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Experimental Particle Physics
Understanding the measurements and searches at the Large Hadron Collider
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Appendix A

Solutions

Chapter 1

1. $[E/\hbar] = 1/T$, which cannot be expressed as power of only c. Other powers of $\hbar$ would leave an unbalanced mass dimension. $[L] = \hbar c/\text{eV}$ and $[M] = \text{eV}/c^2$.
2. Essentially to cross-check each other's results. It also results in intense competition, and occasionally a wrong (but stunning) result from one collaboration potentially driving the other to *reproduce* that.
3. Dark matter is not antimatter, because we do not see the unique gamma rays that are produced when antimatter annihilates with matter.
4. $M_{\text{inv}} = \sqrt{(E_1 + E_2)^2 - (p_{1x} + p_{2x})^2 - (p_{1y} + p_{2y})^2 - (p_{1z} + p_{2z})^2} = 125.4$ GeV, which is the Higgs boson.
   For future reference: if the four-momenta were expressed in terms of collider coordinates: $M_{\text{inv}} = 2p_{\text{T}}^1 p_{\text{T}}^2(\cosh(\eta_1 - \eta_2) - \cos(\phi_1 - \phi_2)$
5. $\gamma = E/m = 6500/0.9838 \approx 6927$, leads to $v/c = \sqrt{1 - 1/\gamma^2} \approx 99\,999\,998\,958$.
6. $\tau = 1/2.5\ \text{GeV} = 0.4 \times \hbar = 2.5 \times 10^{-25}$ s.
7. There is no frame where a photon has zero momentum. However, there exists a frame, the center-of-mass frame, in which the electron–positron system has zero momentum. This incompatibly makes it kinematically impossible. However, *virtual photons* can temporarily violate conservation laws, leading to pair production.
8. We have, $m_e^2 = m_e^2 + 0 + 2E_\gamma(E_e - p_e \cos\theta)$ So, $E_e = p_e \cos\theta < p_e$. Whereas, $E_e = \sqrt{m_e^2 + p^2} > p_e$.
9. For conservation of strangeness, $-1 + 0 = X + 1 + 1 \Rightarrow X = -3$. Checking the mass: 1672.45 MeV < 1321.31 MeV + 498 MeV.

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10. No, as they respectively violate momentum and charge-conjugation. Neutral λ decay to a proton and pion violate parity, but can proceed via weak interaction.

Comparison of linear and circular colliders.

	Linear collider	Circular collider
Energy ramp up:	Restricted by the length	Multiple *kicks* while going around
Luminosity:	Low, as beams cross only once	Beams cross many times
Energy loss due to synchrotron radiation:	Less	More
Cost:	Less	Expensive magnets are needed

Comparison of lepton and hadron colliders.

	Lepton collider	Hadron collider
Synchrotron radiation energy loss:	More	Less
Focussing beams:	Easier with large *e*/*m* ratio	Harder with large *e*/*m* ratio
Cross-section:	Smaller, only electroweak, much cleaner environment	Much larger, hadronic, messier
Final states:	Only charge neutral	No such restrictions
Probed energies:	Fixed	Protons are composite, range of energies
Physics aim:	Tune c.m. energy to a discovered particle being probed	Scan an energy range for discovery

Chapter 2

1. The energy lost by a particle going through turn in a circular accelerator is proportional to $E^4R^{-1}m^{-4}$, where E, m are the energy and mass of the particle, and R is the radius. That explains why energy loss for leptons is much larger, and all proposd future electron/positron colliders are linear. Also, anti-protons are harder to make than protons, which is why LHC moved to *pp*. Muon colliders have the advantage that muons are heavier than electrons, so less energy loss, but muons can decay.
2. Protons move at speeds closer to speed of light, so they will traverse the 27 lm LHC ring in $\approx 10^{-8}$ s. We clearly cannot keep injecting protons at the rate.

3. Field strength of the bending magnets is the limiting factor. The protons are accelerated by RF electric fields, and the dipole magnets bend them into a circular orbit, and quadrupole magnets focus them.
4. When calculating $\Delta\phi$, it must be within 0 to 2π. In order to achieve that, if $\Delta\phi < 0$, 2π is added to it.
5. As the detectors cover the full $\phi = 4\pi$ area, so particle with any value of ϕ can be measured.

Chapter 3

1. Although hadron colliders can probe a wide range of energies, the main target was the Higgs boson. The promising decay modes in the mass range of interest were two photons, two τ leptons, two W bosons and two Z bosons. So the focus was on good lepton and photon identification capacity, as much detector coverage as possible, good momentum mass and angular resolution. Also efficient b-jet and τ identification needed pixel detectors close to the beamline, and well segmented calorimeters for jet and MET construction.
2. The most prevalent final state particle is the photon. This is because the majority of the produced hadrons are mesons, and most prevalent mesons are the light pions, which decay to two photons. Next are the hadrons.
3. There can be multiple reasons. The collision may not have happened at the centre of the detector, leading to what is termed a *displaced beam spot*. It can also be coming from pile-up interaction.
4. The electron charge is measured from the curvature of the associated tracks. The higher p_{T} they have, the straighter the tracks become, so misidentification probability increases. The tag electron is required to have *tight* characteristics that ensure that its charge is very likely to be correctly reconstructed, while the probe electrons will be the electrons used in the analysis. The probability of wrong charge assignment is then the number of events where the probe has the same reconstructed charge as the tag (which is assumed to be correct), divided by the total number of events passing tag-and-probe mass requirement.
5. All the objects used in the construction of MET have some threshold p_{T} requirement.
6. The JVF depends on tracks, while for forward jets beyond $|\eta| > 2.5$, the tracker does not exist.
7. Calculation of differential cross-sections in perturbative QCD needs IRC safety. All experimental observables are IRC safe by definition, there are no infinities experimentally because of the finite size of the particles.
8. We are limited by calorimeter resolution, as typical cell resolution in η and ϕ is 0.1×0.1.
9. Jets are *smaller* in the forward region.
10. Energy deposits from electrons and photons are typically included in jet construction, as deposits in both electromagnetic and hadronic calorimeters

are considered. Muons deposit their energy only in muon chambers, so they are typically not included. Even though the jet reconstruction is democratic, electron reconstruction is affected if there is real hadronic activity close-by.

Chapter 4

1. (a) For a hadronic collision, we have three possible hard scattering processes, qq, qg and gg. With the higher energy of the proton at the LHC, there are more gluons, making gg dominant, as opposed to qq in Tevatron.
   (b) The ratio of energies (which is termed Björken-x) of partons with respect to the proton (or anti-proton) required for formation of a $t\bar{t}$ pair is much higher in Tevatron than in LHC, as the beam energy is lower. The PDFs show that higher x values are dominated by valence quarks, while lower x values are dominated by gluons.
   (c) The s channel production is initiated at LO by $q\bar{q}$ annihilation, which is more abundantly produced in $p\bar{p}$ collisions.
2. We can generate a large number of random, uniformly distributed points inside the square, and test.
3. Parton shower can be thought of as the mechanism which gives rise to jets from partons. However, it must be realised that we never really have a single quark, rather a quark–anti-quark pair to start off with. As they move apart, they produce more anti-quark pairs from vacuum. Then hadronisation involves forming colour neutral hadrons from combination of these quarks. All the conservation laws hold for initial partons and final hadrons, but not for the jets.
4. Running of the strong coupling constant hints at what value it should have for higher energy jets. However, the determination is dependent on scale choice (should we use leading jet p_{T} or the average p_{T} or the H_T for multijets?) and non-perturbative corrections.
5. To obtain the correct shape for the leading jet p_{T} spectrum, one must apply the event weight, then normalize each slice to the corresponding cross-section, filter efficiency, sum-of-weights (or total number of events), and luminosity. The usual problems are not having all the slices, not having all the events in a slice, or not using the correct weight. If the event weights are calculated by the generator, then sum-of-weights should be used, whereas if event weights are only added to flatten the individual slice p_{T} distribution after the generation (such as by throwing out some events, and reweighting the rest), then total number of events should be used.
6. When calculating this process at NLO, the $t\bar{t}$ contribution has to be subtracted. Several method are used, one of them is to reject the events where invariant mass of the $W^-\bar{b}$ system is close to mass of the top quark.

7. (a) Not all generators, such as HERWIG or SHERPA keep the intermediate Z bosons in the event records.
   (b) With increasing p_{T} more and more b quarks are produced in the PS via gluon splitting. So requiring four b quarks from ME will ignore as an example two from shower and two from ME. However, the distinction between ME and PS is operational at best, and depends on the generator set-up. So these two samples will result in double counting, as the two b quark at the ME sample with extra b quarks from showering will cover some of the same phase space as the four b quark ME sample.
8. The tunes of the generators are performed inclusively, not just for specific sub-processes. Turning of MPI in PYTHIA for example will result in the initial state shower increasing its activity to compensate, since both the MPI and shower processes are competing with each other in the evolution of the interleaved shower and MPI equation.
9. If the generation uses a LO PDF, we expect the distribution to be narrower than in data (and than using a NLO PDF).
10. Usually the hadronic calorimeter shower shape variables are found to be least well modelled, so that tends to affect internal structure of jets the most.

Chapter 5

1. If we do create a miniature black hole, that will have at most have a mass equal to the energy of the pp collision, or up to 13 TeV. That corresponds, via $E = mc^2$, to a mass of just 5×10^{-23} kg, and most likely less, and a decay (via Hawking radiation) time of 10^{-83} s, too tiny to have any effect.
2. If the pile-up vertex is very close to hard scatter vertex, they can appear merged. Tracks from pile-up tend to have much less p_{T}, so the effect on sum p_{T} will be negligible, but track multiplicity may be affected.
3. We define μ as the number of pp pairs interacting in a bunch crossing. We aim to correct for this by scaling the selection efficiency of an event so that on average the predicted μ distribution matches that in data, which is known as μ reweighting. It depends on how good the modelling of pile-up is in the generator used to produce the overlay distributions.
4. We usually reject negatively weighted events during the analysis, but use the total cross-section generated. So we then need more events to attain the same statistical accuracy as would be in an MC with only positive weights. For multileg generators, there will always be a distribution of weights, leading to weights greater than unity for most *common* events. Sometimes in order to avoid spikes in distributions, these are set to unity.
5. This can be due to non-application of the (same) trigger in the simulated sample. If we do not have all the objects which fire the trigger at the trigger plateau, then this would lead to such a behaviour.
6. The staggered cuts are preferred, because for theoretical (soft emission) and experimental (resolution) reasons, objects are not perfectly balanced.

7. At the LHC, more positively charged W bosons are produced. W^+ predominately has $u\bar{d}$, while W^- predominately has $d\bar{u}$. Since protons are uud, we have more probability of u quarks participating in W formation. In Tevatron $p\bar{p}$, there was no such difference.
8. There will be no change in the first case. However, in the second case, if we have a three jet event, with one jet close to signal lepton, then step 5 will remove that jet, and the event will pass exact two jets criteria in 6. However if we swap, step 5 will kill the event.
9. The implicit assumption here is that all the background processes have the same shape over the entire range. Otherwise, we may ignore the contribution of a background which may, for example, start having a flatter shape toward the higher values.
10. It must be dominated by one single process.
11. We will have more fake electrons from jets.
12.
    - (a) A single jet and missing energy. Largest background is W+jet events. Can be reduced by vetoing lepton.
    - (b) Four leptons. Largest background is SM ZZ production. Can be reduced by opposite charge and Z mass window requirements.
    - (c) Four jets. Largest background is multijet and combinatorial Can be reduced by b tagging and top-mass requirement.
    - (d) A single jet and missing energy. Largest background is W+jet events. Can be reduced by vetoing lepton and also by ISR tagging.
    - (e) Two leptons and two jets. Largest backgrounds are $t\bar{t}$ and Z+jets. Can be reduced by b veto, Z-mass window requirement.
    - (f) Diphoton. Largest backgrounds are SM diphoton production, diphoton decay of π^0 in jets. The latter can be reduced by requiring isolated photons.
13. We get 25 signal events. Assuming a 40% signal efficiency, we get 10 events. We definitely need about 10 events for the analysis to be feasible.
14. Human bias!
15. The b tagging efficiency is not 100%, so one b-tagged CR can have signal contamination. A further MET requirement may help.

Chapter 6

1. Yes, the range given by mean value and uncertainty are overlapping. No, larger uncertainty.
2. The default in ROOT is to do simple errors, $\sigma = 1/\sqrt{N}$. This will get the errors wrong in a weighted distribution. In that case, sum of squares of weights need to be used (which in ROOT terms mean using *Sumw2* function).
3. If the background is purely data-driven, then there can be uncertainty assessed on the method used, but it can be minimal. Then the systematic uncertainty on signal yield, which is from simulation, will be a contributing factor.

4. There are systematic uncertainties, which are determined using data. For example jet energy scale and resolutions uncertainties are often determined using *in situ* or data-driven methods. In those cases, more data can help constrain the systematic uncertainty better.
5. The top-down approach demands that we know of all possible sources of potential systematic effects *a priori*. However, then assessing the uncertainties is more straightforward. The bottom-up approach is more *democratic*, but it has its own challenges. It is sometimes difficult to estimate what variations of the input objects are reasonable (in terms of their effect on the final observable), and it is often also difficult to separate statistical fluctuations from real systematic effects.

Chapter 7

1. Tracks correspond to charged particles. Two (or any even number of) charged particles cannot make a singly charged τ lepton, we need one or three. We get one in about half the cases.
2. τ leptons decay to single pion or three pion jets, as opposite to *usual* jets with large hadron multiplicity. This is because the τ lepton is light, so the decay proceeds via a process called weak charged current interaction, where the quark pairs from the virtual W form the pions instantaneously. The branching fraction for this decay mode is several orders of magnitude smaller than the usual dijet decay mode of on-shell W bosons.
3. The leptonic branching fraction for both the τ is roughly 0.35×0.35, and needing two same flavour leptons further reduces it by a factor of two, so we are at about 6%. Then we have to consider the kinematic cuts and acceptance, which usually reduces the τ contamination in signal to sub-percent levels.
4. Semi-leptonic $t\bar{t}$ implies presence of one neutrino, leading to real missing energy. In the hadronic decay mode, the missing energy results from mismeasured objects, and threshold requirements.
5. If we produce a DY pair with $p_{\mathrm{T}}^{\ell\ell} \approx 0$, then $M_{\ell\ell} \approx 2p_{\mathrm{T}}^{\ell\ell}$.
6. This is because when the measurement is done with an identified hard scatter (as in the case of UE), preferentially events with a higher activity are selected.
7. As the events were required to have a larger radius jet, we preferentially selected events with higher overall activity.
8. If we just merge the neighbouring bins, then obviously each bin will go up. To avoid this, usually bin entries are divided by bin width.
9. There are several options:
    - Divide each bin content by bin width.
    - Divide each bin content by bin unity.
    - Divide each bin content by sum of entries.
    - Divide each bin content by integral.

- Divide each bin content by (integral/bin width), If already divided by bin width.

Histograms with fixed and variable bin size behave differently when bin width is included in normalisation.

10. Smooth distributions from simulation are needed to decide analysis strategy.
11. *This problem is motivated by https://cds.cern.ch/record/2320419*. The number of events from a specific process X, with a cross-section of σ_X, is given by, $N_X = L\sigma_X$, where L is the luminosity. Assuming average number of pp collisions in a bunch crossing is given by μ, this implies that the corresponding average number of inelastic collisions is $L\sigma_X\mu$. The probability that an inelastic interaction gives a hard scatter process Y with a cross-section of σ_Y is $P_B = \sigma_Y/\sigma_{\text{inel}}$. Putting all together, the number of events which have both processes X and Y from multiple pp interactions is: $N_{XY} = L\sigma_X\sigma_Y\mu/\sigma_{\text{inel}} = L\sigma_{t\bar{t}}^2\mu/2\sigma_{\text{inel}}$, where we have used $t\bar{t}$ process for both X and Y, and the factor of 2 in the denominator avoids double counting of identical processes. Taking $\sigma_{\text{inel}} = 80$ mb and $\sigma_{t\bar{t}} = 832$ pb (both at $\sqrt{s} = 13$ TeV), and using $t\bar{t}$ semileptonic branching fraction of 44%, we get: $N = 150 \times 10^3 \times (832 \times 0.44)^2 \times 50/(2 \times 80 \times 10^9) \approx 1400$. This number is the expected number of events before acceptance and efficiency has been taken into account.
12. Expected events 15. So statistical error is $\sqrt{15} = 3.8$. We saw 20, so roughly that is 1.3σ away. This actually corresponds to measuring σ with the more conservative estimate of $\sigma = S/\sqrt{B}$, where S is the excess of signal events. Alternatively, by using $\sigma = S/\sqrt{S + B}$, we get 1.12σ. In order to use $S/\sqrt{S + B} = 5$, if N is the number of background events needed for discovery, then the excess will be $S = N/3$, assuming proportionality. Then we can write $N/3 = 5\ \sqrt{N(1 + 1/3)}$, or $\sqrt{N} = 17$, or $N = 290$. To have a $290/15 = 20$ times increase in event yields, 200 fb^{-1} luminosity is needed.
13. Observing zero events in the data means $N_{\text{bg}} = N_{\text{sig}} = 0$. If we expected S signal events, using Poisson distribution, the probability to observe zero events is e^{-S}. So we can set an upper limit on the expected signal yield S with $e^{-S} < \alpha$, where $\alpha = 5\%$ for 95% CL. That gives $S \leqslant -\ln 0.05 \approx 3$.
14. (a) This was an example of a missing systematic uncertainty. The jet energy corrections needed to be slightly different for quark and gluon initiated jets, as the latter are broader and contain a larger number of hadrons. The overcorrection of gluon jets, which do not uniformly populate the phase space, caused mismodelling of the background distribution.

    (b) The absence of jets rules out the gluon–gluon fusion production mechanism of this new resonance, and the only remaining alternative of photon–photon fusion cannot give such a high cross-section. The result should not have been insensitive to photon isolation, as new resonance will produce well isolated photons.

15. They are usually the papers which introduced widely used programmes or techniques. The original PYTHIA manual features prominently (it crossed 10 000 citations as of April 2019), and GEANT4 manual is up there as well. Other prominent ones include papers describing CT* series of PDFs, and anti-k_t clustering paper.