Text Key:

**Purple text = Examiners comments either verbal or annotation on thesis hard copies.**

**Red text = small typos/text changes that have been made.**

**Blue text = Author’s remarks/changes**

All page numbers refer to thesis as submitted in order to easily reference the examiners’ annotated copy of the thesis as submitted.

**CORRECTIONS:**

Acknowledgements:

* Move **Annabel Shaw** from family and loved ones to the end of my list of friends given the end of our relationship.
* Add **Sioni Summers, and Thomas James** to coffee bit.

**Examiner 1 = Internal.**

**Examiner 2 = External.**

Abstract:

* **Examiners: Multiple numbers underlined with comment “#s.f. a bit large” (sig figures).**

Introduction:

* Page 23: ~~While~~ **T**he top quark**’s** **~~has the same properties as the other five quarks, its~~** mass of 173+/-0.4 GeV [21], not only places it near the electroweak …

An Introduction to the Standard Model and Top Quark Physics:

* The Standard Model:
  + **Examiners** (Page 25):**What is kB?** **(Is this a viva question or correction? Added clarification in parenthesis).**
  + Fundamental Particles:
    - **Examiners** (Page 25): “… six leptons, fundamental particles experience the electromagnetic and weak force”. **Neutrinos don’t interact with EM. Replaced with** “… fundamental particles that do not experience the strong force”**.**
    - **Author** (Page 26) – The spin-0 Higgs boson accounts for fundamental particles acquiring mass. WHOOPS. **Also picked up by Examiners.**
      * **Replaced with:** “… fundamental
    - **Author** (Page 27): Table 2.2 – “Gauge Bosons” heading changed to “Bosons”.
    - Examiners: (Page 27, Table 2.2) **Weak isospin and colour charge entries for gluons are each other’s respective columns.**
      * **Entries now in the current columns.**
  + Gauge Symmetries:
    - **Examiner 2**: (Page 28) “For the case of QED, as U(1) has only one generator, which self-commutes, **and** is zero.” ***Disagree* on grammar grounds as added “and” would make sense if “as” was not present.**
  + QED:
    - **Author** (Page 29): “… Heisenberg's uncertainty principle, it***s* (or *the*)** field experiences random fluctuations.” **(Examiners also picked up on this)**.
    - **Examiner 1**: (Page 29) “reduced”. **is it measured? Viva question. Discussed in viva.**
  + Weak Interactions:
    - **Examiner 1:** (Page 30) **What is chirality?** Explain … chirality/left-handed fermions and T = +/- ½ **Clarified offline that this was a viva question.**
  + Electroweak Unification:
    - **Examiners**: (Page 30) **“… gauge group hypothesises that its …”** – technically a theory cannot hypothesise something. Only a person can …
      * **Replaced with:** **“…** gauge groupand **~~hypothesises that it’s~~ describes the** two seemingly disparate constituent forces – weak and electromagnetic – **~~are described~~** as a single …”
  + Spontaneous Symmetry Breaking:
    - **Author** (Page 31): “Brout, Engler, Higgs,**[insert space]** Guralnik, Hagen …” (**Examiners also picked up on this**).
    - **Examiners**: (Page 31) Explain: “… infinite number of ground states.”
      * **Discussed in viva. Also slight rephrasing:** “ … infinite number of **degenerate** ground states”.
    - **Author:** (Page 32, Figure 2.1) **Rephrase** - “The **~~potential's~~** infinite **number of degenerate ground states** **~~minima~~** form a circle in phase space …”
    - **Author** (Page 32): **Added uncertainties on the Higgs Mass!**
  + QCD:
    - **Author** (Page 33): “This results in the colour confinement **of partons** [31, 46, 53].”
    - **Both examiners**: (Page 33) “decreases with **decreasing** distance (increasing momenta).”
* Top Physics:
  + Page 33: **~~Given that~~** **As** the top quark was more massive than initially assumed **~~however~~**, …
  + **Examiner 2**: (Page 34) “Measurements of the Wtb vertex allow**s** for the …”
  + Top quark pair production:
    - **Author** (Page 35): Missing second bullet point; **·** Higher centre-of-mass energies results in smaller Bjorken *x*
    - **Author** (Page 35): Reorder bullet points to emphasise greater importance of the latter point. And add bullet point!
  + Single top quark production:
    - **Examiner 2:** (Page 36) Inked lines between paragraphs two and three. No paragraph break? **Merged paragraphs one and two.**
    - **Author** (Page 37): Figure 2.5(a) – bbar is NOT from the sea! Due to charge asymmetric initial state
    - **Examiner 1**: [underlined] (Page 37) “on-shell W boson”. **Viva question. Discussed.**
    - **Examiner 1**: [underlined] (Page 37) “… tW production is observable at the LHC ….”
      * **Correction? Produced alternative version:** “In contrast to being negligible at the Tevatron, **the** tW **~~production is observable~~** **cross section** at the LHC **is sufficiently large to make it accessible, resulting in it being** **~~and was~~** discovered in 2014.”
    - **Examiner 1**: (Page 38) “… destructive interference between the tH and HW vertices” **WHY?** **Viva question or correction? Added additional text that follows the above.**
      * **“﻿This destructive interference occurs due to the large matrix element contributions from both tH and HW Feynman diagrams being of the same order of magnitude but having opposite signs.”**
  + Single top production in association with a Z boson:
    - **Author** (Page 38): In contrast, ttZ **[insert space]** has a lower … (**Examiners** also picked up on this).
    - **Author** (Page 38): “**trilepton**: when the W boson decays into a lepton and neutrino and the Z boson decays into a lepton and anti-lepton **[insert full stop].**”
    - **Author** (Page 38): **hadronic**: both the W boson and Z boson decay into a quark and anti-quark **[insert full stop].**”
    - **Examiners** (page 39-40): “…trilepton final state, **~~as~~** while it has a smaller …”
      * **Author’s suggested text**: “… the trilepton final state **as despite it having** a smaller …”
    - **Examiners** (page 39): Underlined Fig 2.7 “the **~~the~~** non-resonant contribution to the tZq process in the bottom right diagram.”
    - **Examiners**: (page 40): [underlined] “… it is the easiest to distinguish against …”
      * **Viva question. Discussion in viva. Also rephrased text slightly:** “… it is the easiest to **~~distinguish against~~** **separate from** ﻿background processes.”
    - **Author** (Page 40): “as a result of the **t**Z and tbarZ cross sections increasing with the centre-of-mass energy at a similar rate to ttZ **[insert space]** and …” (**Examiners** also picked up on this).
    - **Examiners** (page 40)**: “**Such an increase in statistics”- colloquial use of the word statistics! **Rewritten:** “**This increase in the tZq production cross section and the large integrated luminosity being delivered by the LHC at sqrt(s) = 13 TeV** has also made …”
    - **Author** (Page 40): Errors for Equation 2.16 (tZq cross section).
  + Beyond the Standard Model Physics:
    - **Examiner 1:** (Page 41) “Explain”[comment in margins next to hierarchy text] why the Higgs vev would be either 0 or ~ order of plank’s constant and why cancellations would need to be fine-tuned. “**Given that the loop corrections for the Higgs mass are quadratically divergent, this would imply that the Higgs vacuum expectation value would be either zero or at the mass scale of any new physics”.**

LHC and CMS:

* LHC:
  + **Examiner 1** (page 42)**:** “The LHC can also operate in a heavy-ion mode, where lead ions are collided at 2.76TeV per nucleon **which** **is** usually **done** for one month a year.”
  + **Examiner 1** (Page 45): Repeating proton bunches, bunch separation and collision rate. **Corrected thesis just states CoM energy and design luminosity in opening paragraph, and have the further details in Section 3.1.2 (Motivation).**
  + **Examiner 1** (Page 45:) Explain the difference between in-time/out-of time PU. How is this possible? **Viva question. Discussed in viva.**
* CMS:
  + Overview:
    - **Examiner 1** (Page 46): Where is the HO in the diagram? (Fig 3.4). **The HO is not usually shown on diagrams of CMS.**
    - **Examiner 1** (Page 47): [underlined] This is due to η ?
      * **Very poor language used in the original text. Provided clearer definition for both y (rapidity) and eta (pseudo – rapidity)**.
  + Tracker:
    - **Examiners**: (Page 47): “… a low channel occupancy (<1%)**.**”
    - **Examiner 2** (Page 48): “ROCs” undefined.
      * **Added definition.**
    - **Examiner 1** (Page 48): How are pixels better than strips for track recon. **Viva question. Discussed in viva.**
    - **Examiner 1** (Page 48): Last paragraph of subsection 3.2.2 (Tracker) before subsection 3.2.2.1 (Silicon Pixel Tracker) needs to be better English! **Added missing text that resulted in the poor language. Rewritten to improve overall paragraph.**
  + Silicon Pixel Tracker:
    - **Examiner 2** (Page 48): “… Tracker Inner Disks (TID**)**, …”
    - **Examiner 1** (Page 48): “… barrel layers at mean radii of 4.4 **cm**, 7.3 **cm**, and 10.2 cm respectively …”
    - **Examiner 1** (Page 48): Nice to have pictures of SPT and SMT.
      * **Chosen two picturesque images for each subsubsection as technical layout is already shown in subsection 3.22 (Tracker).**

Page 48: Make it clear that the Phase-1 pixel has always been planned

* + Silicon Microstrip Tracker:
    - **Author** (Page 49): Correct z0 -> z
  + ECAL:
    - **Examiners** (Page 49): “… scintillation light when the electromagnetic shower de-excites …” phrasing of EM shower and spelling for de-excites. **Rephrased.**
    - **Author** (Page 49): “Avalanche photo**~~s~~**diodes … amplify the light and **convert** it into an …”. **Examiners also picked up on these**.
    - **Author** (Page 49): more radiation hard vacuum **phototriodes** in the endcap disks.
    - **Examiners** (Page 49): EE resolution to be added to supplement the EB one present. **Resolution is from an EB paper for the crystals in front of the test beam, but measurement is for PbWO4 crystals in general (and cannot find a similar quote for EE). Other theses use the same reference and value without a separate “EE resolution”.**
  + Muon Chambers:
    - **Author** (Page 53): DTs - Correct z0 -> z’s
    - **Examiner 1** (Page 55): Nice to have performance plots of all detectors
      * **Added efficiency/resolution plots for reconstructed particles in Chapter 5 (see below) illustrating the combined performance of the detectors using the PF algo. Lots of detector diagrams in this Chapter are already present.**
  + Trigger and Data Acquisition Systems:
    - **Examiners** (Page 56): “…the High Level Trigger (HLT), as it**’s** not feasible …”
    - Level-1 Trigger:
      * **Examiners** (Page 56): “Tracking information is not used in the L-1 Trigger as it was not possible to read … every event”. **Phrasing**.
      * **Author** (Page 56): **Fixed broken reference. Same as previous reference. Also picked up by examiners.**
  + LHC and CMS Performance:
    - * **Examiners** (Page 56): “at  **= 13** TeV”

TMTT:

* The HL-LHC:
  + **Examiners** (Page 60): **(HL-LHC) *(Fixing HL-HLC typos)***
  + **Examiners** (Page 61): **(HL-LHC) *(Fixing HL-HLC typos)***
  + **Examiner 1** (Page 61): **Question:** “As it is not practical to increase the number of proton bunches due to the resultant hear loads induce by electron clouds ...”
    - **Discussed in viva.**
  + **Examiner 2** (Page 61): **Question asked during viva: “**what is the electron cloud?”
    - **Discussed in viva.**
  + **Examiners** (Page 61): “… during Long Shutdown 3 **(LS3)**, which …”
  + **Examiners** (Page 61): “geometrical reduction factor**~~,~~** .”
* The Phase-II Outer Tracker Upgrade:
  + **Author** (Page 61): “… innermost layers) **[insert space]** and …” **Also picked up by examiners.**
  + **Author** (Pages 61-62): Capitalised start of bullet points.
  + **Examiners** (Page 62): [Question] “… either 25x100um² or 50x50um².” **Why the different sized modules? Viva question.**
  + **Author** (Page 62): As with **~~to~~** the previous pixel detectors, the Inner Tracker is also designed.
  + **Examiner 2** (Page 64): [Question] “The advantages of the tilted geometry …large incident angles … overall costs of the system.”
    - **Discussed in viva.**
    - **Amended text slightly (better grammar):** “﻿… large incident angles but **that it** also reduces …”
  + **Author** (Page 64): Further details on the two pT-modules can be found in **[correct reference ordering]**
  + **Page 64: Fix reference ordering in** Figure 4.2 and end of the paragraph at the top of the page.
  + **Examiners** (Page 64): “… to the **~~FW~~ hardware/firmware** buffers …”
  + **Examiners** (Page 65): “… to the off-detector **~~electrons~~ electronics** …”
* A Time-Multiplexed Track Finder:
  + **Examiner 2** (Page 65): [Question] “Hough Transform” **Discussed during viva.**
* The Track Finding Architecture:
  + **Author** (Page 66): “as previously demonstrated by the Phase-I Calorimeter Trigger Upgrade [**fix reference]** …” **Also picked up by examiners.**
* The Track Finding Processor:
  + **Examiners** (Page 67): “This process also greatly reduces the combinatorics that …” **Phrasing**. **”A highly parallelised initial coarse track finding that identifies track candidates that are consistent with a track in the r-phi plane, greatly reducing the data volume and combinatorics that have to be considered by the subsequent stages.”**
  + Hough Transform:
    - **Examiner 2** (Page 70): [Question] “By choosing an appropriate value of T … optimal value of T was determined to be 58cm.”
      * **Discussed during viva.**
    - **Examiner 2** (Page 70): [Question] “A detailed description of the firmware implementation of the Hough Transform ….”
      * **Discussed during viva.**
  + Kalman Filter:
    - **Examiners** (Page 70): “the presence of **~~these~~ such incorrectly associated** stubs would **~~negatively impact the accuracy of the track parameters fitted to the genuine tracks~~  degrade the resolution of the helix parameters fitted to reconstructed tracks associated with a particle.**”
    - **Examiners** (Page 70): “In addition, **~~over half of the tracks candidates found by the Hough Transform in simulation~~** **simulation studies indicated that approximately half of the track candidates created by the Hough Transform did not ~~correspond to a genuine track~~ have stubs associated to the same particle in at least four tracker layers** (i.e. were fake).”
    - **Examiners** (Page 70): “Therefore, a Kalman Filter was developed to precisely fir the track parameters given its ability to simultaneously **~~filter~~** **remove** **~~out~~ these** **~~incompatible~~** **incorrectly associated** stubs and **~~perform the track fit~~ “fake” tracks while** **obtaining the best possible estimate of the reconstructed track’s helix parameters**.”
    - **Author** (Page 70): “While the Kalman Filter is the optimal **~~linear~~** filter **for linear systems** and, **~~in certain circumstances,~~** the optimal **~~non-~~**linear filter **for non-linear systems** , it …”
    - **Author** (Page 71): “Details of the mathematics involved in the Kalman formalism is given …” **Rephrased a little bit to flow better.**
      * **“A full description of the Kalman formalism is given in [X]. The details of the *TMTT* project's implementation of the Kalman Filter using FPGAs for online track reconstruction is given in [Y,Z]”.**
  + Duplicate Removal
    - **Examiner 2** (Page 72): [Underlined text - question?] “green and yellow HT cells”
      * “… in the **~~green~~ yellow cell** and two **~~yellow~~** **green** HT cells from the five stubs …”
    - **Examiners** (Page 72): “…as the DR algorithm **~~loses a few percent of efficiency~~** **rejects a small number of non-duplicated tracks** due to resolution effects **resulting from the discretised implementation of Hough Transform arrays**, the …”
* Simulation Studies:
  + **Examiners** (Page 72-73): “…events **with an average PU (**<PU>**)**  of 200 **~~events~~** **interactions** …”
  + **Examiners** (Page 73): “It was found that **~~running the~~** **using** **a** SF **stage** before the Kalman Filter **stage** did not improve **~~its~~ the overall** **performance of the system** due to the **~~efficiency~~** **effectiveness** of the Kalman Filter’s filtering.”
    - * Reconstructed Tracks:
        + **Examiners** (Page 74): “… at least four layers**/disks** of the tracker …”
        + **Examiners** (Page 74): “… that produce a track that satisfies the following **~~conditions~~ definition**.” (definition for track)
        + **Examiners** (Page 74): “A track is **~~a~~** defined as …”
  + Linearised ­χ² Track Fitting Studies
    - **Examiners** (Page 74): “… a **L**inearised χ² **~~track~~** **F**it **algorithm**.”
    - General Form of a­ χ² fit:
      * **Examiner 2**(Page 75): “… si, we initially linearly expand …”, change in voice used and define i.
      * Equation (4.5): missing brackets for delta **(**h) and fi(h**)**.
      * **Examiner 2**(Page 76): Viva question re. suitability for implementation on FPGAs. Discussed in viva.
    - ­ χ² Track Fitter Software Implementation:
      * **Author** (Entire section/chapter where appropriate): **Replaced “approximated maths” with “discretised maths” – phrase sounds better/more accurate upon reflection.**
      * **Examiner 1** (Page 77): “After this validation process**~~es~~**, ….”
      * **Examiner 2** (Page 77): [Question?] First paragraph of the page re. the “approximated expressions”. Perhaps elaborate clarify? **Viva question, was asked, but rephrased a tad for clarity.**
      * **Examiner 2** (Page 77): Define resolution – add/odd(?) biases.
        + Resolution: (Fitted helix parameter – TP helix parameter)
      * **Examiner 2** (Page 78): [Questions] Figure 4.9: Error Bars? Structure? What about biases?
        + **Q: structure – asked in the viva, clarified in text that worsened performance in the forward regions comes from reduced lever-arm, orientation of modules, and increased material traversed.**
        + **Biases: Only brought up by examiner 2. Unsure what biases would be present in the simulation!**
        + **Error bars issue resolved by running over more events.**
        + **Also changed legend text from “maths” to “implementation”.**
      * **Examiner 1+2** (Page 78): [Question] Figure 4.9: Error Bar circled.
        + **See above.**
      * **Examiner 2** (Page 78): “being incorrectly associated with a matched tracked in the forward regions, as shown in Table 4.1, significantly degrades the resolution obtained.” **? mark in the margins! Discussed as part of the structure corrections mentioned above.**
      * **Examiners** (Page 79): “The reason … were …” **tenses**. **Rephrased.**
      * **Examiner 1** (Pages 79-80): “... fake rate being halved…”, “purity … increasing.”, “… resolutions in the endcaps.”, “…linearised chi2 track fit … discontinued.”, “… higher track finding efficiency with 100.0% purity for matched tracks and z0 and cot(theta) resolutions …” Underlined by Examiner 1 – suspect for questions for viva, but I think these parts can be rephrased into a better form.
        + **Rewritten/rephrased each part, including obvious typos and poor English.**
        + **Worse due to exclusion of higher order terms. Excluded due to additional free parameters making LUTs unfeasibly large.**
      * **Author** (Page 80): **Resolved large error bars in Fig 4.10 relative pT plots by finding a bug that resulted in binning artefacts.**
    - Tracking at low transverse momenta studies:
      * **Examiners** (Page 81): “… threshold of 2GeV**.** The …” missing full stop.
      * **Examiner 2**  (Page 81): “The focusing on recovering tracking efficiency below 3 GeV with the Hough Transform.” Phrasing. **Rephrased**
      * **Examiners** (Page 82): Figure 4.11 caption top/bottom references ought to be -> left/right.
        + **Done.**
      * **Examiners** (Page 82): “The impact of multiple scattering on the Kalman Filter …” Underlined by Examiner 1 – suspect for questions for viva, but I think these parts can be rephrased into a better form.
        + **Rephrased. New text is below Figure 4.12 on corrected thesis page 86.**
        + **Also expressed 3GeV on Page 82 in terms of 1/GeV as Fig 4.11 plots eff against 1/pT. Also corrected Fig4.11 x-axis label from 1/Pt to 1/pT.**
      * **Examiners** (Page 84): Correct z0 -> z.
      * **Examiners** (Page 85): [Question re. Figure 4.14] The clear jump in fraction of duplicate tracks in RH plot. **Added clarifying statement to note that at the time of writing that this feature was not understood.**
      * **Examiners** (Page 85): [Question re. Figure 4.14] “The fraction of genuine tracks with duplicates as a function of 1/pT …” Clarify definition! Especially with respect to LH plot y-axis.
        + **HT result – number of duplicate tracks per TP**
        + **KF result – fraction of tracks which are duplicates**
        + **Remade plots for number of duplicate tracks per TP.**
      * **Examiners** (Page 85): Figure 4.14 caption top/bottom -> left/right.
      * **Examiners** (Page 85): [Question] Last paragraph, related to question re. Figure 4.14.
        + **Discussed in viva.**
      * **Examiners** (Page 86): [Question] Figure 4.15 – the first bin (high pT) why no multiple scattering scatter point has better efficiency?
        + **Estimated error is larger than actual due to the density effect reducing the effective stopping power on the charged particle.**
        + **New text added on corrected thesis page 90.**
      * **Examiner 1** (Page 86): “… whole chain improves when multiple scattering is accounted for in the Kalman Filter …” Underlined by Examiner 1 – suspect for questions for viva, but I think these parts can be rephrased into a better form. **Rephrased – see above correction.**
      * **Examiners** (Page 87-88): “The **resolutions** of both multiple scattering coefficients are superior across all pT compared to when multiple scattering is not considered at all …” REALLY? Arrow to top left plot of Figure 4.16 for 1/pT resolution – clear that this is worse/similar for this helix parameter. The arrow to the top paragraph of page 88 (re., the worse 1/pT resolution in the range 0.181-0.261 is worse when multiple scattering is considered) has a tick! The latter paragraph is correct!
        + **Rewritten to be consistent and provide better explanation for the observed resolutions.**
        + **New explanation is in the last paragraph on page 91 (continues onto page 92) of the corrected thesis.**
      * **Author** (Page 87): Fix colour of constant k plot points in Figure 4.16.
      * **Examiners** (Page 87): “The **resolutions** …” Double line in margins. New paragraph? Rephrase? **Rewritten – see above correction.**
      * **Examiners** (Page 88): **BOTH EXAMINERS** **Maybe a summary; it just ends.**
        + **Added a summary! Page 93 in corrected thesis**

Event Simulation and Object Reconstruction:

* **Author**: Add LOTS of plots showing the efficiency of the various circumstances. **Examiners also picked up on this: “maybe include performance plots.”**
  + **Added for all reconstructed objects except muons (could not find any 2016 13 TeV plots for reco-only efficiency which is >=99% reco efficiency + the loose PF muon ID efficiency, which is PF muon/tracker muon track efficiency, plot is in the relevant Section 7.2.2). Muon track efficiency is given in charged particle tracks figure (5.1)**
* **Author** (Page 89, 2nd opening paragraph): The event simulation and **object~~ion~~** reconstruction algorithms
  + Event Simulation:
    - Event Generators:
      * **Examiners** (Page 90): “… with a specialist generator **~~that~~** that models a specific physics object …”
      * **Examiners** (Page 91): “These negatively weighted events are not simply discarded as they are required to correctly simulate the NLO cross section by applying a scale factor, SFNLO”. Underlined this passage with annotation: **“Q!”** Perhaps more detail?
        + **Rephrased this, new text on page 96 of the corrected thesis.**
      * **Examiners** (Page 91): “It can also **be** used to take the output …”
  + Object Reconstruction:
    - Particle Flow Algorithm
      * **Author** (Page 94): granularity detector considered (**HCAL**/ECAL). **Both examiners also picked up on this.**
    - Electrons:
      * **Examiners** (Page 94): “As the magnetic field bends **the** electrons’ trajectories in the φ direction, their **~~is~~** energy across φ, the ECAL crystals are …” Phrasing (wrt underlined part).
        + **Rephrased this, rephrased text page 101 on corrected thesis.**
      * **Examiners** (Page 95): “From this combined set of seeds, electron tracks are iteratively build using a**~~s~~** combinatorial Kalman Filter …”
      * **Author** (Page 95): “These electron tracks undergo a final fitting by **~~the~~** the GSF to precisely determine the …”
    - Muons:
      * **Examiners** (Page 96): “If at least one **~~one~~** muon segment in the …”
    - Jets:
      * **Examiners** (Page 97): **Define k for sequential combination algorithms.** 
        + **Defined – text at bottom of page 104 on corrected thesis.**
      * **Examiner 2** (Page 97): **Question:** underlined section wrt. cone size.
        + **Discussed in viva.**
      * Jet Energy Corrections:
        + **Examiners** (Page 98): “The uncertainties associated with these JEC**s** are treated as …” **(small s)**
    - b-tagging:
      * **Examiners** (Page 98): “… by the CMS B-Tag and Vertexing (BTV) Physics Object Group **(POG)**.”
    - MET*:*
      * **Examiners** (Page 100): **Question:** MET – **discussed during viva.**

Analysis Strategy and Event Selection:

* Signal Region:
  + **Author** (Page 101): **Introduce forward referencing to the event selection definitions (P110-112).**
    - **“The selection criteria for the physics objects that are Sections 6.1 and 6.2 are defined in detail in Section 6.6”**
  + **Examiner 2** (Page 102): “This mass window was found to be sufficiently **[MISSING WORD]** account for detector resolution effects.” *﻿***This mass window was chosen as was sufficiently wide to account for detector resolution effects, leading to a high acceptance rate of leptons produced from Z boson decays.**
  + Page 102: “… and as **~~as~~** passing the loose jet identification criteria …” **Both examiners also picked up on this.**
    - What about tight jets? Unclear as no forward referencing – the cut name is PF loose, used as a “tight” jet cut. **Referred to a highly efficient jet ID (and fake rejecting) criteria, described later.**
  + **Examiner 1** (Page 102): “… to the known W boson mass of **~~of~~** 80.4 GeV [21] is considered.”
  + **Examiner 2** (Page 102): “The leading b-jet however, is not … from the W boson decay.” **Repetitive rephrase. Removed repetitive rephrase.**
  + **Author** (Page 102): The leading and sub-leading electrons pT > **35** GeV(**15** GeV) respectively and be within eta < **2.40. …** The leading and sub-leading muons pT > **26** GeV(20 GeV) respectively and be within eta < **2.40.**
  + **Examiners** (Viva): Be clear that I mean +/- 20 GeV and not +/- 10 GeV.
    - **Clarified:** “… an invariant mass that is within **±** 20 GeV …”
  + **Examiners** (Viva): Justify the b-jet upper limit.
    - **Added text:** “This limit was chosen as it was found that there was minimal signal (< 1%) present for events with more than two b-tagged jets. ﻿Consequently, given the background dominated nature of this search, it would have been challenging to separate this small signal contribution from the background processes.”
* Control Region:
  + **Examiner 2** (Page 103): “In any high energy particle physics analysis, accurate modelling of the background processes is essential in order to extract the signal yield.” **Not strictly true. For high S/B analyses might not be critical to understand background accurately. ﻿For any high energy particle physics analysis lacking a high signal to background ratio, the accurate modelling of the background processes is essential in order to extract the signal yield and make a precise measurement.**
  + **Examiner 1** (Page 103): “… is essential in order **to** extract the signal yield.”
  + **Examiner 2** (Page 103): “... enriched control regions that are topologically similar and orthogonal …” **What does this mean? Meant that their variable shapes are similar without occupying the same analytical phase space “… background enriched control regions whose kinematic distributions are similar to the signal region's were …” See rewritten section’s 2nd paragraph for full text.**
  + **Examiner 2** (Page 103): “… so that they occupy a topologically similar phase space …” **Repetition. See rewritten section’s 2nd paragraph**
  + **Examiner 1** (Page 103): **Explain control region?? [check modelling] See rewritten section’s 2nd paragraph**
  + **Author** (Page 104): remove 6.2’s last sentence. The following subsections are self-explanatory!
  + **Examiner 2** (Page 104):“... this control region’s topology may not be …” **Misuse of the word topology. Really you probably mean kinematic distributions or something similar. Solution: better defined Control Regions in the above text and replaced this problematic phrase with “this control region may not provide a sufficiently similar kinematic phase space to the signal region”.**
  + Background Control Region:
    - **Examiners** (Page 104): **Correct pT thresholds used for this control region. 35 GeV for electrons and 26 GeV for muons.**
* Experimental blinding:
  + **Examiner 1** (Page 104): “Despite even the best intentions, there is the **~~for~~** potential **for** experimental procedure …”
  + **Examiner 1** (Page 104): **Explain BDT? Not defined – now defined as MVA as choice of BDT is introduced in later Chapters.**
  + **Author** (Page 105): **Corrected sigma(top) and sigma (W) following the bullet points – were the wrong way around!**
  + **Examiner 2** (Page 104): **Incomplete specification of the optimisation of the chi2 and sigma values. What were the optimisation criteria?**
    - **Specification of sigma values already present in the text!**
    - **For σt = 30 GeV and σW = 8, χ2SR and χ2CR were defined as 5 and 30, respectively. χ2SR corresponds one sigma of the tZq signal contained within χ2CR, andχ2CR as five sigma of the measured σW.**
    - **Added to conclusions also and include future work to include defining the SR and SB on the basis of the expected signal strengths.**
  + **Author** (Page 105): Stray **)** before “optimised chi2 values.” **Examiners also picked up on this.**
  + **Author** (Page 106): Figure 6.1 top/bottom -> left/right. **Both examiners also picked up on this.**
  + **Examiner 2** (Page 106): Figure 6.1- **Q: Why circles [?]-like structure visible (and physically motivated). Asked during viva.**
    - **Commented upon the optimisation of the shape of the chi2 variable in Chapter 8 (Conclusions).**
* Trigger Strategy
  + **Both examiners** (Page 106): “… and will likely be limited by **~~statistics~~ event yield**, it is …
  + **Examiner 2** (Page 106): “The logic for this for each of the channels is illustrated in **T**able 6.1.”
  + **Examiner 2** (Page 106): “… maximum possible statistics can be …” **Use “event yield” in lieu of statistics.**
  + **Author** (Page 106) Table 6.1: Updated table to ensure that the trigger logic within is clearer.
  + **Examiner 2** (Page 106): “… control region**[missing space]** (see Section 6.2.2.).”
* Event Cleaning:
  + **Both examiners** (Page 107): “… with beam or detector from …” **detector? [Examiner 1] Missing words? [Examiner 2] “… a number of filters are applied to remove events containing beam backgrounds or detector noise from further consideration.”**
  + **Examiner 1** (Page 108): “… at radii up to 5m”Perhaps “of up to 5cm”? **Yes. Amended accordingly:** “… at radii **of** up to 5**c**m.”
* Physics objects:
  + **Examiner 2** (Page 108): “In order to meet suppress the backgrounds in the for a signal enriched region …” **Poor English – rewritten. “In order select events consistent with the objects expected to be in the final states of the signal enriched region and background enriched control regions described …”**
  + Lepton Selection:
    - **Examiner 2** (Page 108): “… their transverse momenta lies in the …” **Consider use of plural. Should probably be “momentum”. Agreed – changed momenta to momentum.**
    - **Examiner 2** (Page 109): **Annotation for final paragraph prior to Electrons subsubsection.** **Would be worth including indication efficiency and fakes rates here …** 
      * **Electron and muon selection efficiencies quoted in respective subsubsections. No need to repeat. Also the fake rates are background process dependent!**
    - Electrons:
      * **Examiner 1** (Page 109): Add reference to Chapter 5 for conversion veto. **Examiner 2 adds: how is “photon-electron conversion” defined? Unsure of the need to reference Chapter 5 – surely definition of veto is sufficient. New text: “ - a conversion veto - is applied for all working points. The photon to electron conversion veto tests if a pair of electron tracks originate from a common displaced vertex. Any electron which fails this criteria is rejected.”**
      * **Examiner 2** (Page 110): “The MVA tuned variables include:” **How are the tuned? More detail required. On the basis of delivering a defined acceptance efficiency whilst maximising training sample (Z+ jets) fake rejection. Proposed text: “﻿The values of the latter were set by the MVA determining the optimum values for a given selection efficiency, using simulated Z+jets and \ttbar+jets events as the signal and background processes respectively.”**
      * **Author** (Page 110): Full 5x5σiηiη – add a brief summary. **Examiners also picked up on this.**
        + **Additional text:** “Describes the lateral extension of the shower along the η direction: i.e. the RMS along the η direction inside the 5x5 iη tower.”
      * **Examiner 2** (Page 110): “… these variables are given in **T**able 6.3.”
    - Muons:
      * **Author** (Page 111): “muons must have eta <= **2.40** to ensure that a muon is fully within the …” **Both examiners also picked up on this!**
      * **Examiner 2** (Page 111): **Better style to avoid forward references [re. muon isolation], since this follows immediately it is probably okay … Rephrased a tad to improve the English in this paragraph.**
    - Jet Requirements:
      * **Both examiners** (Page 113): Energy fractions are wrong. **Checked CMS twiki page – they are correct! (**[**https://twiki.cern.ch/twiki/bin/view/CMS/JetID13TeVRun2016**](https://twiki.cern.ch/twiki/bin/view/CMS/JetID13TeVRun2016)**)**
    - b-tagging Requirements:
      * **Examiner 2** (Page 113): ): “… defined in **T**able 5.1 in Section ...”
      * **Examiner 2** (Page 113): “… as large statistics as possible ...”
        + **Rephrased:** “… as large **~~statistics~~ a sample** as possible ... ”.
* Background Processes:
  + Z+Jets and W+jets backgrounds: Rephrase title: **Vector Boson in association with multijet backgrounds. Examiner 1 picked up on lower case jets for “W+jets”. New title avoids this mistake!**
    - **Examiner 2** (Page 114): “QCD multijet events …” **Use of QCD redundant as all jets are QCD processes. Removed “QCD” …**
  + Top Physics backgrounds:
    - **Examiner 2** (Page 114): “… only ttbarZ**[missing space]** where …”
    - **Examiner 2** (Page 114): “…ttbarH**[missing space]** and tHq…” Background Estimation:
* Data and Simulation Samples:
  + **Examiner 2** (Page 116): Include reference for CUETP8M2T4 et al tunes.
    - **Added reference.**
  + **Examiner 1** (Page 116): “… start of the most **luminous** runs …” Could use “data taking” … “… most luminous **data taking** runs …”
  + **Examiner 2** (Page 116): “… underlying **event tune** was used by PYTHIA …” Suspect they want an explanation as to what a “tune” is.
    - **Introduced underlying event concept and the need for tunes in Section 5.1**
  + **Examiners** (Page 116): **isr -> ISR** and **fsr -> FSR**
    - **Capitalised the above.**
  + **Author:** Table 7.2 resize
* Simulation Corrections:
  + **Examiner 2** (Page 119): “… effects observed in data corrective scale … ” **Grammar**.
    - **Fixed.**
    - **“As s**imulation is unable to fully recreate all the effects observed in data, corrective scale factors are used to reweight MC samples on a per event basis to account for **mismodelled variables. ﻿**These scale factors were used to correct simulation for any modelling discrepancies in the lepton identification, isolation and reconstruction efficiencies, lepton and jet energy scales and resolutions, b-tagging efficiencies, the poor modelling of pileup in simulation, and the **resolutions of the detectors”.**
  + **Author** (Page 119): Miscalibrated Tracker APV **Chips** (7.2.1 title)
    - **Author** (Page 119): Split up first sentence into two.
    - **Author** (Page 119): Paragraphs 2+3 can be one paragraph
  + Lepton Efficiency
    - **Examiner 1** (Page 119): “plots for the performance” [ID/iso/reco for centrally derived corrections?]
      * **Added tight ID (inclusive of isolation) efficiency plots for electrons. No veto-ID plots are publicly available. Reconstruction plots are in Subsection 5.2.5 (Electrons).**
      * **Added tight ID+Iso efficiency plots for muons. Loose ID plots are in Subsection 5.2.6 (Muons) as the loose ID is just the PF muon efficiency.**
      * **Brief discussion re. the efficiency of these requirements and how well simulation describes data.**
    - **Author** (Page 120): Table 7.3 - Stylistic change: bold table headings for “ee” and “mumu”.
    - **Examiner 1** (Page 120): “[NXTriggers+lepton triggers] -> εtrigger ≥ 0?”
      * **Viva question. Discussed in the viva.**
    - **Examiner 1** (Page 120): 2nd paragraph, beginning “As the trigger requirements …” More detail, add reference, include plots.
      * **Reference already provided for, additional detail and plots (as functions of lepton pT) added. Further plots (for eta dependence given in Appendices).**
    - **Examiner 2** (Page 120): 2nd paragraph, beginning “As the trigger requirements …” **Question: What about other control region? Z+jets?**
      * **The SF concerns all final states with the relevant two leptons. i.e. the lepton ID/iso and trigger requirements for the signal and all control regions were the same. Rewritten to be clearer.**
      * **“﻿A constant scale factor was found to be sufficient to account for the differences ﻿in the trigger efficiency between data and simulation for the $ee$, $\mu\mu$ and $e \mu$ final states considered.”**
  + Rochester Corrections: *“*These corrections are tuned in the second step using the Mµ***Mµ*** peak for…” **Both examiners also picked up on this. Unitalicized in actual text, just highlighting the part of the phrase that needed correcting!**
  + B-tagging Efficiency:
    - **Examiner 1** (Page 121): There’s a mark without a clear purpose – perhaps a clarification as to what the author meant to be asked during viva or to be clarified in the thesis text?
      * **Suspect viva question, added clarifying text.**
      * **“… and having events with potentially undefined variables such as the top mass (i.e. the top mass cannot be defined in an event with zero b-tagged jets).**
    - **Examiner 2** (Page 121): Underlined last two lines with **Q** next to them. **Viva question.**
* Signal Region Background Estimation:
  + **Both examiners** (Page 122): Correct Figure B.1 to Figure 7.1! Check and confirm. If it is the Appendix figure, why there and reference/highlight in appendix properly.
    - **Same ref had *been* used for 7.1 and B.1 and LaTeX chose B.1!**
    - **Fixed for all cases.**
  + **Examiners** (Page 122): Figure 7.1 - **Should NPLs be on the plot?**
    - **Yes. The text referring to NPLs though was poorly worded – was referring to non-Z decay sources.**
    - “…reduced the **~~non-prompt lepton~~** contributions **from processes lacking a leptonic Z boson decay**, completely removing the W+jets process.”
  + **Examiner 2** (Page 122): Figure B.1/Figure 7.1 **LH plot, jet and b-tag cuts point on Data/MC plot has annotation: “Looks significant?” Viva question – discussed in viva.**
  + **Both examiners** (Page 123): Table 7.4 – “**non-prompt leptons** **(NPLs)**” in figure caption & errors on data entries in the table are “not needed”.
    - **Examiner 2 adds: Align columns on decimal points!**
    - **Stylistic changes: bold table headings; aligned on decimal points and =/-**
  + **Examiner 1** (Page 124): Figure 7.2 **Only stat not system[amtic errors]**
    - **General question/comment/observation. Clarified in viva and figure captions.**
  + **Examiner 2** (Page 124): Figures 7.2 + 7.3: **Q wrt. data/MC plot structure. Viva question – discussed in viva.**
* Data-driven Background Estimation:
  + Non-Prompt Leptons:
    - **Examiners** (Page 125): “… and same **~~charge~~ sign** SUSY searches …”
    - **Examiners** (Page 126): Table 7.5 – SF and errors for 0.0 entries.
    - **Author** (Page 126): Table 7.5 -Stylistic changes: bold table headings; aligned on decimal points and +/-.
  + Z+jets Background:
    - **Examiner 1** (Page 130): Add **LO** and **NLO** and subheadings on plots (Figs 7.5-7.7) to make things clearer.
      * **Included in legend**
    - **Examiners** (Page 128-129): Tables 7.6 + 7.7 - errors on data entries are not needed.
    - **Author** (Page 126): Tables 7.6-7.7 - Stylistic change: bold table headings; aligned on decimal points and +/-.
  + ttbar Background:
    - **Both examiners** (Page 132): Figure B.29 should be 7.8 like comment on page 122.
      * **See above.**
    - **Examiner 2** (Page 132): “From **T**able 7.8 …”
    - **Examiners** (Page 133): Table 7.8 - errors on data entries are not needed.
    - **Author** (Page 126): Table 7.8 - Stylistic change: bold table headings; aligned on decimal points and +/-.
    - **Author: Updated plots so that the pT cuts are pT > 35 and pT >26 for electrons and muons, respectively, see above comments re. wrong pT cuts used for emu ttbar control region. Contents of Table 7.8 updated also.**
* Systematic Uncertainties:
  + **Examiner 2** (Page 135): First paragraph is bracketed with **Q** annotated. **Presume viva question.**
  + Experimental Uncertainties:
    - Parton Density Functions:
      * **Examiner 2** (Page 136): At end of subsection **“αS?”**
        + **Added extra text re. the uncert of αS used for the PDFs.**
    - Non-prompt Lepton Contributions:
      * **Examiner 2** (Page 136): **Add reference**
    - Lepton Efficiencies:
      * **Both examiners** (Page 137): “When comparing the trigger efficiencies in simulation between the **~~for the~~** and Z+jets samples …”
      * **Examiner 1** (Page 137): Star by Eqn 7.3.
        + **Viva question.**
      * **Tables 7.9 - 7.10:** Stylistic changes: bold maths table headings.
      * **Expanded on ttbar and Z+jets bit with reference to eta trigger efficiency plots in the appendices. Not included in main body due to spacing and those plots don’t add any new information.**
      * **Corrected typo for ee Z+jets stat uncert value.**
      * **Removed emu Z+jets entry due to lack of stats and usefulness given that Z doesn’t decay into emu.**
  + TheoreticalUncertainties:
    - Cross section normalisation:
      * **Examiner 2** (Page 138): Add reference for 30% normalisation uncertainty recommended by CMS.
      * **Both examiners** (Page 138): “… it is now CMS policy to assume an uncertainty of 10%.” Justify your analysis. Add reference.
        + **Justified following offline discussions with top physics contacts and combine tool experts.**
  + Pre-fit Impact of the Systematic Uncertainties:
    - **Examiner 2** (Page 140): Table 7.11 – **Too concise**.
      * **New less concise table title.**
      * **Fixed normalisation uncertainties.**
* Multivariate Analysis Techniques:
  + Boosted Decision Trees:
    - **Examiner 1** (Page 143): “and which hyperparameters, the set of options …” ? above underlined hyperparameters. **If the “?” refers to the examiner wanting a definition, it is immediately afterwards!**
    - **Examiner 2** (Page 144): **Define discriminating power! See definition in 7.6.1’s bullet point list (top of page 155 of corrected thesis).**
  + BDT Optimisation and Evaluation:
    - BDT Hyperparameter Optimisation:
      * **Examiner 1**(Page 152): At bottom of page/last paragraph “small differences lead to big differences.” **Added a remark to this effect.**
      * **Examiner 2** (Page 152): Table 7.20 – Minimum child weight RH column – 1 x 10-**~~0~~**5
      * **Examiners** (Page 153): Fig 7.20 – define which is ee and µµ. In text and on plots. **Defined in figure captions.**
      * **Both examiners** (Page 155): Correct x –axis range for Fig 7.21-222’s “totHtOverPt” and remove empty plot in Fig. 7.21!
        + **Remade plots with correct axis ranges and no empty plots.**
    - BDT Evaluation:
      * **Examiner 1** (Page 156): Fig 7.23 {Add if [illegible – material?] about the bins.
        + **Suspect asking how the bin sizes were determined.**
        + **Corin Hoad’s explanation:** “basically everything starts on one big bin, then it it split at the median (unweighted), so on recursively until the error exceeds some value or the number of signal events/background events would go be below some value. so at least background event (after weighting) and no more than 10% statistical error in signal or background”
        + # The recursive binning strategies will stop splitting once these limits: are reached

min\_signal\_events: 0

min\_background\_events: 1

max\_signal\_error: 0.1

max\_background\_error: 0.1

* + - * **~~These output discriminant distributions are used to extract the signal strength and its statistical significance in the following chapter. ﻿~~The output distributions were binned using a recursive binning strategy that ensured that each bin contained at least one background event and that the statistical error did not exceed 10\% for either signal or background. ﻿** **﻿These conditions were applied to ensure that when performing the maximum likelihood fit described in the following chapter, each of the distributions' bins contained sufficient statistics to avoid causing~\cite{combineBinning}:**
        + **﻿statistical fluctuations that would result in an artificial enhancement or suppression of the sensitivity in a given bin;**
        + **﻿excessively large fluctuations in shape-based systematic uncertainties, with respect to the nominal, that would influence the measurement's sensitivity;**
        + **﻿ill-defined ﻿probability density functions, due to bins populated by zero background or signal events, resulting in zero trust of the significance of a data event as it is impossible to determine if the significance is the result of a negligible background or lack of statistics.**
      * Also, how does one work out systematics for MVA?
        + **Question asked during the viva.**

Results*:*

* Statistical Methodology:
  + **Examiner 1** (Page 157): “The Higgs Analysis Combined Limit (combine) tool [179] **~~tool~~**, a framework …”
  + Page 157: **As upper limits were not determined and the CLS method not used for the result presented (previously submitted with short notice re. permission to present a measurement), rephrased 8.1 paragraph accordingly.**
  + **Examiner 1** (Page 158): Star **\*** by Equation 8.4. **Viva question?**
  + Likelihood model:
    - **Author** (Page 158): corrected reference ordering.
  + CLS method:
    - **Changed subsection title to “﻿Signal Strength Modifier Calculation and Significance” to better reflect that limits are not being set, but a measurement and its significance was made.**
    - **Examiner 2** (Page 158): “Citation needed” for CLS method.
      * **No longer relevant, but did found the appropriate reference!**
    - **Examiner 1** (Page 159): Star **\*** by Equation 8.5. Circle over the offset hat (**^**) over **θµ** in both numerator and denominator.
      * **Fixed offset.**
    - **Examiner 1** (Page 159): Lines next to start of final paragraph and “Asmiov dataset” underlined and annotated “**explain**”.
      * **Part viva question and part further explanation, I think?**
      * **Rewritten – see page 172 of corrected thesis.**
    - **Examiner 2** (Page 159): (Bottom of the page) “this concerns how to set a limit … but you don’t set a limit! Explain how significances are obtained (briefly).”
      * **Rewritten entire subsection to reflect that limits weren’t set.**
        + **Test statistic and text moved from 8.1.2 to 8.1.1 and rewritten a tad.**
        + **Subsection now discusses on how signal strength measurement is made, and significances were obtained.**
* Statistical Analysis Results:
  + **Examiner 1** (Page 160): “At 95% CL” **circled by examiner**. Squiggly line next to paragraph.
    - **Also Examiner 2** (Page 160): “At 95% CL” **circled by examiner**, annotated “**Q**”.
    - **Limits were not set! Thus 95% comment leftover from before unblinding occurred does not make sense. Removed “At 95% CL” from sentence.**
  + Post-fit BDT Discriminant Distributions:
    - **Examiner 2** (Page 161): Figure 8.1 – “under s+b hypothesis?”
      * **Added clarification in Figure 8.1 caption.**
* Discussion of other searches for tZq at the Large Hadron Collider:
  + **Examiner 1** (Page 163): Figure 8.2 **“Critical conclusions [discuss in detail]”. Discussed the impact of the systematics in further detail!**
  + **Examiner 2** (Page 163): Figure 8.2 “**DISCUSS**”
    - **See correction above.**

Conclusion:

* Summary of the tZq analysis:
  + **Examiner 1** (Page 165): Line by side of final paragraph. Underlined “ … understand the larger than expected observed significance …” Comment: **Interpretation of measurement**. **Interpreted as suggested better phrasing.**
    - “Given that these results have not been fully reviewed by the CMS collaboration, further work is required in order to **~~understand the larger than expected observed significance of this~~** **interpret this measurement** and to achieve the standard required for journal publication on behalf of the CMS collaboration.”
  + **Examiner 2** (Page 165): “Any speculation on possible reasons?” [for the differences between expected and observed results] Viva question. Honest answer was “nobody had any idea” - that will be for future work to understand!
* Future Measurements:
  + **Author: Added new text to end of paragraph three re. future work on defining the signal/side-band regions for blinding.**
  + **Author: Added new text re. which uncertainty reductions would most improve the result.**
* Summary of the TMTT track finding processor studies:
  + **Author:** *“…*the three **proposed** track finding*…”*
  + **Examiner 1** (Page 167): Lines by side of first paragraph and star. “… these candidates and **~~and~~** precisely …”
* Future system development:
  + **Author:** Rename 9.4: “Future **track finding processor** system development”

Appendices:

* Appendix B:
  + **Author:** B.1 Signal Region: Get plots onto same page as heading.

Bibliography:

* **Author:** Fix ordering in text – it starts from the list of tables/plots currently.
* **Examiner 2**: Fix DOI links.
* **Examiner 2**: Fix arxiv links.
* **Examiner 2** (Page 213): Typo for [6] “acclrateurs”
* **Author:** Fixed various typos in imported bibtex citations.