Acknowledgements:

* Move **Annabel Shaw** from family and loved ones to the end of my list of friends given the end of our relationship.

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 …
* **~~While the top quark has the same properties as the other five quarks,~~**
  + **WHAT?**
  + **The top quark’s mass of 173.0 +/- 0.4 GeV …**

An Introduction to the Standard Model and Top Quark Physics:

* The Standard Model:
  + QED: “… Heisenberg's uncertainty principle, it***s* (or *the*)** field experiences random fluctuations.”
  + Page 27: Table 2.2 – Gauge Bosons heading -> Bosons.
  + Higgs: “Brout, Engler, Higgs,**[insert space]** Guralnik, Hagen …”
  + **Rephrase:** *Infinite minima*
  + Page 32: Higgs Mass!
  + QCD:
    - Page 33: “This results in the colour confinement **of partons** [31, 46, 53].”
    - Or *“This results in* ***~~the~~*** *colour confinement[ 31, 46, 53].”*
* Top Physics:
  + Page 33: **~~Given that~~** **As** the top quark was more massive than initially assumed **~~however~~**, …
  + *Page 33: Last sentence rephrase.*
  + Top quark pair production:
    - Missing second bullet point: **·** Higher centre-of-mass energies results in smaller Bjorken *x*
    - Page 35: Reorder bullet points to emphasise greater importance of the latter point. And add bullet point!
  + Single top production:
    - Figure 2.5(a) – bbar is NOT from the sea! Due to charge asymmetric initial state
  + Single top production in association with a Z boson:
    - In contrast, ttZ **[insert space]** has a lower …
    - **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].**
    - **hadronic**: both the W boson and Z boson decay into a quark and anti-quark **[insert full stop].**
    - 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 …

*LHC and CMS:*

* *LHC:*
  + 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.
* *CMS:*
  + Silicon Microstrip Tracker (page 49): Correct z0 -> z
  + ECAL: (page 49) : Avalanche photo**~~s~~**diodesECAL: (page 49) :more radiation hard vacuum **phototriodes** in the endcap disks
  + *Make it clear that the Phase-1 pixel has always been planned*
  + Muon Chambers, DTs (page 53): Correct z0 -> z’s
  + Level-1 Trigger: **Fix broken reference! Same as previous reference.**

*TMTT:*

* *The Phase-II Outer Tracker Upgrade:*
  + … innermost layers) **[insert space]** and …
  + Capitalised start of bullet points
  + *Further details on the two pT-modules can be found in* ***[correct reference ordering]***
  + *As with* ***~~to~~*** *the previous pixel detectors, the Inner Tracker is also designed (page 62).*
  + *Fix reference on page 66.*
  + ***Fix reference ordering in*** *Figure 4.2*
* *The Track Finding Architecture:*
  + “as previously demonstrated by the Phase-I Calorimeter Trigger Upgrade **[fix reference]** …”
  + *“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 …”*
  + *Or: “While the Kalman Filter is the optimal linear filter and****~~, in certain circumstances, the optimal non-linear filter,~~*** *it …”*
  + *“Details of the mathematics involved in the Kalman formalism is given …”* ***Think that this paragraph can be rephrased to flow better.***
* *Linearised ­χ² Track Fitting Studies*
  + *General Form of a­ χ² fit:*
    - *Equation (4.5): missing brackets for delta* ***(****h) and fi(h****)****.*

*Event Simulation and Object Reconstruction:*

* 2nd opening paragraph: The event simulation and **object** reconstruction algorithms
  + *Object Reconstruction:*
    - *Particle Flow Algorithm*
      * Page 94: granularity detector considered (**HCAL**/ECAL).
    - *Push MET subsection onto new page?*

*Analysis Strategy and Event Selection:*

* *Signal Region:*
  + ***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***
  + Page 102: “and as ***~~as~~*** passing the loose jet identification criteria “
    - What about tight jets? Unclear as no forward referencing – the cut name is PF loose, used as a “tight” jet cut.
  + 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.**
  + Be clear that I mean +/- 20 GeV and not +/- 10 GeV.
  + Justify the b-jet upper limit
* *Experimental blinding:*
  + Stray **)** before “optimised chi2 values.”
  + Figure 6.1 top/bottom -> left/right.
* *Trigger Strategy*
  + *Table 6.1 - ensure table logic is clear.*
  + Table 6.1 - !M and !E for Single Electron and Single Muon.
* *Physics objects:*
  + *Lepton Selection:*
    - *Electrons:*
      * *Full 5x5σiηiη – add a brief summary.*
        + *Describes the lateral extension of the shower along the η direction: i.e. the RMS along the η direction inside the 5x5 iη tower.*
    - *Muons:*
      * *“muons must have eta <=* ***2.40*** *to ensure that a muon is fully within the …”*
* *Background Processes:* 
  + Z+Jets and W+jets backgrounds: Rephrase title: **Vector Boson in association with multijet backgrounds**

*Background Estimation:*

* *Data and Simulation Samples:*
  + *Table 7.2 resize*
* *Simulation Corrections:*
  + *Miscalibrated Tracker APV* ***Chips***
  + *APV: Split up first sentence into two.*
  + *APV: paragraphs 2+3 can be one paragraph*
  + *Rochester Corrections: “*These corrections are tuned in the second step using the Mµ***Mµ*** peak for…”
* *Data-driven Background Estimation:*
  + *ttbar Background:*
    - **pT cuts should be pT > 35 and pT >26 for electrons and muons respectively.**

*Results:*

* *DATA IS OF GOOD QUALITY - NOT EXPECTING RESULTS TO CHANGE*
* *Statistical Methodology:*
  + *Likelihood model:*
    - Page 158, swap last two references around.

*Conclusion:*

* *Summary of the TMTT track finding processor studies:*
  + *“…the three* ***proposed*** *track finding…”*
* *Rename 9.4: “Future* ***track finding processor*** *system development”*

*References:*

* *135* – T. C. Collaboration -> CMS collaboration
* *149 – needs making clearer*
* 161 – T. A. Collaboration -> Atlas collaboration

**TO DO LIST**

* Look up examiners:
  + Dr Jonathan Michael Hays
    - Origins of mass of fundamental particles.
    - Higgs searches
  + Professor Akram Khan
  + Dr Rajagopal Nilavalan
* What did my PhD involve?
  + Professional development
  + tZq
  + TMTT
  + Shifts
  + Outreach
* What does my thesis involve?
  + Succinctly describe analysis:
    - Each stage of the analysis – Z+jets backgrounds, key points!
    - It is compatible with SM (more than SM) and saw signal.
    - Order importance of why search for tZq.
* Describe design choices for CMS
  + Sub-detectors must be accessible in a reasonable time frame to service them without removing cables or services and fast recommissioning.
  + Physics case:
    - Higgs
    - SUSY
    - Massive Vector bosons
    - Extra dimensions
    - SM
  + Detector requirements:
    - Good muon ID
    - Good charged particle momentum resolution and reconstruction efficiency.
    - Good EM energy, diphoton and dilelectron mass resolution.
    - Good MET and dijet resolution.
  + Based around a large superconducting 4T solenoid
    - Precise measurement of muon + charged particle momentum.
    - High B field for compact spectrometer without demands on muon chamber resolution/alignment.
  + How good is the error/B field in the tracker?
    - Δp/p ~ 10% at p=1 TeV/c.
* ATLAS vs CMS:
  + Common to both:
    - Detailed inner tracker information.
    - Both provide hermetic coverage.
    - Calorimetry and muon systems provide triggering information.
    - Good energy and position resolution for calorimeters to resolve jets.
    - Calorimeters contain hadronic events -> low occupancy muon chambers.
  + Differences:
    - Varying granularity of individual detector elements.
    - Outer radius of inner tracker.
    - Strength and shape of B field.
    - Choice of detection medium for calorimetry.
    - Different detector and readout technologies.
    - Strategies for background rejection and trigger strategies.
    - Cost containment and optimisation.
  + Choices stem from magnet choices:
    - dp/p α p/Bl²
    - Either large lever arm – ATLAS.
    - Or powerful B field – CMS.
  + ATLAS:
    - ECAL - liquid argon detector.
    - HCAL – Tile calo
    - Tracker – pixel+strip+gas.
      * All the Silicon (and associated services) in CMS increases MS, conversion, and showering (as if a calo).
      * TRT = 370k drift tubes/straws. Straw layers interleaved with radiators. Straws filled with gas mixture.
  + Performance:
    - CMS Tracker ~x3 better.
    - CMS ECAL ~2-5x better.
    - CMS HCAL ~x2 worse
    - CMS Muon Chambers ~x1.4 worse.
* Why APDs and VPTs for ECAL?
  + APDs are insensitive to shower leakage particles escaping.
    - Photon passes through n and p layers and excites free electrons and holes in the depletion region. Electrons and holes create new ones and so on … avalanche! The reverse bias results in a current flowing proportional to number of incident photons.
  + VPTs more radiation tolerant.
    - Photon hits cathode, emits electron, passes through anode mesh, strikes dynode, secondary electrons collected on anode.
* What is Beta\*?
  + Beta function is cross-section/transverse emittance.
    - Low emittance = particles confined to a small distance with nearly the same momentum.
  + Small is narrow and squeezed beam.
  + Beta\* is Beta at the IP.
* Describe Hough Transform and Kalman Filter.
  + HT: Feature extraction used for image analysis. Traditionally used to identify lines in an image, but has been extended to arbitrary shapes.
  + KF:
    - State vector
    - State
    - Kalman Gain = {0,1}. If K~1, measurement is accurate and est is unstable. If K~0, estimate is stable (small error).
  + R-Z/Seed Filter filter:
    - Removes stubs inconsistent with a straight line in the r-z plane.
    - Sort stubs in layer order.
    - Loop over stubs in HT cell.
    - Select first two stubs and if consistent with z0, loop over other stubs.
  + Cot(theta)? Or tan lambda?
    - Tan lambda is the dip angle. Cot(theta) is the cotangent of the dip angle – i.e. tan lambda=theta.
* Difference between TMTT and offline KF.
  + TMTT only does it to fit hits assigned to a track.
  + Tracker uses CTF to seed initial candidates (2-3 hits), then a CKF to build a track, then KF passes to clean, and finally selection.
  + ECAL uses KF to build initial candidates (GSF too intensive to use except for refitting track seeds and final fitting).
  + CKF in muon systems.
* Describe Yukawa Coupling – coupling between scalar and dirac fields.
  + Historically used to describe the nuclear force between nucleons (fermions) that’s mediated by pions (pseudoscalar mesons).
* Describe asymptotic freedom – unbound at small distance.
  + Strong coupling constant increases with momenta.
* Explain ttH and tW/WH interference:
  + Both tH and WH diagrams produce large contributions.
  + But Feynman diagrams have opposite signs and similar contributions ~igWgmtop
* What is isospin?
  + Quantum number related to strong interactions. Isospin symmetry is a subset of flavour symmetry. QM description is similar to spin, wrt. how it couples. It is a dimensionless quantity that is not related to any actual spin!
  + Weak isospin is the gauge symmetry of the weak force that only couples to LH fermions. Isospin in contrast couples to LH and RH particles and is a global symmetry. Weak isospin is understood as the eigenvalue of a charge operator, where the conserved quantity is T3.
* What is chirality?
  + An object has chirality if it cannot be mapped to its mirror image by rotations and translations.
  + Different to helicity, which is the projection of spin vector onto momentum vector.
    - If massless, the two are the same.
    - If massive and non-relativistic, change of reference frame can reverse helicity.
  + Chiral symmetry for vector gauge theories with massless dirac fields = rotating LH/RH components makes no difference.
    - Massive fermions breaks chiral symmetry explicitly.
* Implications of non-unitary CKM matrix!
  + There must be branching to somewhere else!
* Which GR predictions contradict the SM?
  + Cosmological constant -> energy density of the vacuum.
* Hireachy problem(s)?
  + A hierachy problem occurs when the fundamental value of a parameter in theory is vastly different from its measured value. Some renormalisations require delicate cancellations between fundamental quantities and quantum corrections.
  + Weak force 1024 stronger than gravity or rather why is Higgs mass lighter than the plank mass.
    - Solution: SUSY.
  + Cosmological constant is also sensitive to quantum fluctuations.
* Massless neutrinos
* Describe van der Meer scans:
  + Beams are swept across each other in the transverse plane. Absolute value of the luminosity can be determined by monitoring the collision rate as a function of the beams’ separation.
  + Spatial distributions of interaction vertices can be used to develop an image of the beam and determine their overlap and absolute luminosity can also be done.
* Describe Lund String Model
  + Model of hadronistation. All (except highest energy) gluons are treated as field lines that are attracted to each other, forming a narrow tube of colour field when separated – in contrast to the EM field lines that spread out due to the non-abelian nature of the strong force.
  + One of the parton fragmentation models used. Explains features of hadronization well, including particle jets formed along the original paths of two separating quarks and sprays of hadrons between the jets by the string itself.
  + Herwig uses cluster modelling instead – simpler, but more energy-momentum parameters, unpredictive, and fewer flavour composition parameters that is simpler and less unpredictive than string.
* Why is KF optimal linear filter?
  + Designed to minimise the mean squared error.
  + Thus when noise is Gaussian, gives the best result/exact conditional probability estimate.
  + Mean squared error is used as the conditional probability at every iteration being a Gaussian is propagated as a Gaussian in the next iteration.
* What is the GSF algo?
  + A non-linear generalisation of the KF – distributions of all state vectors are Gaussian mixtures that provide a good approximation of the Bethe-Heitler distribution that models bremsstrahlung energy loss.
* Describe event generation in detail:
* Describe jet reco algorithms:
  + Cone algos – not usually infrared- & collinear-safe (except SIS-cone)
  + Sequential clustering - infrared- & collinear-safe by design.
    - Simple and clean.
    - Find the distance between particles i and j and between i and the beam.
    - Consider all i and j, if the smallest distance is dij, then combine i and j and find the next smallest.
    - If smallest distance is diB, remove particle i and call a jet.
    - Parameter “p” governs relative powers of energy vs geometrical scales to distinguish kT (=1), C/A (=0) and anit-kT (=-1) algos.
    - Anti-kT produces circular cone shaped jets and insensitive to UE & PU.
* Describe renormalisation and factorisation scales:
  + UV divergences: large infinite momenta
    - Renormalisation scales.
  + IR divergences: i) virtual or real particle reaches zero momentum or ii) a massless particle radiates a massless particle.
    - i) cancels out, ii) does not.
    - Cross section is factorised for a given energy scale into hard part and “normalization” from PDFs.
  + Why are both scales set to be the same?
    - Common practice to guess µ =Q.
    - Inclusive DIS usually both are set to be the same.
* Describe matching algorithms (differences between MLM and FxFx):
  + Matching vs merging?
    - Matching is the matching of MEs to PS.
  + Hard scattering is generated by ME generator but PS and hadronization is usually performed by PYTHIA.
  + Two stages need matching in order to create a smooth transition between the too.
  + pT threshold at which ME partons are matched to the PS is known as the ME-PS threshold.
  + For POWHEG:
    - Matching threshold depends on tuned parameter hdamp.
    - Dampens real emissions with a factor of h²/(pT²+h²), with the default value of h = mTop.
  + Madgraph\_aMC@NLO uses MLM and FxFx.
    - FxFx = MLM-like merging of NLO calculations.
    - MLM = runs shower, obtains Sudakov suppression and rejects event if any emission > tcut. <https://arxiv.org/pdf/0706.2569.pdf>
    - MLM works for any shower, with minimal modifications and theoretically not perfectly well-controlled.
      * Generate ME event with phase space cut QME
      * Reweight αS using scales for emission corresponding to event.
      * Shower event with starting scale.
      * Cluster shower emissions to jets using Qjet > QME, with events kept if each jet matches to one parton in the ME event.
* What is a deterministic annealing algorithm?
  + Splits phase space if there are no clusters within a set difference along the direction of the principle axis.
  + Repeat until clustering is complete.
  + 
* Why separate MC samples?
  + Statistics!
* Why does PU need correcting?
  + Minimum bias events rely on the underlying event and MC is generated before data PU profile is known.
* Why different PDF sets?
  + Produced by different collaborations that perform the fits using new data/theoretical predictions.
* How are uncertainties for PDF sets determined?
  + PDFs have a number of free parameters that are experimentally determined.
  + The free parameters are expanded around their best values and orthogonal eigenvector sets of PDFs depending on their linear combinations of the parameters variations are obtained.
  + “Replica” datasets are obtained by allowing the parameters to fluctuate randomly by amounts determined by the size of the data uncertainties.
  + Uncert is then the quadratic sum of the uncerts arising from each eigenvector.
* Define Deep Inelastic Scattering?
  + Inelastic = target absorbs some of the kinetic energy.
  + Deep = high energy of the probe, allowing it to resolve “deep” inside the hadron.
* Concisely explain blinding
* How is hadronic punch-through measured?
  + Punch-through = high energy pions producing energetic secondary particles that escape HCAL+Solenoid confinement.
  + Test beams were used to measure impact and found to be well described by simulation. Appears as random large clusters.
* How much signal/Z+jets/ttbar is discarded?

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | tZq | Z+jets (LO) | Z+jets (NLO) | ttbar |
| Lepton cuts | 480.406 | 32,006,730 | 32,483,790 | 249,822 |
| Z mass cuts | 437.17 | 30,244,930 | 30,643,260 | 70,476 |
| Jet cuts | 217.9079 | 119,927.3 | 132694.7 | 12,448.46 |
| b-tag cuts | 140.3915 | 17,204.15 | 19375.24 | 9663.45 |
| W mass cuts | 86.0537 | 8957.48 | 9280.6 | 4942.18 |

* Loss of signal though jet cuts? ~6%
* Is the leading b-jet from the top?
  + 66% of the time (post skimming)
    - Rest are from u/d/s/g
  + When only one b-jet, 100% of the time from a top quark (gen).
  + Better W and top mass from nBjet = 1?
  + Does considering W->bq impact results? ~0.9% for reco signal.
* Is the b-jet from the top decay central? Yes – 94.4% are central



* Boosting vs bagging:
  + Any element has the same probability to appear in a new data set for bagging, while boosting has weighted observations, increasing the probability certain elements will be used more often.
  + Bagging has each model being built independently (simple average), i.e. in parallel. Boosting is sequential.
  + Boosting reduces bias, but is susceptible to overtraining.
* How does XGBoost differ from other gradient boosting algos?
  + Modelling details:
    - More accurate approximations to find the best tree model:
      * Advanced regularisation for Regression Trees to better control over-fitting.
      * Computing second-order gradients of the loss function, which provides more info about gradient direction and how to minimise the loss function.
  + Improved data structures = better processor utilisation = faster
  + Better multicore support = faster
    - The ensemble cannot be parallelised as each tree is dependent on the previous but node building within each depth of the tree can be.
* Describe BDT optimisation:
  + Features/inputs:
    - Recursive feature elimination with default training parameters.
    - Feature with lowest importance removed and BDT retrained.
    - AUROC recorded at each step – used to select top “n” features, which for less then “n” steps, the AUROC has significant decline.
  + Hyperparameters:
    - Create a regression model!
    - Need to define a metric to be minimised … but the function is a black box … so regression used to approximate minima instead by first evaluating the model at random values before using choosing more intelligently.
    - The model is constructed using a Gaussian process and the metric is based on the AUROC that favours consistent performance.
    - Gaussian process is a set of random variables that the vector of the variables are distributed as a Gaussian.
* Correlated and uncorrelated nuisance parameters?
  + Correlated are common to both channels, such as luminosity.
* Log normal and log uniform distributed nuisance parameters:
  + Log normal = random variable whose logarithm follows a normal distribution.
  + Log uniform = random variable whose logarithm follows an uniform distribution.
* Results:
  + Past tZq:
    - 8 TeV: Searched for SM and FCNC tZ(q) production.
      * EFT for FCNC.
      * 2.4(1.8) sigma, SM consistent and FCNC limits x2 better than prior ones.
    - 13 TeV:
      * ATLAS:
        + Lepton pT cuts are flavour blind.
        + mZ = +/- 10 GeV.
        + 2 jets, 1 b-jet
        + Ttbar CR used to estimate the NPL contribution from VV as ttbar SR/CR have similar NPL contributions.
        + Ttbar verification and CRs and diboson VR/SR (MET > 20/60 GeV).
        + Neutral Network (all backgrounds except ttbar due to stats).

Validation region results good for expected/observed.

* + - * + SM consistent result signal strength; 4.2(5.4) sigma.
      * CMS:
        + ttZ and WZ CRs.
        + WZ backgrounds are separated by jet flavour for better modelling of heavy jet backgrounds.
        + Fit to BDT discriminant for signal/ttZ and MET for WZ.
        + BDT also includes variables calculated by the matrix-element-method.
  + Current tZq:
    - 7.2(5.7) and 5.4(6.0) sigma for 2016 and 2017
    - Signal strengths compatible with SM (1.36 and 1.01)
    - Improves on past searches by overcoming limitations caused by NPLs and the uncertainty in their prediction.
    - Uses grad BDTs to identify NPLs; exploits jet closest to the lepton (in terms of ΔR, rel iso, rel iso inside a fixed cone, impact parameters, and kinematics.
      * 85(92)% efficient for electrons(muons).
      * Mis-ID = 1.5%
      * Eff improves by 12(8)% and NPL rejection ~2(8) times better.
      * “Loose” criteria optimised for NPL background prediction.
    - BDTs are used for each SR (jet-binned).