A list of specific questions from students and their answers that I have received and answered by e-mail

**QUESTION 1: Asked 23/2/2017**

Quoting I:

- **Q:** I have a query regarding Q.8 in worksheet 1 – I did not understand how to arrive at the answer to the question even having followed the event tutorial recommended? Can you help explain?

- **A:** Dear I

  The essential part of the question envidaged addressing these key points:

  1. Reconstruct from the observed momenta the masses of particles C and D which had decayed into the pair of kaons and the muons respectively. Can you then obtain the mass of B?
  2. What quantum numbers could possibly be associated with particles C and D? By extension what type of hadronic particle are particles A and B? Considering length scales or timescales involved between creation and decay of these particles what decay processes are in action?
  3. From the above and by reference to other data, such as the cross section for electron positron annihilation (see lectures/notes and look at resonances), or the masses of mesons, identify the quark composition of particles A, B, C and D.

The previous outline answer suggested the following:

- **Hint:** Always consider baryon number conservation first when looking at a jet of particles. Thus you can immediately determine which particles are mesons and which are baryons.

Then when looking at both jets in a two jet event (not the case here as we are only looking at one of the two jets) – then the baryon number must also be conserved across the entirety of the two jets. If the two jets are observed in an $e^+e^-$_collision, e.g. as in LEP, then the sum of baryon numbers over all particles in the two jets must sum to zero, because there were zero baryons to begin with. This might also be true if there was a net number of baryons of 2 in one jet and of -2 in the other jet (implying more antibaryons than baryons).

See detailed explanation at:  
[https://www.tcd.ie/Physics/People/Cormac.McGuinness/Teaching/PY4P02_event_tutorial.pdf](https://www.tcd.ie/Physics/People/Cormac.McGuinness/Teaching/PY4P02_event_tutorial.pdf)

- You felt this answer was incomplete as the event tutorial did not describe the reasoning by which one could obtain the necessary answers. I outline the reasoning here giving a detailed account of the necessary steps. **In no way is all of this detail and additional extra background necessary in order to get a full mark for an answer to the question.**

- **Part 1:** Answering the first part above to obtain the mass of B.

  It is easy to reconstruct the rest mass energy of the decaying particle e.g. of particle C, from the momenta of the muon decay products and hence that the rest mass of the flavourless meson that is particle C has a rest mass given by (in general):
\[ M^2 c^4 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 c^2 = E_1^2 + E_2^2 + 2 E_1 E_2 - p_{1x}^2 - p_{2x}^2 - p_{1y}^2 - p_{2y}^2 - p_{1z}^2 - p_{2z}^2 - \vec{p}_1 \cdot \vec{p}_2 c^2 \]
\[ = m_1^2 c^4 + m_2^2 c^4 + 2 E_1 E_2 - 2 p_{1x} p_{2x} + p_{1y} p_{2y} + p_{1z} p_{2z} c^2 \]

where \( p_1 \) and \( p_2 \) (or \( \vec{p}_1 \) and \( \vec{p}_2 \)) are the momenta (or vector momenta) of the two decay products, and \( p_{1x}, p_{1y}, p_{1z} \) and \( p_{2x}, p_{2y}, p_{2z} \) are the \( x, y \) and \( z \) components of \( \vec{p}_1 \). The rest mass energy of the decaying particle in this 2-body decay is \( Mc^2 \). For each individual particle:
\[ E^2 = m^2 c^4 + p^2 c^2 \]  
which if given the individual vector components translates as
\[ E^2 = m^2 c^4 + \vec{p} \cdot \vec{p} = m^2 c^4 + p_{x}^2 + p_{y}^2 + p_{z}^2 c^2 \]  
allowing one to determine \( E_1 \) and \( E_2 \) knowing \( p_1 \) and \( p_2 \) and \( m_1 \) and \( m_2 \).

- For particle C both decay products are muons and have the same rest mass which is given to you in the table provided. You should obtain \( p^+ = 13.444 \) GeV/c and \( p^- = 16.339 \) GeV/c and \( E^+ = 13.445 \) GeV/c and \( E^- = 16.339 \) GeV/c; and thus for particle C the rest mass energy \( Mc^2 \) is calculated to be : \( 3.681 \) GeV/c\(^2 \) – this turns out to be the energy of the second \( \psi \) \( cc \) resonance when produced through high energy electron-position annihilation events.
- For particle D – the similar reconstruction of the momenta of the two observed \( K \) mesons gives for particle D a rest mass energy of \( 1.02 \) GeV/c\(^2 \).

**How to obtain the rest mass energy of particle B?** The mass of particle B can again be obtained through the use of the reconstructed momenta of particles C and D. Because of conservation of momentum, the momentum of particle C is the vector sum of the momenta of the two decay products of C. Thus you have the momentum of C in \( x, y, \) and \( z \) directions. Similarly, because of conservation of momentum, the momentum of particle D is the vector sum of the momenta of the two decay products of D. With these vector momenta of the decay products of particle B, and the energies of particles C and D – recall conservation of energy must apply – then the rest mass energy of the decaying particle B can be calculated. I do not explicitly list it here, but it should be \( \sim 5.28 \) GeV/c\(^2 \).

**Part 2:** Identifying the quantum numbers that can be associated with particles C and D and by extension with particles A and B.

Firstly, note that a long track immediately implies a long lifetime. This is not necessarily always imply a relatively long-lived weak decay but could be a suppressed strong decay or less likely electromagnetic decay process.

In this case, particle C decays into a positive and negative muon, i.e. a lepton and anti-lepton of the same family; charge must be conserved implying particle C is neutral; lepton and lepton family number is conserved implying particle C has zero lepton number; the baryon number of the muon and anti-muon are zero and baryon number is conserved, implying that particle C has zero baryon number => particle C is a neutral meson! It must also be a long lived one that can decay electromagnetically producing the charged lepton and anti-lepton. Further if it decays electromagnetically via an intermediate photon then it must also have a \( J \) value of 1. Candidates would thus be flavourless neutral meson e.g. with quark flavours such as \( uu, ss, cc, \) or \( bb \). These would be for instance the \( \rho(uu), \phi(ss), J/\psi cc \) or higher mass \( \psi cc \) resonances, or indeed the \( Y(bb) \) and its sequence of resonances.

When this was asked as an exam question the plot of all of the resonances produced through high energy electron-position annihilation events was shown and this spanned the energy
range from 0.5 GeV to the Z resonance at 91.2 GeV and thus showed all of the $J = 1$ flavourless mesons such as the $\rho(uu), \phi(ss), J/\psi \; cc$ or higher mass $\psi \; cc$ resonances, or indeed the $\Upsilon(bb)$ and its sequence of resonances. In this instance in the worksheet you are asked to consider other sources of information available to you i.e. consult your notes or handouts.

Hence particle C can be identified as having quark composition as $cc$, if one simply knew that the charm quark meson resonances dominated the intermediate energy region in that plot and were less massive than bottom quark meson resonances.

In a similar fashion particle D can be identified as a flavourless meson, whose rest mass energy is $1.02 \; GeV/c^2$. This is the $\phi$ meson with quark composition $\phi(ss)$ and as it can also be produced by electron position annihilations, it is also observable in the plot provided at the time of this question appearing as an examination question. It decays into the two K mesons as noted, and clearly is seen to have a long lifetime as it is a long track in the event topology shown, so why can we say it is a strong decay rather than a weak decay? Both of the products, the $K^+$ and $K^-$ each contain one of the strange or anti-strange quarks, and no weak decay process is needed in this event as strangeness gets conserved. Instead it is a strong decay but one which is suppressed and hence gives a long lifetime and a narrow width to the resonance.

The $\psi \; cc \; (3.681)$ and the $\phi(ss)$ have comparatively long lifetimes as they have suppressed strong decay or electromagnetic decay routes. In this instance the $\psi \; cc \; (3.681)$ is seen to decay electromagnetically while the $\phi(ss)$ decays via a hadronic channel. These decays could occur the other way around according to the relative probabilities involved in the branching ratios for the decays of these two particles, in that it could be the case that the $\phi(ss)$ decays electromagnetically instead of strongly and vice versa for the $\psi \; cc \; (3.681)$.

Particle B must be a neutral meson which decays into particles $\psi \; cc$ and $\phi(ss)$. If it too is a long lived particle then either it is because it decays weakly or because it has a suppressed strong decay mode. By inspection it cannot be the latter, thus it must be a weak decay. This is the case as one cannot have a heavier mass meson which gives a strong decay into these two neutral mesons.

The only higher mass quark that decays weakly and can be observed in a meson is a bottom quark as a top quark will decay instantly. Thus the particle B must contain a bottom quark or antiquark that decays into either the charm or anti-charm quark respectively. This must be the weak decay route involved as the bottom quark cannot decay into the strange quark – nor the bottom antiquark into the strange anti-quark.

As no leptons are produced in the two body decay of particle B any W boson produced in the decay of the higher mass bottom flavoured fermion must then produce a pair of other dissimilarly flavoured quark and antiquark (i.e. if a virtual W+ is produced via the decay then this may give an up and anti-down, or a charm and anti-strange). By inspection then the other quark/anti-quark in particle B must be a strange flavoured quark. That is B is either a $bs$ or a $sb$ quark combination. A Feynman diagram could be drawn whereby the two 3-point vertices are $b \rightarrow c + W^-$ followed by a $W^- \rightarrow s + c$ and the $s$ within the original meson now accompanying the $s$ and the $c$ the $c$ to give the two flavourless mesons.

Finally, consider particle A. Again it must be a neutral meson, but this is not necessarily a meson with zero quantum numbers as many neutral mesons decay into positive and negative pions. The longest lived neutral mesons are K-mesons containing a strange quark. Thus the
neutral A could well be a neutral K-meson such as a \((ds)\) or a \((sd)\)

**QUESTION 2: Asked 23/3/2017**

Quoting E?:

- **Q:** I have some questions from reading Martin and Shaw.
  1. On page 37 the book discusses the decay rate of \(\mu^- \to e^- + \nu_e + \nu_\mu\) where we can essentially neglect the mass of the electron and neutrino. The rate is proportional to \(G_F\) [units \(E^2\)] and the mass of the muon [units \(E\)]. The book then says “It follows that the decay rate must be given by an expression of the form \(KG^2\mu^5\) because the rate has a natural dimension \([E]\)”.

Why not \(KG\mu^3\) or \(KG\mu^7\) etc?

- 2. On page 183, eq (7.3) states \(|q| = O(r^{-1})\) for short distances.

On page 191 the book says the quarks do not interact by the strong force “until they are separated by a distance of order 1 fm, which according to (7.3) gives rise to a typical momentum transfer of order 200 \(\text{MeV}/c\) between them.” I do not see where this figure comes from.

- 3. On page 226 figure 8.10, should these four vertices not be \(ud\) etc? This isn’t listed in the errata.

- **A:** Dear E
  1. Every _vertex_ involving a \(W\) boson has \(G_F\) associated with it. The \(W\) boson has a vertex at both ends of its path hence giving a probability in proportion to \(G_F^2\), giving \(E^{-4}\), which if it is to give a decay rate in energy units must, then the \(G_F^2\) be multiplied by a factor of \(E^5\) and hence the factor \(m_\mu^5\).

2. To begin the quark-quark or QCD potential I usually write in my lectures has the form \(V \propto -\frac{4\alpha_s}{3} + k \cdot r\) (Lectures 11/12, Handout 6, pages 5, 11 and following) while Martin and Shaw write it in two parts in equations 7.1 and 7.2 as \(V \propto -\frac{4\alpha_s}{3} \) for small \(r\) and \(V \propto \lambda \cdot r\) for large \(r\).

The numerical value arises from using natural units where \(h = c = 1\) under which Length: \(1\ \text{GeV}^{-1} = 0.197\ \text{fm}\) - hence \(1\text{fm} \to 200\MeV^{-1}\) - conversion factors between Natural units expressed in real units are just inside the back cover of Martin and Shaw. i.e. from equation 7.3 if \(q = 0(r^{-1})\) thus at a distance of 1 fm then the typical momentum exchanged would be \(q \sim 1/(1\text{fm}) \sim 200\MeV/c\)

For a full discussion there are two issues here - firstly the linear term \(k \cdot r\) where the coefficient \(k\) is of order 1 \(\text{GeV}/\text{fm}\), while the contribution of the \(r^{-1}\) term may be smaller (some values are discussed in M&S, albeit in natural units, on page 175) - the contributions of these two terms at 1 fm gives the scale of typical potential energy and hence of typical momentum exchange needed to bring particle together.

However the key issue is also \(\alpha_s\) WHOSE STRENGTH VARIES WITH \(r\)! At small distances (large energies) \(\alpha_s\) decreases, so one might conclude that the likelihood of strong exchange is lessened at small \(r\) - this peculiarity is known as ASYMPTOTIC FREEDOM. When pulling two quarks apart from each other, having raised the total energy, increasing \(r\) and hence reducing kinetic energy, two things simultaneously happen – potential energy increases AND \(\alpha_s\) increases, so strong exchange typically gets triggered over a range of \(r\) close to 1 fm and typically not before.
3. I think you misunderstand the diagrams and the process shown!

Consider the first diagrams as either: $$u \to d + W^+$$ OR $$u + W^- \to d$$

and the second diagram as either: $$u \to d + W^-$$ OR $$u + W^+ \to d$$

Charge is conserved; quark flavour is not, but baryon number is conserved i.e. a quark does not change to an antiquark.

Thus the coupling strength is $$g_{ud}$$

Looking it as a Feynman diagram fragment - as time goes from left to right - the first diagram shows an $$u$$ either absorbing a $$W^-$$ converting to a $$d$$ quark, or emitting a $$W^+$$ and converting to a $$d$$ quark. The $$W$$ line is drawn upright, and thus it is (deliberately) ambiguous as to whether it is a $$W^+$$ or a $$W^-$$ - recall that one is the antiparticle of the other and thus if one moves the lower point either forward or backward in time (right or left) then one definitively selects whether it is a $$W$$ absorption event or a $$W$$ emission event, simultaneously clarifying the charge state.

This general 3 pt vertex could be redrawn by grabbing the W line and pulling it to the left, and grabbing the u line and pivoting it about the vertex till it points to the right. Such a diagram would then be $$W^- \to d + u$$

See also question below which ends up touching on this.

QUESTION 3: Asked 3/4/2017

Quoting D?:

- Q: I have a quick question about Feynman diagrams. I noticed in the lectures that we had the vertices in the Feynman diagrams staggered so they occurred at different times. We were very explicitly told in our (Theoretical Physics) QFT class to draw the vertices aligned so they occur at the same time, since the exchange of virtual particles happens within the bounds of the uncertainty principle. I can kind of see the logic to both approaches. Should we favour one over the other in the exam or would either be acceptable?

- A: In my view (in this course) it is a matter of personal choice, and I would accept either in the examination, but with the specific proviso that for a vertical virtual particle line e.g. for exchange of a W boson - it should be then explicitly labelled as both $$W^+ / W^-$$ as it could be either (particle or antiparticle) and still conserve charge.

If instead the line representing this virtual particle exchange was slanted i.e. with an explicit
time of its creation/emission being earlier in time than its annihilation/absorption and not simultaneous, then it must clearly be a definite $W^+$ or a definite $W^-$ where charge is explicitly conserved at each vertex. For electromagnetism and photon exchange a virtual photon is its own antiparticle, and so the consideration in this respect is not needed.

Why I have chosen this method in the lectures? - In order to be consistent with discussion of Feynman diagrams as in Martin and Shaw in an attempt to minimise any confusion, while explicitly stating that the time-ordering of the start and endpoint of the virtual particle does not matter, the interpretation of the event differs ever so slightly in terms of causality or simultaneity, but the physics is the same. (See or listen again to discussions on this point in Lecture 3 although only discussed in the context of the electromagnetic interaction at that point)

Hope that has answered your question.

QUESTION 4: Asked 3/4/2017

Quoting E?:

- Q: The final remarks also mentioned that the derivation of $R_\mu$ is important. I went to find the derivation in Martin and Shaw but it said the derivation was beyond the scope of the book and recommended another textbook (Mandl and Shaw p146-150): Is this the derivation you mean?
- A: Martin and Shaw discuss $R_\mu$ (or $R$ as they write) in section 6.4.1 (p169) and define it in terms of the ratio of the rate of production of hadrons versus muons at a specific center of mass energy in electron and positron collisions i.e. $R_\mu = \frac{\sigma e^+ e^- \rightarrow \text{hadrons}}{\sigma e^+ e^- \rightarrow \mu^+ \mu^-}$ about which there is no disagreement. The explicit form of the cross section for the creation of muons in electron-positron collisions is of the form: $\sigma e^+ e^- \rightarrow \mu^+ \mu^- = \frac{4\pi\alpha^2}{3s} = \frac{4\pi\alpha^2}{3E^2_{cm}}$ which I discuss (without derivation) in Lecture 12 and in handout 6, page 12, and on page 169 of Martin and Shaw the footnote 20 does refer to Mandl and Shaw for this derivation.

Similarly to Martin and Shaw I do not derive this cross section, nor do I expect you to be able to do so (though it is easy) – but knowledge of the derivation of this cross section or its exact formula is almost irrelevant to deriving the functional form of $R_\mu$.

- Why? I tried to make the point in the lecture that by inspection of the relevant Feynman diagram for the $e^+ e^- \rightarrow \text{hadrons}$ process and that of the $e^+ e^- \rightarrow \mu^+ \mu^-$, the only difference between the diagrams is in the final vertex. In this final vertex in the case of the creation of hadron jets seeded by a quark and antiquark of type Q, the charges of these fractionally charged quarks is charge $Q_q$ and hence, all the other terms being the same, such as the center of mass energy available to create muon-antimuon pairs or quark–antiquark pairs, the ratio of the cross sections is very simply equal to the ratio of the probabilities associated with each diagram. These will be of order $O(\alpha^2)$ for muon-antimuon creation but of order $O(Q^2_q \alpha^2)$ if only one possible quark of type Q were possible to create, and in only one possible colour state. Under that circumstance the ratio $R_\mu = Q^2_q$.

However, as for all except the lowest energies there will typically be at least two kinds of quarks that can be created, and there will always be three possible colour-anticolour states that these can be created in then we will have $R_\mu(s) = 3 q Q^2_q$ for all possible $q = u, d, s, c, b$ which are kinematically dependent upon the squared center of mass energy $s$ available in the interaction. i.e. where b quarks are only possible to create once above the threshold where $\sqrt{s} > 2m_b$
Thus the derivation of \( R_\mu \) I would ask for is purely based on the comparison of the vertices in the relevant Feynman diagrams giving the very simple formulae above. It continually surprises me that Martin and Shaw do not explicitly state this simple ratio in their discussion of \( R_\mu \).

QUESTION 5: Asked 21/4/2017

Quoting E (representing several):

- **2015 1. (e)** I could only think to say that the two spins are now aligned which is a higher energy state, but I don’t know what other information was required.

- Yes the two spins are aligned. The energy difference arising from this alignment is a so-called colour magnetic interaction which for a meson gives a mass according to the meson mass formula of: \( m_{qq} = m_{q_1} + m_{q_2} + \Lambda \frac{S_1 S_2}{m_1 m_2} \) and the total mass is thus sensitive to the relative spins of the individual quarks. The value of \( S_1 \cdot S_2 \) can be obtained from \( S = S_1 + S_2 \); giving \( S^2 = S_1 + S_2 \quad 2 = S_1^2 + S_2^2 + 2S_1 \cdot S_2 \); from which \( S_1 \cdot S_2 = \frac{1}{2} \left( S^2 - S_1^2 - S_2^2 \right) \)

  For a \( J = 1 \) meson, \( S = 1 \) and thus \( S_1 \cdot S_2 = \frac{1}{2} \left( 1 \cdot 1 + 1 - 2 \cdot \frac{1}{2} + 1 - \frac{1}{2} \cdot 1 + 1 \right) = \frac{1}{4} \)

  For a \( J = 0 \) meson, \( S = 0 \) and thus \( S_1 \cdot S_2 = \frac{1}{2} \left( 0 \cdot 0 + 1 - 2 \cdot \frac{1}{2} + 1 - \frac{1}{2} \cdot 1 + 1 \right) = -\frac{3}{4} \)

The mass difference is thus due to the relative spins, the masses of the individual quarks, but in proportion to the magnitude of the parameter \( \Lambda \).

**HOWEVER – the course material on masses and mass formulas for mesons and baryons was removed from the course in 16/17 and from then onwards.** For the last two years this has been included as grayed out material in the handouts, in part to explain previous exam questions. You would not be expected to answer this question in the detail above based on what you have been lectured on this year. Your answer “say that the two spins are now aligned which is a higher energy state” is all that could be expected from you or your fellow students this year, but would no longer be worth 5 marks as it was in 2015. If asked this year it might be worth 1 mark and would expect your answer.

QUESTION 6: Asked 21/4/2017

Quoting E:

- **2015 3. (c)** On the next page I have added my attempts of these four reactions but I am not sure they are correct.

- **A:**

  The diagram on the left is “correct” but could not obtain full marks, the one on the right is extremely improbable and could not be called correct as it is not the simplest nor the most
probable. The first however does not tell the story of the interaction well. Consider it as the incoming neutrino exchanges a $Z^0$ with a quark within the proton and “knocks” that quark out of the proton by transferring momentum to THAT quark. In your diagram on the left the trajectory of the down quark should be strongly angled downwards from the point at which it absorbs the $Z^0$. This indicates a rapidly changing position as the vertical axis is “position”, the horizontal being time, and thus a change in momentum from before the $Z^0$ is absorbed. The outgoing down quark can then radiate a photon producing a down and anti-down. The outgoing down is paired with the anti-down forming a neutral pion, while the newly created down remains with the two up quarks in the proton.

Note that the creation of the extra meson is indicative of inelastic scattering and implies an exchange in energy as well as momentum. In elastic scattering an exchange of $Z^0$ and of momentum can occur, but the total energy (in the centre of mass frame of the interaction) of the particles before and after is the same. With the creation of a meson as a result of the interaction, that is definitely not the case.

- **A:**
  Yes – but now in the context of the more correct diagram described above.

- **A:**

Again, although nothing superficially technically wrong with this diagram, it again does not tell the story of the interaction and could not obtain full marks (If only one mark were to be awarded for the diagram it might be given 1). The $W$ that is exchanged (or $W^+$ if one shifts the lower $W$ vertex forward in time along the d quark line) must result in a change of trajectory of the d quark at the same time as the transformation of it into an up quark. Again, like the first instance, a gluon radiated by the outgoing up (previously down) quark could create a down and anti-down that are paired as shown, though in redrawing the diagram one would place the positive pion underneath the p. At present the trajectory, or momenta, of the two up quarks in the original proton change for no apparent reason.

- **A:**

Well this is wrong! Basically because if one examines the diagram there is no interaction between the incoming anti neutrino and the proton i.e. there are no connecting bosons between any quark within the proton and the antineutrino. What happens? This diagram simply makes no sense – there is no “story” to the interaction as I have described above. Instead if the emitted $W$ is absorbed by an up quark, changing it to a down, knocking it out of the proton, and then as it leaves the hadronisation process involves a gluon producing a down and anti-down to give the neutron
and neutral pion.

QUESTION 7: Asked 21/4/2017

Quoting E:

- 2015 4. (b) This is a question about the detector questions in general. They tend to be worth a lot of marks. I was interested to know the level of detail you would expect for full marks for this question.

- A: How do you track trajectories? How do you determine positioning? How do you determine energy? How do you determine momenta? How do you identify particles as muons, electrons, hadrons, mesons, baryons, photons? Any answer should give a nod to the materials used and why these matter (e.g. high Z, low Z, dependence e.g. of ionisation or pair production on Z), the way in which these different particles interact, the way in which the trajectories of these are not straight or straight, and perhaps stopping distances and hence size of detectors for higher energy particles, for example what is the outermost detector? The answer should clearly discuss some details of the operation of these instruments such as their construction, but also the physical principles that are exploited to make the measurements in question that they are built to measure, detailing where necessary e.g. how the energy of a gamma ray or incident energetic electron is measured/estimated in an electromagnetic calorimeter.

If there are 10 marks or 40% of the 25 marks available for this then if you allocate 50 minutes for a question then one might expect to spend 20 minutes answering this. I would estimate this at between 2-3 pages depending upon your writing.

QUESTION 8: Asked 21/4/2017

Quoting E:

- 2015 4. (d) I am only familiar with the parton distribution function from the discussion on inelastic electron scattering and I don’t see the connection with conservation of transverse momentum.

- There is essentially zero transverse momentum for the proton as a whole, it is a very collimated beam going in the forward direction only with very little divergence, so the fraction of transverse momentum that a quark might have, even if approaching 1 is still essentially zero. This is not true for the axial momentum that a quark might have, refer to the parton distribution function, so the total momentum in the lab frame of any quark-quark interaction (one each from the two colliding protons) is not well defined, and could effectively range from −1 to +1 in the lab frame of the actual protons axial momentum, e.g the parton in one proton having \( x=0 \), and the parton in the other proton that it interacts with having \( x=1 \), where \( x \) is the fraction of the momentum carried by that parton in that proton.

QUESTION 9: Asked 21/4/2017

Quoting E:

- 2014 3. (b) iv. I understand the importance of \( R \) with regard to learning about the number of colour charges and the strength of \( \alpha_s \) but I don’t know why you would choose to plot \( R \) if you just wanted to measure the energies of charmonium/bottonium resonances. E.g. would you not get all the information you wanted about the resonances from the first graph in the following link, from the hadron cross section alone. Is it just that the flat background of \( R \) is easier to work with?

Let me say “Yes” – it is easier to sketch, and informative as to the values of R before and after the set of charmonium or bottomium resonances. The ratio R means something in addition to the energy dependence of the cross section that is otherwise evident in the plot you show.

2014 4. (b) Our guess for this question was that $e^+e^-$ interactions involved $\alpha$ (~1/137) and so diagrams involving two photons would be significantly less likely, so the single photon diagrams were useful by themselves. For the quark-antiquark interactions $\alpha_s$ (~1) would be involved so you would have to consider several orders of diagrams?

Yes, as you say “the single photon diagrams were useful by themselves” and give a first order result that is nearly correct, but then also you can apply perturbation theory methods for the electromagnetic electron-positron interactions to higher order, as each successive order of diagram is a smaller and smaller correction. Perturbation theory only works for small perturbations. The point about QCD is specifically that perturbation theories do not work, and one cannot do this, i.e. successive corrections to higher orders. You would need to explicitly make this point in answering the question, but your brief summary does not explicitly state this. One could add more detail about QCD in that 2nd, 3rd and 4th order diagrams involving increasingly complex gluon loops and quark loops with anti-screening and screening with the differing colour charges, where each higher order diagram is a large fraction of the probability or rate of the first order diagram makes it almost impossible to do QCD calculations easily (or at least to do so at low energy where $\alpha_S$ is large).

QUESTION 10: Asked 21/4/2017

Quoting E:

2013 Q. 4 (c) I should probably start with my confusion about lecture 19. At the start of the lecture the slides show the Higgs interactions for the conditions that $M_H < 2M_W$ and $M_H > 2M_W$. Are these slides under the pretense that we don’t yet know the rest mass of the Higgs, and these are the possibilities of the interactions that could possibly be detected? Or is it that the relativistic mass of the Higgs that is increasing, which allows new decays such as that to two real $Z^0$?

A: Yes – the slides are under the pretence that we don’t yet know the rest mass of the Higgs (i.e. pre 2012), so as to explain how the search for the Higgs could be, and was in fact, conducted and how the decay pathways could be checked for and measured. I would have thought this “pretence” as you put it was clearly described in the lecture and from slide 9 of that lecture 19. Perhaps you can suggest how I should reword this?

Q: If it were the latter case I could see why increasing the centre of mass energy would allow more probable decays, like the ‘golden channel’, but I still don’t see how from the rest frame of the Higgs a decay into two real $Z^0$’s is possible.

A: A decay into two real $Z^0$’s is not possible as that is not kinematically allowed as $M_H < 2M_Z$. The decay of a Higgs into a real and a virtual $Z^0$ is possible. In which case the combined centre of mass energies of the two decay products of the real $Z^0$ would give the rest mass of the $Z^0$, whereas the decay products arising from the virtual $Z^0$ cannot via their combined centre of mass energies add up to the mass of a $Z^0$. (One then combines the centre of mass energies and momenta of the real and virtual Z to obtain the rest mass of the particle from which they decayed, i.e. the rest mass of the Higgs.)
The point is that the “golden channel” is still possible even where $M_H < 2M_Z$, but much more suppressed in likelihood than if $M_H > 2M_Z$. This is clearly seen in slide 11 of lecture 19 where it shows the figure 9.17 from Martin and Shaw. In this case the “golden channel” still represents the way about 2% of all Higgs decays occur, whereas the two gamma channel is about 0.2% of all Higgs decays.

- Perhaps however I have mistaken your question and your objection? Where $M_H > 2M_Z$, the rest mass of the Higgs is sufficient to create two real $Z^0$'s, but with some extra energy left over. That extra energy simply goes into the kinetic energies of the two $Z^0$'s in the rest frame of the decaying Higgs with the excess energy shared equally as kinetic energy among each of the two $Z^0$'s increasing their momenta from zero (only possible if $M_H = 2M_Z$), with conservation of momentum before and after the decay, the vector momenta of the two $Z^0$'s are of course equal and opposite.

**QUESTION 11: Asked 21/4/2017**

Quoting E:

- **Q:** 2012 2. (c) We couldn’t think of a Feynman diagram for the decay $\Sigma^+$ into a neutron and $\pi^+$
- **A:** I won’t answer this completely. It would surprise me if you cannot find this in Martin and Shaw. However, look at the beginning quark composition: $uus$ and the final quark compositions: $udd + ud$. It is a Weak decay, the $s$ quark must decay into an $u + W^-$, the $W^-$ is a virtual particle and must either decay into an $d + u$ (no leptons are involved so no other choice), or be absorbed by another quark. Baryon number and charge are conserved, but the charge of the baryon changes. Do both up quarks stay in the subsequent baryon? **Have not just created a third up quark from the decay of the strange quark?** If one of these up quarks is “forced” to leave i.e. change its momentum, how might one account for this in a Feynman diagram?

So with no $u$ present in the final state something different occurs, and the emitted $W^-$ is absorbed by another quark? What possible quark could that be? $u + W^-$ gives? How do we then get an antiquark necessary for inclusion in the meson? We may have transformed a baryon into another baryon of lesser mass, but then how do we conserve energy and momentum? Perhaps a gluon creates a quark and antiquark pair of the same flavour, and the ones necessary to complete the process as described.

**QUESTION 12: Asked 21/4/2017**

Quoting E:

- **Q:** 2011 1. (d) I know that you can produce the $W$ from a quark and an antiquark in the colliding proton and antiproton beam, but I don’t know how you could produce a $W$ from a proton-proton beam.
- **A:** Because there are antiquarks in the proton, but only if one looks hard enough, i.e. at lower length scales, shorter time scales, and higher energy scales. The invitation in this part of the question is to discuss the parton distribution function. From high energy deep inelastic scattering of electrons off protons, the results are only explained in terms of “snapshots” of the distribution of momenta over the valence quarks, the additional quarks and antiquarks from quark loops, and the presence of gluons taking up larger proportions of the total momentum if the “snapshot” of the internal structure of the proton occurs over a very short time interval. This is known from deep-inelastic electron-proton interactions (as well as from similar neutrino- and muon-beam experiments on protons) and these snapshots occur for extremely high energy photon exchange between the incoming electron and the individual charged constituents within the proton (both quarks and antiquarks) which
requires large energies available for the incoming projectile.

- Thus for very high energy proton-proton collisions, the quarks of one proton can “see” anti-quarks within the second proton (and vice versa). Thus a quark + antiquark collision can occur and can generate a W or Z boson, of differing charges depending upon the types of quarks and antiquarks involved in the collision, and provided the centre of mass energy of the two particle collision is tuned into the rest mass energy of the W or of the Z.

- See end of lecture 13 on parton distribution functions and look for the antiquark component.