# Searches for new phenomena in final states involving leptons and jets using the ATLAS detector

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# Leptons and jets signatures

- LHC in Run2 is delivering 13 TeV pp collisions and high Luminosity:
  - formidable dataset to push the reach of all the searches
  - tough technical challenge

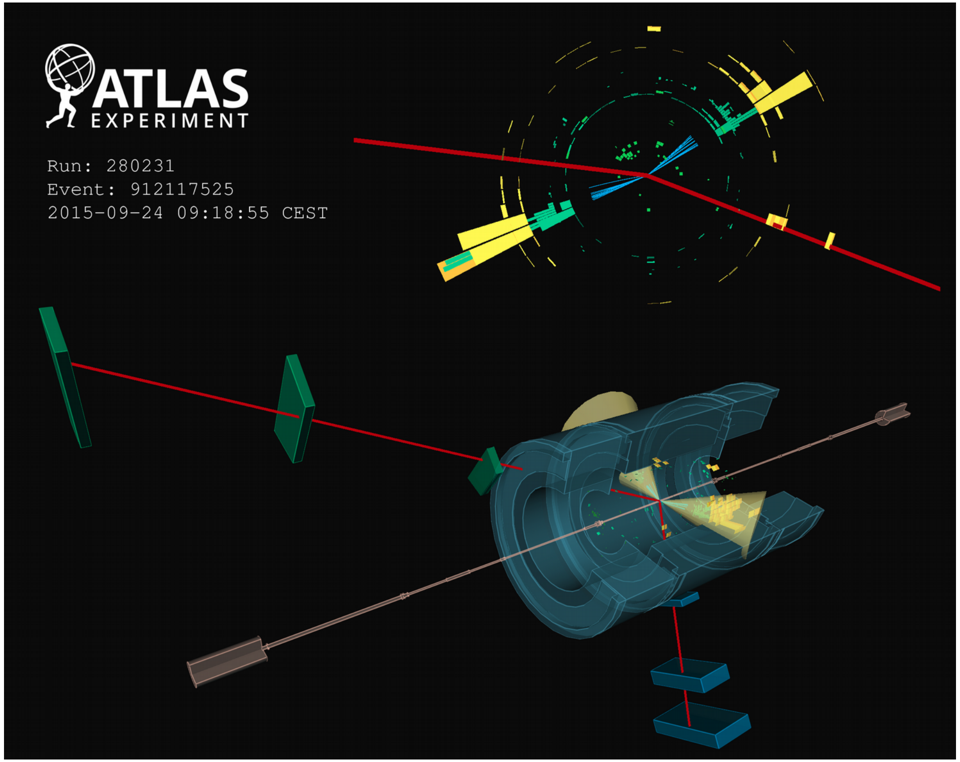
- Final states featuring leptons and jets are used to investigate a very wide range of phenomena

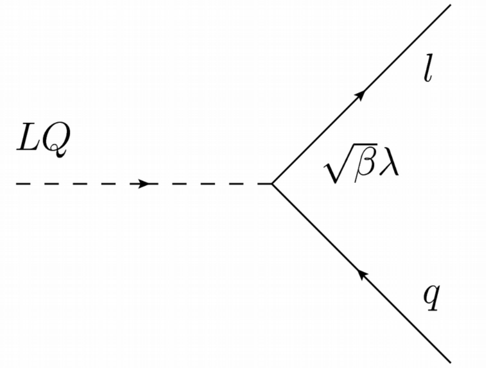
- Non exhaustive selection of ATLAS results with leptons+jets final states presented:
  - Vector like quark — *Olaf Nackenhorst*
  - Heavy resonances decaying to top — *Saverio D'Auria*
  - VV in lνqq, llqq, ννqq — *Kalliopi Iordanidou*
  - Higgs interpretations llqq, ννqq — *Leonardo Carminati*

- Covered in this talk:
  - Leptoquarks — **New J. Phys. 18 (2016) 093016**
  - TeV-scale gravity — **Physics Letters B 760 (2016) 520-537**

# Search for scalar leptoquarks

- Inclusive search for new physics phenomena resulting in final state signatures of lepton-jet resonances in 3.2 $fb^{-1}$ of 13 TeV pp collisions.
- Leptoquarks (LQ) feature in a number of theories and their existence would provide a connection between quarks and leptons.
- Renewed interest pushed by recent results from LHCb on *measurement of the ratio of branching fractions between* $B^0 \to D^{*-}\tau^+\nu_\tau$ *and* $B^0 \to D^{*-}\mu^+\nu_\mu$ *using three-prong hadronic τ decays*, supporting a ~3σ tension on lepton universality.



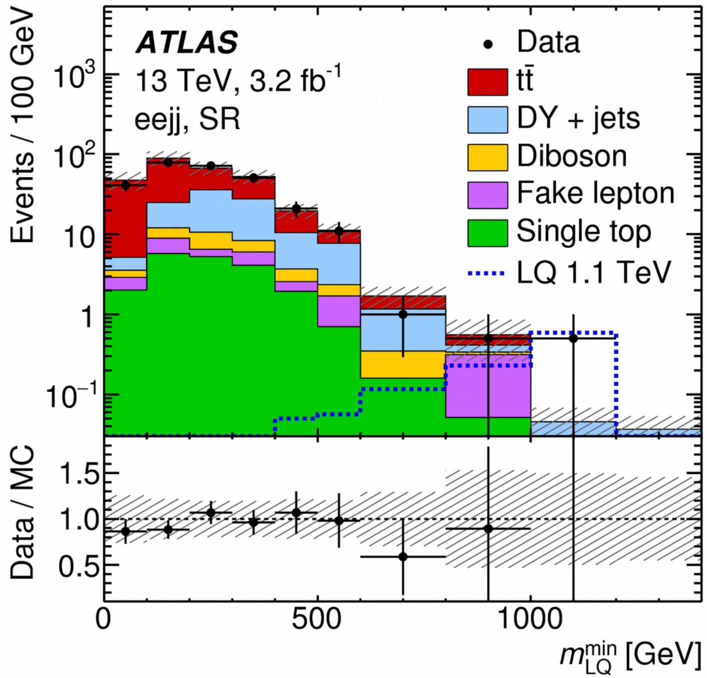



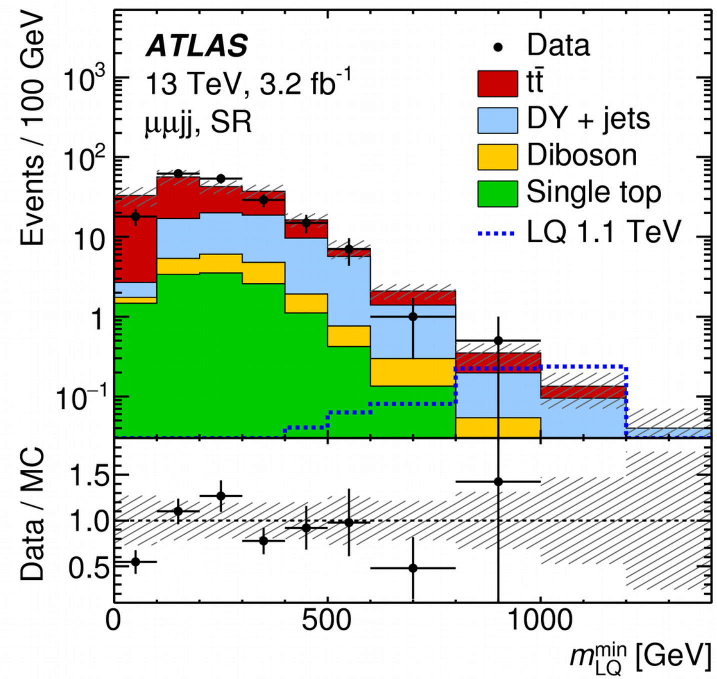

- LQ can decay directly to lepton–quark pairs.
- Benchmark model considered:
  - LQs assumed to couple to quarks and leptons of the same generation;
  - pair production of scalar LQs;
  - final states studied: *eejj* and *μμjj* .

| Preselection | | $2e$, $E_T \geq 30$ GeV ($2\mu$, $p_T \geq 40$ GeV) + $2j$, $p_T \geq 50$ GeV |
|---|---|---|
| SR, CR, VR | $m_{ll}$ | Dilepton invariant mass |
| | $S_T$ | Scalar sum of the transverse momentum of the two leptons and the two leading jets |
| | $m_{LQ}^{min}$ | Minimum invariant mass of the two lepton–jet pairs in an event.<br>The lepton–jet pairs are chosen such that the invariant mass difference between them is smallest. The lower mass of the 2 combinations is used as the discriminating variable following dedicated sensitivity studies. |

- Signal (SR), control (CR) and validation (VR) regions, to optimise signal significance and constrain the normalization of the main background sources
- Profile-likelihood fit of signal + background templates.
- Systematic uncertainties incorporated into the likelihood as constrained nuisance parameters.
- Simultaneous fit performed in SR and CR to extract normalisation factors for backgrounds.

| Region | Channel | #e | #$\mu$ | $m_{\ell\ell}$ [GeV] | $S_T$ [GeV] |
|---|---|---|---|---|---|
| $t\bar{t}$ CR | both | 1 | 1 | – | – |
| DY+jets CR | $eejj$ | 2 | 0 | [70, 110] | – |
| | $\mu\mu jj$ | 0 | 2 | | |
| SR | $eejj$ | 2 | 0 | >130 | >600 |
| | $\mu\mu jj$ | 0 | 2 | | |
| VR | $eejj$ | 2 | 0 | >130 | <600 |
| | $\mu\mu jj$ | 0 | 2 | | |



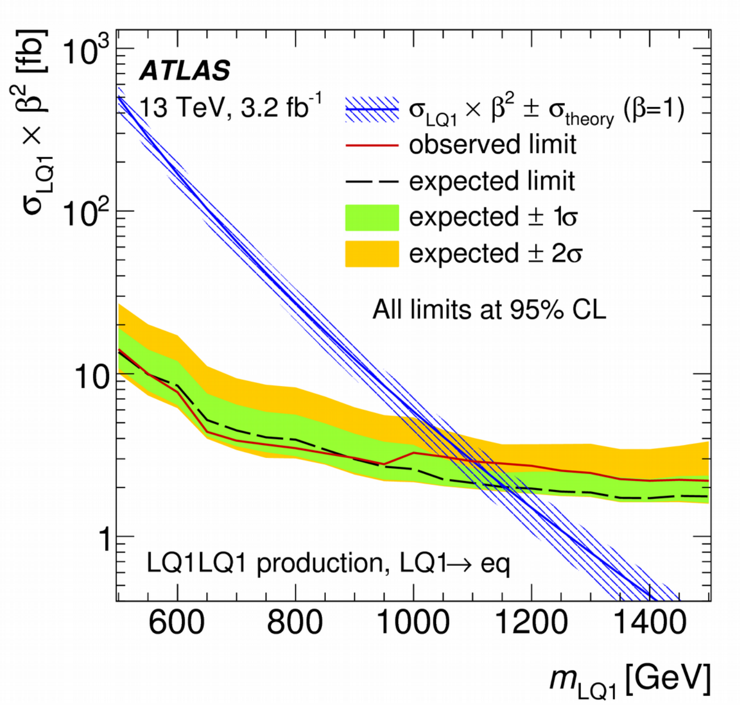

- The results are consistent with SM expectations.
- The normalisation factors for the main background components are compatible with unity within the uncertainties.

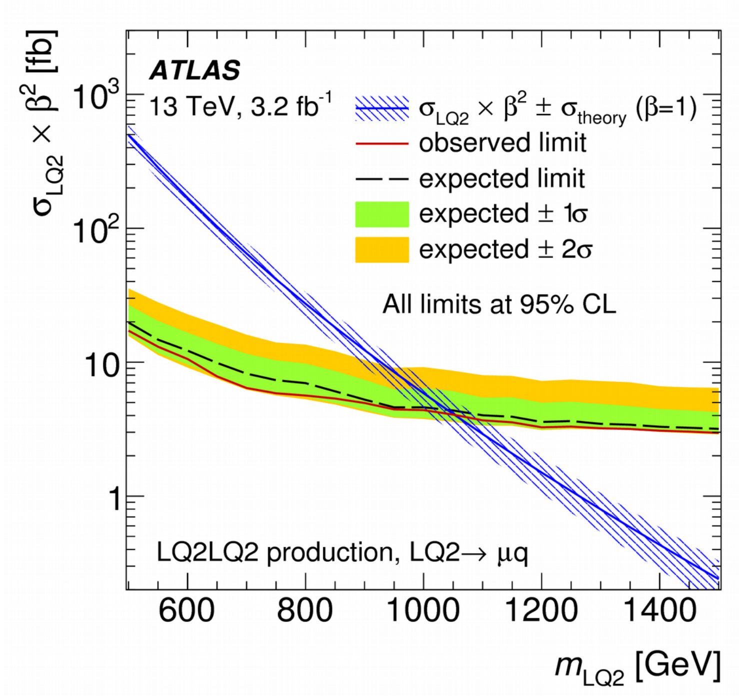
| Channel | DY+jets | $t\bar{t}$ |
|---|---|---|
| $eejj$ | $0.9 \pm 0.1$ | $1.0 \pm 0.1$ |
| $\mu\mu jj$ | $0.9 \pm 0.1$ | $1.0^{+0.2}_{-0.1}$ |

Background normalisation factors

# LQ - Limits

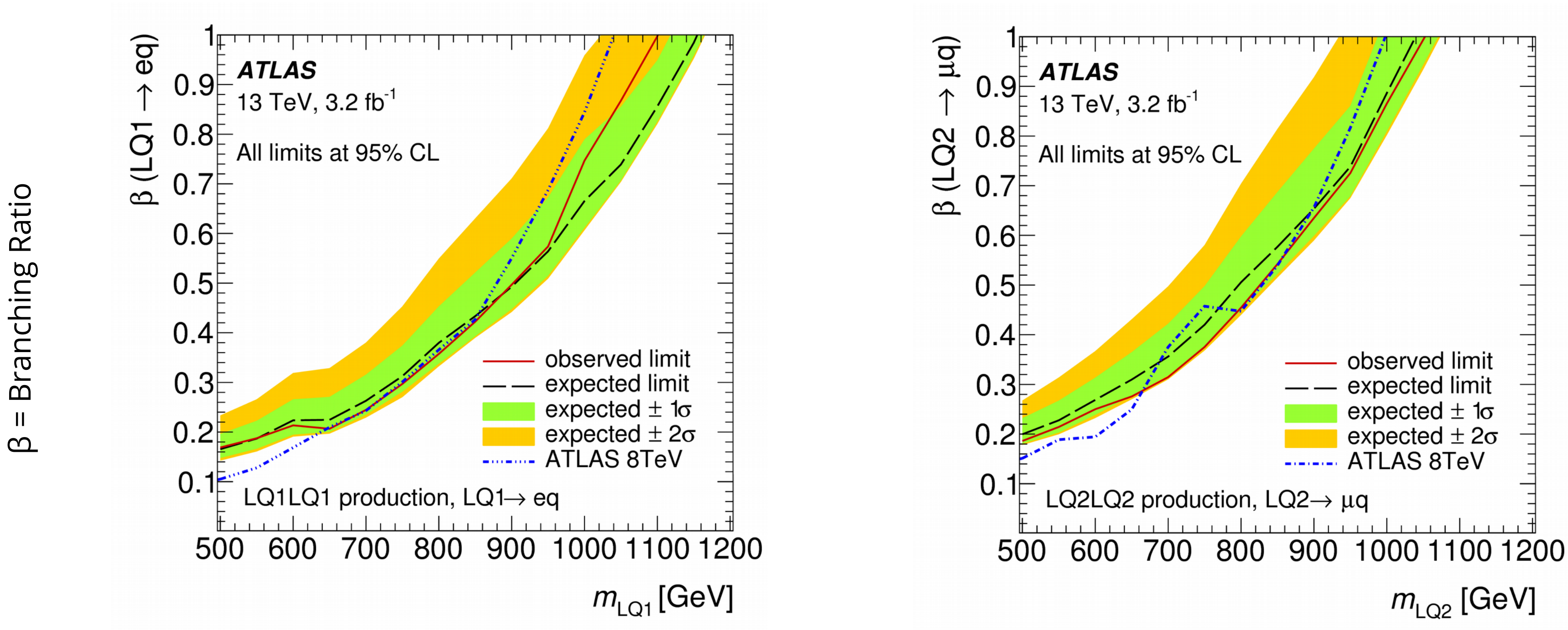
β = Branching Ratio



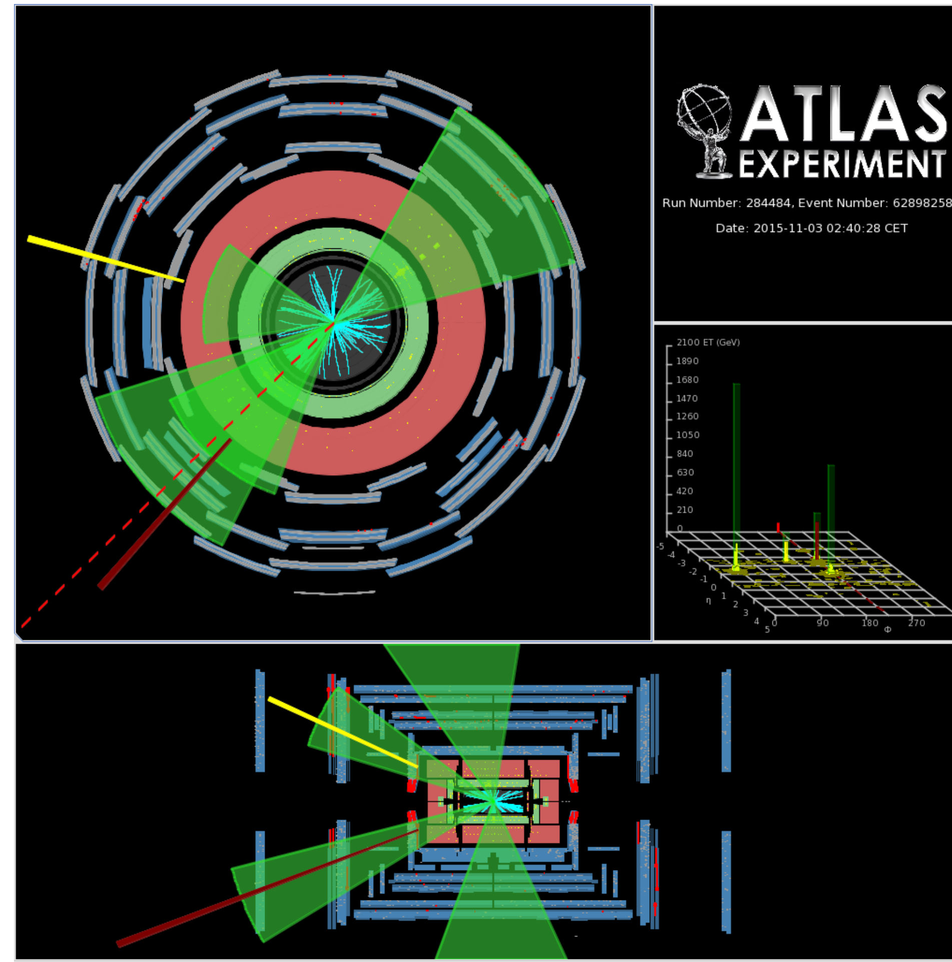

- Limits on the LQ signal strength were derived using pseudoexperiments and following a modified frequentist CLs method.
- Dominant uncertainties in the signal event yields arise from lepton scale factors and are of the order of 2–5% at low masses and up to 10% at high masses.

| $\beta$ | 95% CL limit on $m_{LQ1}$ [GeV] Expected | $m_{LQ1}$ [GeV] Observed | $m_{LQ2}$ [GeV] Expected | $m_{LQ2}$ [GeV] Observed |
|---|---|---|---|---|
| 1.00 | 1160 | 1100 | 1040 | 1050 |
| 0.75 | 1050 | 1000 | 950 | 960 |
| 0.50 | 900 | 900 | 800 | 830 |
| 0.25 | 680 | 700 | 580 | 600 |




- The theoretical cross section scaled by $\beta^2$ is used to obtain the limits on the branching ratio as a function of the LQ mass
- Comparison between 13 TeV and 8 TeV limits:
  - $m_{LQ}$ <= 650 GeV, 13 TeV limits are weaker due to the much lower integrated luminosity and background effects;
  - $m_{LQ}$ >= 900 GeV, 13 TeV limits are stronger due to the gain in the production cross section at higher com energy.

- A search for physics beyond the Standard Model, in final states with at least one high transverse momentum ($p_T$) charged lepton (electron or muon) and two additional high-$p_T$ leptons or jets, in 3.2 $fb^{-1}$ of 13 TeV pp collisions.
- For several models of TeV-scale gravity interesting signatures are expected in the form of non-perturbative gravitational states such as microscopic black holes.
- Benchmark models for TeV-scale gravity are characterized through two parameters:
  - $M_D$ : fundamental scale of gravity
  - $M_{th}$ : minimal threshold for continuous production.




A visualisation of the event with the highest $\sum p_T$ observed in the 2015 data in the electron channel.

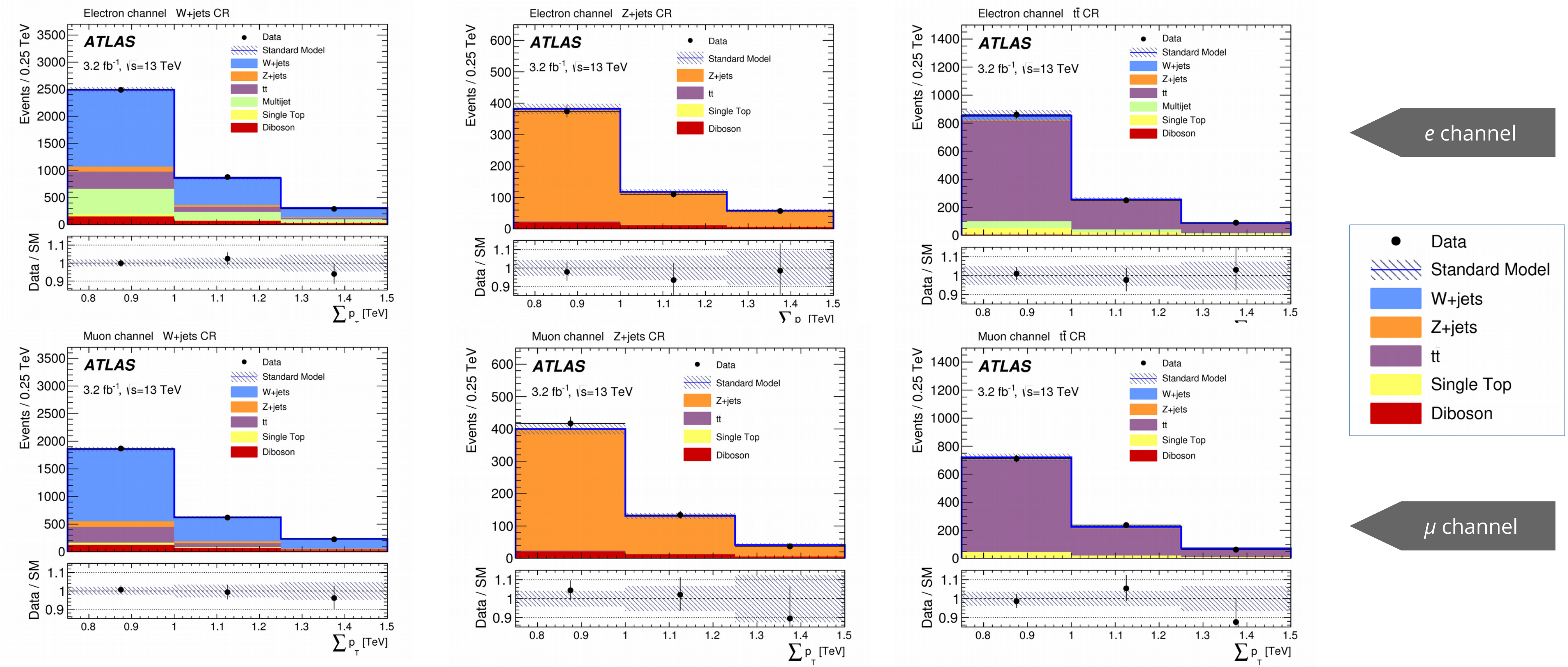
# TeV-scale gravity – Analysis strategy

- The upper end of the distribution of the scalar sum of the $p_T$ of leptons and jets ($\Sigma p_T$) is sensitive to the production of high-mass objects.
- 2 channels (electron and muon) according to the highest $p_T$ lepton.
- 2 non-exclusive SRs:
  - $\Sigma p_T$ > 2 TeV (`SR-2TeV`)
  - $\Sigma p_T$ > 3 TeV (`SR-3TeV`)

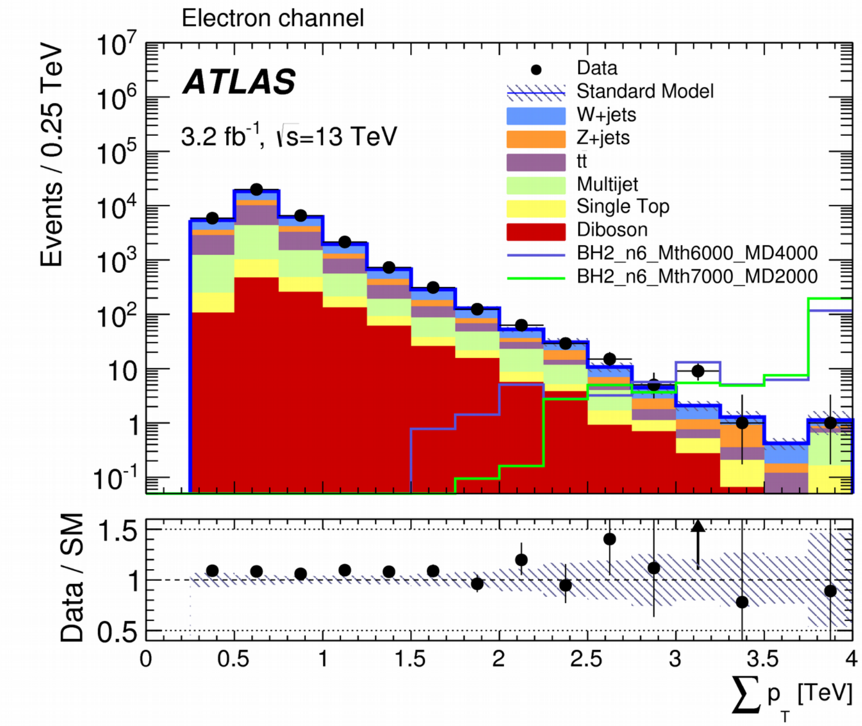
| **Selection** | **Control Regions** | | | **Signal regions** |
|---|---|---|---|---|
| | $Z$+**jets** | $W$+**jets** | $t\bar{t}$ | |
| $\sum p_{\mathrm{T}}$ | 750–1500 GeV | | | > 2000(3000) GeV |
| Number of objects (leptons or jets) | $\geq$ 3 objects with $p_{\mathrm{T}} > 60$ GeV | | | $\geq$ 3 objects with $p_{\mathrm{T}} > 100$ GeV |
| Leading lepton (electron or muon) | Isolated with $p_{\mathrm{T}} > 60$ GeV | | | Isolated with $p_{\mathrm{T}} > 100$ GeV |
| $m_{\ell\ell}$ | 80–100 GeV | n/a | | n/a |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ | n/a | > 60 GeV | n/a | |
| Number of leptons | = 2, opposite sign same flavour | = 1 | | $\geq 1$ |
| Number of $b$-tagged jets | n/a | = 0 | $\geq 2$ | n/a |
| Number of jets | n/a | | $\geq 4$ | |

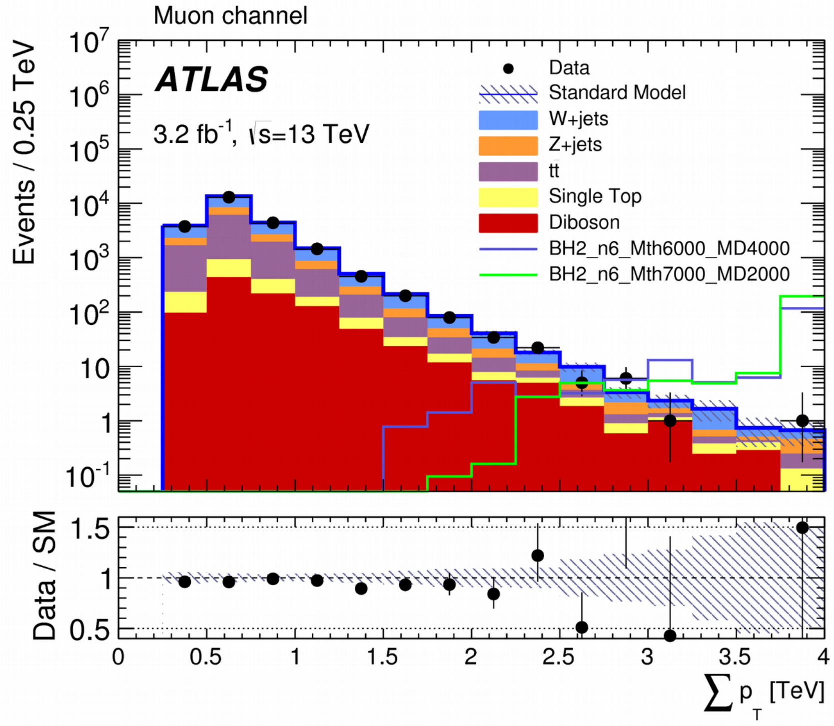
- Validation Regions (VR): same event selections as SRs, but in the range 1500 < $\Sigma p_T$ < 2000 GeV.
- Dominant backgrounds: *W+j*, *Z+j* and *ttbar* (evaluated with MC simulation)
- For electron channel background originating from jet incorrectly reconstructed as electrons (called "*multijet*") is estimated from data using a Matrix Method.

# TeV-scale gravity – Control regions




- Expected background yields in VRs predicted by a likelihood fit to all CRs of both lepton channels.
- The MC simulation provides a good description of the CR data, with scale factors of 0.81 ± 0.07, 1.01 ± 0.08 and 0.95 ± 0.08 for *W+j*, *Z+j* and *ttbar* respectively.



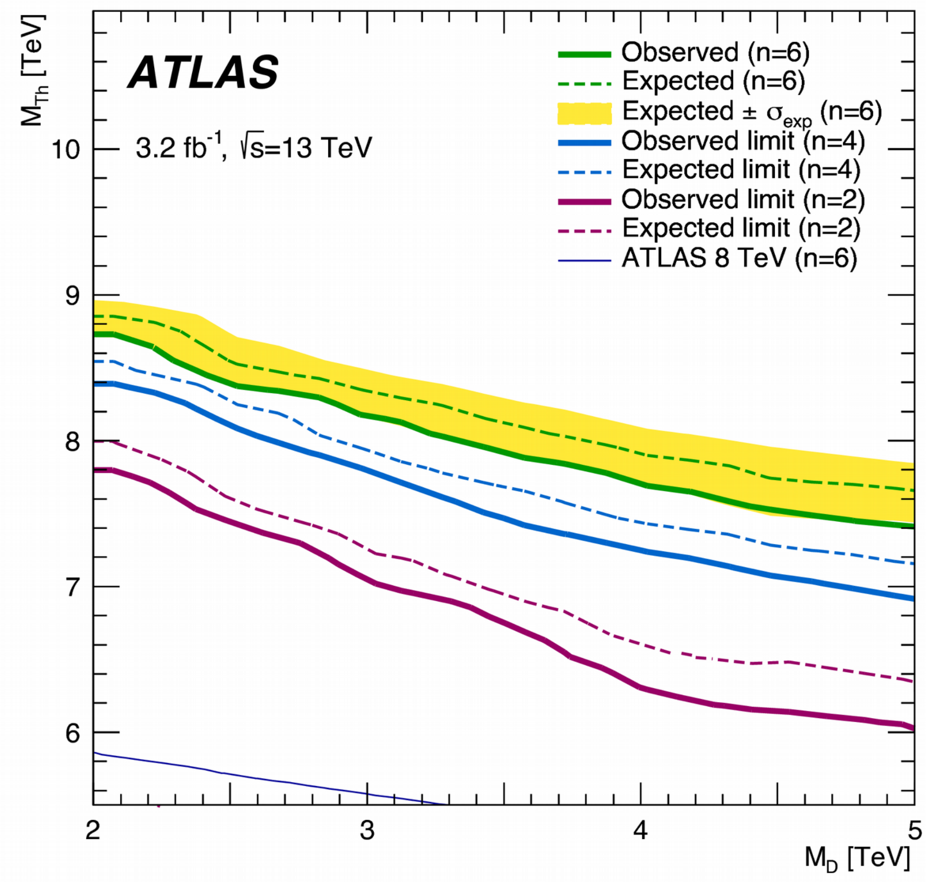




The selection is that of the signal regions except for the final requirement on $\sum$ pT

- Results are extracted from profile likelihood fits using 3 background normalisation parameters for the *W+j*, *Z+j* and *ttbar* backgrounds.

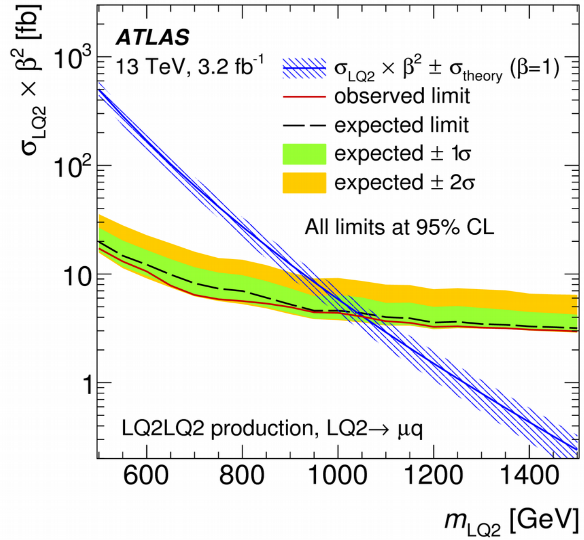
| | SR-2TeV (electron) | SR-2TeV (muon) | SR-3TeV (electron) | SR-3TeV (muon) |
|---|---|---|---|---|
| Observed events | 123 | 69 | 11 | 2 |
| Expected bkg events | $104 \pm 9$ | $78 \pm 6$ | $4.6 \pm 0.8$ | $5.3 \pm 1.2$ |
| Expected $t\bar{t}$ events | $13.8 \pm 3.1$ | $11.4 \pm 2.5$ | $0.65 \pm 0.18$ | $0.55 \pm 0.15$ |
| Expected $W$+jets events | $32.0 \pm 3.5$ | $33.9 \pm 3.2$ | $1.76 \pm 0.31$ | $2.0 \pm 0.4$ |
| Expected $Z$+jets events | $16.6 \pm 1.5$ | $12.6 \pm 1.4$ | $1.09 \pm 0.18$ | $0.77 \pm 0.24$ |
| Exp. single-top-quark events | $6.1 \pm 0.9$ | $5.2 \pm 0.7$ | $0.59 \pm 0.18$ | $0.54 \pm 0.14$ |
| Expected diboson events | $11.4 \pm 1.4$ | $14.5 \pm 1.5$ | $0.22 \pm 0.18$ | $1.5 \pm 0.5$ |
| Expected multijet events | $24 \pm 7$ | $0.0 \pm 0.0$ | $0.32 \pm 0.24$ | $0.0 \pm 0.0$ |

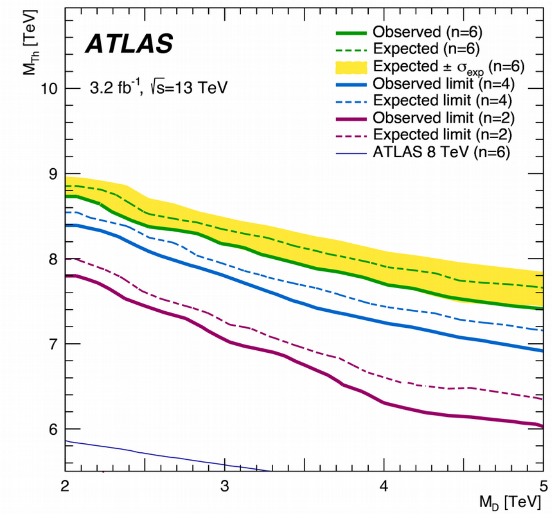
- Model-independent cross-section upper limits on any potential new physics contribution: fits to all CRs and to SRs combining the electron and muon channels.
- Model-independent upper limits of 12.1 fb (3.4 fb) at the 95% CL on the maximum σxAxε for new physics producing a lepton in conjunction with at least two other objects, each with $p_T$ > 100 GeV, in the `SR−2TeV` (`SR−3TeV`) region.
- Fits including predicted signal yields in all CRs and SRs simultaneously are used to extract exclusion limits for specific black-hole signal models.




n = number of additional flat extra dimensions

- ATLAS searches for LQ and TeV-gravity scale phenomena clearly improved their reach respect to LHC Run1.
- Many ATLAS results presented are based on the study of final states with leptons and jets.
- ATLAS collaboration features a wide and well established physics program for the study of final states with leptons and jets.
- Reconstruction and identification performances continue to improve thanks to focused effort and application of modern techniques.
- Full LHC-Run2 statistics will push the reach of all the searches even further.



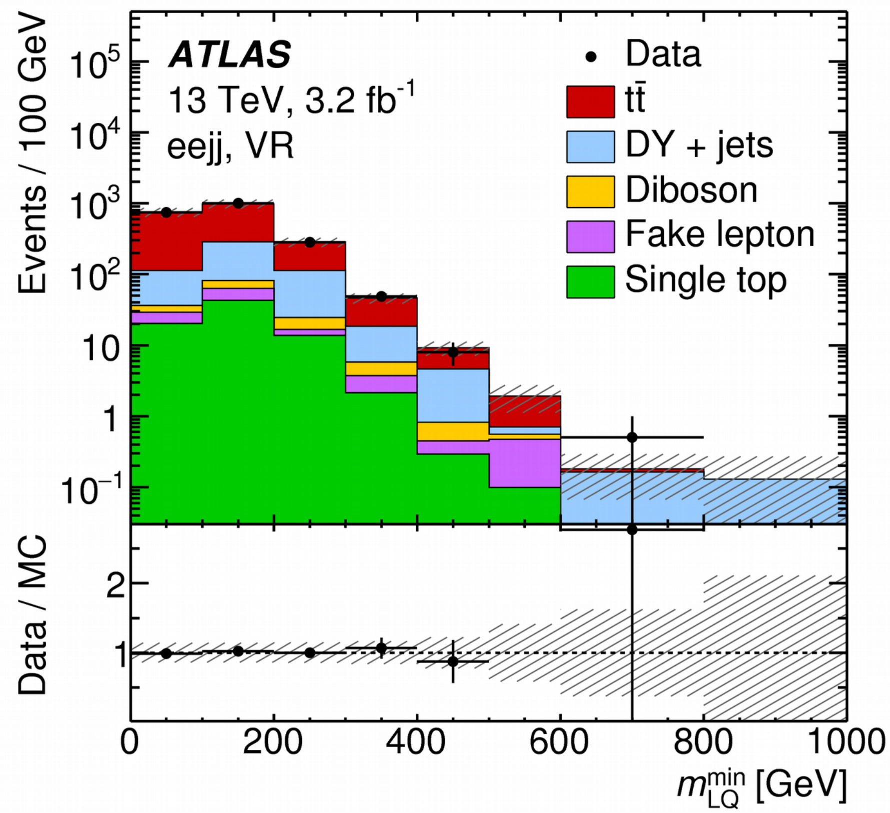



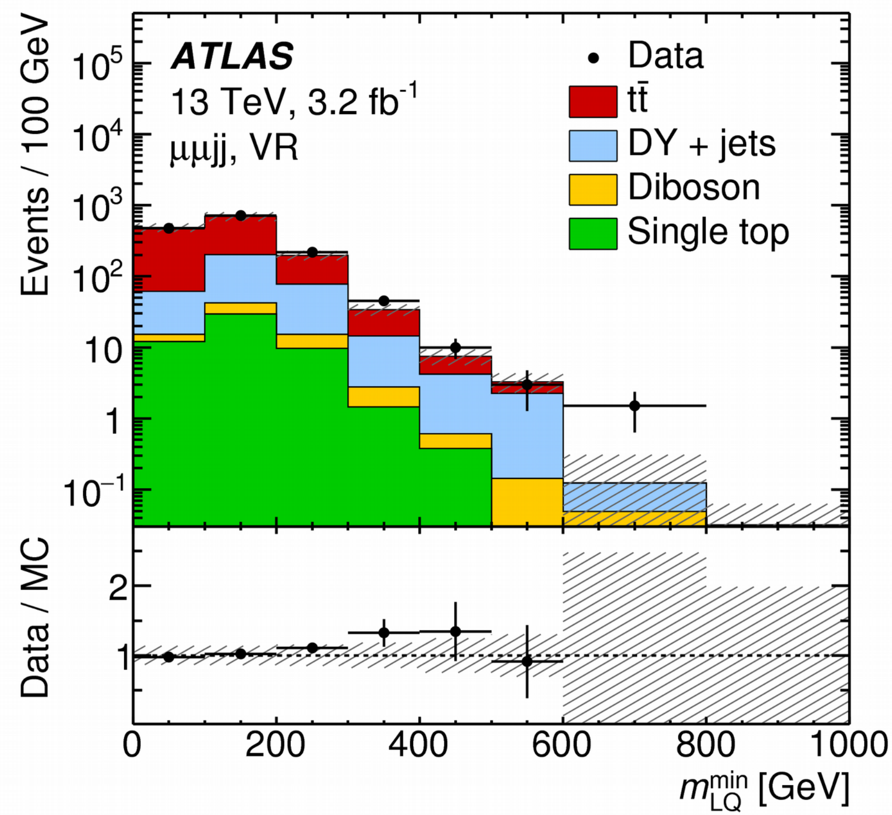
# LQ – Physics objects definitions

| | e | μ | jet |
|---|---|---|---|
| Trigger | 2e , $E_T \geq 17$ GeV | 1 μ, $p_T \geq 25$ GeV , isolated<br>OR 1 μ $p_T \geq 50$ GeV | - |
| $E_T$ | $E_T \geq 30$ GeV | $p_T \geq 40$ GeV | $p_T \geq 50$ GeV |
| $\|\eta\|$ | $\|\eta\| < 2.47$<br>($1.37 < \|\eta\| < 1.52$ excluded) | $\|\eta\| < 2.5$<br>($1.01 < \|\eta\| < 1.10$ excluded) | $\|\eta\| < 2.8$ |
| Reconstruction & Identification | ε between 75% and 92% rising with $E_T$ | ε ~ 80% | anti-$k_t$ (R=0.4)<br>no flavour tagging |
| Isolation | Track & calo based<br>ε ≥ 99% | Track based<br>ε ≥ 99% | - |
| Primary vertex | $\|d_0/\sigma_{d0}\| < 5$<br>$\|z_0 \sin\theta\| < 0.5$ mm | $\|d_0/\sigma_{d0}\| < 3$<br>$\|z_0 \sin\theta\| < 0.5$ mm | - |
| SFs & event weights | Applied to reconcile simulation with data | | |

| Overlap removal | | |
|---|---|---|
| 1 | μ-e | e removed if track shared |
| 2 | e-j | $\Delta R(e,j) < 0.2 \rightarrow$ j removed<br>$0.2 < \Delta R(e,j) < 0.4 \rightarrow$ e removed |
| 3 | μ-j | $\Delta R(\mu,j) < 0.4$ & j has < 3 tracks → j removed<br>otherwise → μ removed |

# LQ – Validation regions



# TeV-scale gravity – Physics objects definitions

| | e | μ | jet |
|---|---|---|---|
| Trigger | single e , $E_T$ > 60 GeV | single μ , $p_T$ > 50 GeV | - |
| $p_T$ | > 10 GeV | > 10 GeV | > 20 GeV |
| η | \|η\| < 2.47 | \|η\| < 2.5 | \|η\| < 2.8 |
| Reconstruction & Identification | Loose ID<br>Tight ID after overlap removal | Medium ID | anti-$k_t$ (R=0.4) , Loose , (flavour tagging) |
| Isolation | Loose , ε ≥ 99% | | - |
| SFs & event weights | Applied to reconcile simulation with data | | |

| Overlap removal | | |
|---|---|---|
| 1 | μ-e | e removed if track shared |
| 2 | e-j | non b-tagged jets removed if ΔR(e,j) < 0.2 |
| 3 | l-j | leptons are removed if ΔR(l,j) < 0.4, with j surviving step (2) and not tagged as originating from pile-up |