Acknowledgements:

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

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 correction in parenthesis).
  + *Fundamental Particles:*
    - **Examiners** (Page 25): “… six leptons, fundamental particles experience the electromagnetic and weak force”. **Neutrinos don’t interact with EM.**
    - Page 26 – The spin-0 Higgs boson accounts for fundamental particles acquiring mass. WHOOPS. **Also picked up by Examiners.**
    - Page 27: Table 2.2 – Gauge Bosons heading -> Bosons.
    - Examiners: (Page 27, Table 2.2) **Weak isospin and colour charge entries for gluons are each other’s respective columns.**
  + *Gauge Symmetries:*
    - ***Examiners****: (Page 28) “as U(1) has only one generator, which self-commutes,* ***and*** *is zero.” Added “and” would make sense if there was no “as” before U(1). Confirm before committing.*
  + QED:
    - Page 29: “… Heisenberg's uncertainty principle, it***s* (or *the*)** field experiences random fluctuations.” **(Examiners also picked up on this)**.
    - ***Examiners****: (Page 29) “reduced”.* ***is it [unable to read note]?***
  + Weak Interactions:
    - *Examiners: (Page 30)* ***What is chirality?*** *Explain … chirality/left-handed fermions and T = +/- 1/2*
  + Electroweak Unification:
    - **Examiners**: (Page 30) **“… gauge group hypothesises that its …”** – technically a theory cannot hypothesise something. Only a person can … **“… gauge group and describes the two seemingly disparate constituent forces – weak and electromagnetic – as a single …”s**
  + Spontaneous Symmetry Breaking:
    - Page 31: “Brout, Engler, Higgs,**[insert space]** Guralnik, Hagen …” (**Examiners also picked up on this**).
    - **Examiners**: (Page 31) *Explain: “… infinite number of ground states.”*
    - **Rephrase:** *(Page 32, Figure 2.1) 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].”*
    - **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~~**, …
  + *Page 33: Last sentence rephrase.*
  + **Examiner 2**: (Page 34) “*Measurements of the Wtb vertex allow****s*** *for the …”*
  + Top quark pair production:
    - Page 35: 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!
  + **Examiners:** (Page 36) *Inked lines between paragraphs two and three.* *No paragraph break?*
  + Single top production:
    - Figure 2.5(a) – bbar is NOT from the sea! Due to charge asymmetric initial state
    - **Examiners**: [underlined] (Page 37) “*on-shell W boson*”.
    - **Examiners**: [underlined] (Page 37) “*observable” (at the LHC).*
    - **Examiners**: (Page 38) Why is there destructive interference between tH and HW vertices?
  + Single top production in association with a Z boson:
    - Page 38: In contrast, ttZ **[insert space]** has a lower … (**Examiners** also picked up on this).
    - 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].**”
    - 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 …”*
    - **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 …”
    - 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!*
    - Page 40: Errors for Equation 2.16.
  + Beyond the Standard Model Physics:
    - ***Examiners:*** *(Page 41) Explain why the Higgs vev would be either 0 or ~ order of plank’s constant and why cancellations would need to be fine-tuned.*

*LHC and CMS:*

* *LHC:*
  + **Examiners** (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.”
  + **Examiners** (Page 45): *Repeating proton bunches, bunch separation and collision rate.*
  + **Examiners** (Page 45:) *Explain the difference between in-time/out-of time PU. How is this possible?*
* *CMS:*
  + Overview:
    - **Examiners** (Page 46): *Where is the HO in the diagram? (Fig 3.4).*
    - **Examiners** (Page 47): [underlined] *This is due to η ?*
  + Tracker:
    - **Examiners**: (Page 47): “… a low channel occupancy (<1%)**.**”
    - **Examiners** (Page 48): “ROCs” undefined
    - **Examiners** (Page 48): *How are pixels better than strips for track recon.*
    - **Examiners** (Page 48): *Last paragraph of 3.2.2 before 3.2.2.1 needs to be better English!*
  + Silicon Pixel Tracker:
    - **Examiners** (Page 48): “… Tracker Inner Disks (TID**)**, …”
    - **Examiners** (Page 48): “… barrel layers at mean radii of 4.4 **cm**, 7.3 **cm**, and 10.2 cm respectively …”
    - **Examiners** (Page 48): *Nice to have pictures of SPT and SMT.*
    - Page 48: Make it clear that the Phase-1 pixel has always been planned
  + Silicon Microstrip Tracker:
    - (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.*
    - (Page 49): “Avalanche photo**~~s~~**diodes … amplify the light and **convert** it into an …”. **Examiners also picked up on these**.
    - (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.*
  + Muon Chambers:
    - (DTs, Page 53): Correct z0 -> z’s
    - **Examiners** (Page 55): *Nice to have performance plots of all detectors*
  + 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***.
      * **Page 56: Fix 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)***
  + ***Examiners*** *(Page 61):* ***(HL-LHC)***
  + **Examiners** (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.
  + **Examiners** (Page 61): “… during Long Shutdown 3 **(LS3)**, which …”
  + **Examiners** (Page 61): “geometrical reduction factor**~~,~~** .”
* *The Phase-II Outer Tracker Upgrade:*
  + Page 61: “… innermost layers) **[insert space]** and …” **Also picked up by examiners.**
  + Pages 61-62: Capitalised start of bullet points
  + **Examiners** (Page 62): [Question] “..either 25x100um² or 50x50um².”
  + Page 62: As with **~~to~~** the previous pixel detectors, the Inner Tracker is also designed.
  + **Examiners** (Page 64): [Question] “The advantages of the tilted geometry …large incident angles … overall costs of the system.”
  + *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:*
  + **Examiners** (Page 65): [Question] “Hough Transform”
* *The Track Finding Architecture:*
  + 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***.
  + *Hough Transform:*
    - **Examiners** (Page 70): [Question] “By choosing an appropriate value of T … optimal value of T was determined to be 58cm.”
    - **Examiners** (Page 70): [Question] “A detailed description of the firmware implementation of the Hough Transform ….”
  + *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**.”
    - “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.**
  + *Duplicate Removal*
    - **Examiners** (Page 72): [Question?] “green and yellow HT cells”
    - **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): “… the following conditions.” 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:*
      * **Examiners** (Page 75): “*… si, we initially linearly expand …*”, change in voice used and define i. **Also picked up by examiners.**
      * Equation (4.5): missing brackets for delta **(**h) and fi(h**)**.
      * *Add an appendix detailing matrix elements D, see Tracklet DN.*
    - *­ χ² Track Fitter Software Implementation:*
      * ***Examiners*** *(Page 77*): [Question?] *First paragraph of the page re. the “approximated expressions”. Perhaps elaborate clarify?*
      * ***Examiners*** *(Page 77*):  *Define resolution – add/odd(?) biases.*
        + *Resolution: (Fitted helix parameter – TP helix parameter)*
      * ***Examiners*** *(Page 78*):[Questions] *Figure 4.9: Error Bars? Structure? What about biases?*
      * ***Examiners*** *(Page 78*):[Question] *Figure 4.9: Error Bar circled.*
      * ***Examiners*** *(Page 78*):  *“being incorrectly associated with a matched tracked in the forward regions, as shown in Table 4.1, significantly degrades the resolution obtained.”*
      * ***Examiners*** *(Page 79*):  *“The reason … were …” tenses.*
      * ***Examiners*** *(Pages 79-80*):  *“... fake rate being halved…”, “purity … increasing.”, “… resolutions in the endcaps.”, “…linearisedchi2 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.*
    - *Tracking at low transverse momenta studies:*
      * ***Examiners*** *(Pages 80-81*):  *“… lower pT threshold of 2 GeV ... performance of the proposed track-finder system was studied.”, “… robustness studies…”, “… demonstrator review.”, “tracking efficiency below 3GeV with the Hough Transform.” Underlined by Examiner 1 – suspect for questions for viva, but I think these parts can be rephrased into a better form.*
      * **Examiners** (Page 81): “… threshold of 2GeV**.** The …” missing full stop.
      * ***Examiners*** *(Page 81*):  *“The focusing on recovering tracking efficiency below 3 GeV with the Hough Transform.” Phrasing.*
      * ***Examiners*** *(Page 82*):  *Figure 4.11 caption top/bottom -> left/right.*
      * ***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.*
      * ***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.*
      * ***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.*
      * ***Examiners*** *(Page 85*):  *Figure 4.14 caption top/bottom -> left/right.*
      * ***Examiners*** *(Page 85): [Question] Last paragraph, related to question re. Figure 4.14.*
      * ***Examiners*** *(Page 85): “… Hough Transform produces more duplicates at low pT…”, “… decreased number of duplicates …” Underlined by Examiner 1 – suspect for questions for viva, but I think these parts can be rephrased into a better form.*
      * ***Examiners*** *(Page 86): [Question] Figure 4.15 – the first bin (high pT) why no multiple scattering scatter point has better efficiency?*
      * ***Examiners*** *(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.*
      * ***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!*
      * ***Examiners*** *(Page 87): “The* ***resolutions*** *…” Double line in margins. New paragraph? Rephrase?*
      * ***Examiners*** *(Page 88):* ***BOTH EXAMINERS******Maybe a summary; it just ends.***

***CONTINUE TRANSCRIBING EXAMINER 2’s NOTES FROM PAGE 89+***

*Event Simulation and Object Reconstruction:*

* *Add LOTS of plots showing the efficiency of the various circumstances.* ***Examiners also picked up on this: “maybe include performance plots.”***
* 2nd opening paragraph: The event simulation and **object** reconstruction algorithms
  + *Event Simulation:*
    - *Event Generators:*
      * ***Examiners*** *(Page 90): “… with a specialist generator* ***~~that~~*** *that models a specific physics object …”*
  + *Object Reconstruction:*
    - *Reorder Muons (5.26) and Electron (5.25) subsubsections?*
    - *Particle Flow Algorithm*
      * Page 94: granularity detector considered (**HCAL**/ECAL). ***Examiners also picked up on this.***
    - *Electrons:*
      * ***Examiners*** *(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.***
      * *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:*
      * *Push 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 …” **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.
  + ***Examiners*** *(Page 102): “… to the known W boson mass of* ***~~of~~*** *80.4 GeV [21] is considered.”*
  + 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
* *Control Region:*
  + ***Examiners*** *(Page 103): “… is essential in order* ***to*** *extract the signal yield.”*
  + ***Examiners*** *(Page 103):* ***Explain control region?? (check modelling)***
  + Background Control Region:
    - ***Examiners*** *(Page 104):* ***Correct pT thresholds used for this control region.***
* *Experimental blinding:*
  + ***Examiners*** *(Page 104): “Despite even the best intentions, there is the* ***~~for~~*** *potential* ***for*** *experimental procedure …”*
  + ***Examiners*** *(Page 104):* ***Explain BDT?***
  + Stray **)** before “optimised chi2 values.” **Examiners also picked up on this.**
  + Figure 6.1 top/bottom -> left/right. **Examiners also picked up on this.**
* *Trigger Strategy*
  + ***Examiners*** *(Page 104): “… and will likely be limited by* ***~~statistics~~ event yield****, it is …*
  + *Table 6.1 - ensure table logic is clear.*
  + Table 6.1 - !M and !E for Single Electron and Single Muon.
* Event Cleaning:
  + ***Examiners*** *(Page 107): “… with beam or detector from …”* ***detector?***
  + ***Examiners*** *(Page 108): “… at raddi up to 5m”**Perhaps “of up to 5cm”?*
* *Physics objects:*
  + *Lepton Selection:*
    - *Electrons:*
      * ***Examiners*** *(Page 109): Add reference to Chapter 5 for conversion veto.*
      * *Full 5x5σiηiη – add a brief summary.* **Examiners also picked up on this.**
        + *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 …”* **Examiners also picked up on this.**
    - *Jet Requirements:*
      * ***Examiners*** *(Page 113): Fractions are wrong. Correct!*
* *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!**

***CONTINUE TRANSCRIBING EXAMINER 1’s NOTES FROM PAGE 116+***

*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:*

* Fix ordering in text – it starts from the list of tables/plots currently.
* 18 – title of paper needs caps in places
* *135* – T. C. Collaboration -> CMS collaboration
* *149 – needs making clearer*
* 161 – T. A. Collaboration -> Atlas collaboration
* 170 – sqrt -> replace with square root sign.

**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.
* SM Predictions:
  + Higgs, W, Z bosons, gluons, top and charm quarks and their properties before observation.
* Solar neutrino problem:
  + Large discrepancy between solar neutrino flux prediction and measurement.
  + Different solar models didn’t resolve it: lower neutrino flux required cooler core, but neutrino energy spectrum required hotter core.
  + Neutrino oscillations possible if neutrinos have mass.
  + Super-K 1998 – atmospheric neutrino evidence.
  + SNO 1999 – solar neutrino evidence.
* 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!
  + Third component (conserved one) is the projection for which flavour states are eigenstates.
  + 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.
* Dielectric = an electrical insulator that can be polarized by an applied electric field.
* 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.
* Motivation behind Phase-2 Tracker:
  + Reduce data-rate from 4MHz to 750kHz.
  + Total latency is 12.5us, 3.5us to correlate tracks, 1us buffer plus 3us safety margin. Total track finding/fitting budget is 5us, of which 1us for packaging.
* 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.
    - Why use r->rT and φ->φT? Stub-line gradient is proportional to rT and so can be positive and negative. Larger range of gradients allows for improved precision wrt. intersection point.
  + KF:
    - State vector = fancy name for variables considered (in this case helix parameters).
    - Ak and Bk are state-transition (propagates helix parameters from one layer to the next) and control-input (not used – ignore external influence) models.
    - Hk is the observation model which maps the true state space into the observed space.
    - 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.
* Tracklet:
  + Pairs of stubs from neighbouring layers of the tracker are linked to form seeds.
  + Seeds are propagated outwards/inwards.
  + Efficiency is maintained by using seeds from multiple pairs of adjacent layers/disks.
  + Use IP in r-φ as a constraint to calculate helix parameters in r-φ and r-z.
  + Pairs of stubs must have |ρ-1| < 0.0057 cm-1 and |z0| < 15cm.
* Associative Memory:
  + ASIC: Pattern recognition for track finding.
  + FPGA: PCA for fitting:
    - Converts sets of measured variables into a set of values of linearly uncorrelated variables.
    - 1st principle component has largest possible variance.
    - Each successive component has highest possible variance under the constraint that it is orthogonal to preceding components.
* 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 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.
    - ; , (for Gaussian beam).
    - Scan in x and y to obtain beam heights.
    - *Does* assume x and y profiles are independent and therefore factorisable.
    - Needs distance calibration.
  + 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.
* Maximum Likelihood Fit:
  + Find parameters that maximises the “likelihood” function.
* Poisson statistics:
  + Events occur with a known constant rate and independently of the time since the last event.
  + For large mean/variance ~ approximately normal.
* 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 a 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).
    - Alterative deep NN trained, but gives nearly identical results.