ GeV to reduce DY;
$m(\tau_h, \tau_\ell, E_T) > 90$ GeV ($\tau_h\tau_\ell$) to reduce DY;
Attemp to perform a shape analysis:
$M(\ell\ell jj)$ or $S_T = p_T(jet_1) + p_T(jet_2) + p_T(\tau_1) + p_T(\tau_2) + E_T$

BACKGROUND: for $t\bar{t}$ fully data-driven method;
Z+jets: normalize MC around Z peak or data-MC scale factor.