Microscopic black holes

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Abstract:

In this report I will write about the possibility of black hole creation when introducing the theory of extra spatial dimensions in the visible (3+1) dimensional universe.

First I will give a little background on the postulation of black hole formation and talk about what properties black holes have in general, for example the event horizon, singularity and the formation of the black hole is discussed. Other theories like general relativity and the gauge theory will be discussed before discussing the main theme.

In the main theme I will discuss the basic concepts of extra dimensions talking about the phenomena that would appear if extra dimensions exist. After this I will discuss the ADD-model and it's interpretation of extra dimensions before I discuss black hole formation in extra dimensional scenarios and Hawking radiation and how it affect black holes.

At last I will discuss two experiments on extra dimensions and black holes. The first experiment is conducted in the main detector at Large Hadron Collider (LHC) in Switzerland where the CMS collaboration look at the transverse energy E_T of events from pp collisions with signals similar to expected signals for black holes. In the second experiment, which is conducted in the Tevatron in the USA, the CDF collaboration look at the missing transverse energy E_{Tmiss} for events from $p\overline{p}$ collisions with one or two high energy jets, where the missing energy is expected to correspond to gravitons.

Introduction:

In the universe there are many amazing phenomena which governs our existence. One of the more interesting and hard to explain is the phenomena black holes.

Macroscopic black holes:

Existence of bodies so massive that they capture even light was postulated as early as in the 18th century by John Michell and Pierre-Simon Laplace but, since physicists could not understand how something massless such as light could be affected by gravity, it was usually ignored for a long time. When talking about black holes people often use two distinct categories, hot (microscopic) black holes and cold (macroscopic) black holes.

After Einstein in the early 20^{th} century showed that photons were affected by gravity and developed general relativity, Karl Schwarzschild found a solution to Einstein's field equations. This solution had a peculiar behaviour at what now is called the Schwarzschild radius, namely the gravitational field of a spherical mass became singular. More general solutions were later found where black holes with both electric charge and angular momentum could exist and in the 1970s black hole thermodynamics was formulated. The black hole thermodynamics are laws which describe the properties of black holes by relating mass to energy, area to entropy and surface gravity to temperature, hence the word "thermodynamics". In 1974 Stephen Hawking could even show that quantum field theory predicted that black holes radiated like black bodies with a temperature proportional to the surface gravity of the black hole.[13][14]

Formation:

There are three proposed sources of black hole formation:

1.) Exotic black hole formations

2.) Collapse of super-massive stars

3.) Primordial black holes

Even though the two dominant ways of formation are proposed to be collapses of super-massive stars and primordial black holes, there are some exotic ways black holes can be created. One of these exotic ways are big gas clusters collapsing into a relativistic star; this star will be so unstable due to radial perturbations caused by electron-positron productions in its core that it collapses directly into a black hole without a supernova explosion.[1]

As said, one of the two dominant ways of forming a black hole is through collapsing stars. Gravitational collapse occurs when the gravitational force directed inwards in the star exceeds the outward forces. The main source of the outward force in an active star is the thermal pressure from stellar nucleosythesis and during a star lifetime the gravitational force and the thermal pressure will be in an equilibrium. When this synthesis ceases due to lack of enough "fuel" inside the star volume the gravitational collapse will start.[15]

The gravitational collapse may be halted by the degeneracy pressure from the star constituents due to the Pauli principle where the particles are not allowed to occupy the same quantum state. A white dwarf is for example formed due to the electron degeneracy pressure and a neutron star is formed due to the neutron degeneracy pressure.[15] Further explanation of degeneracy pressure can be found in [9]. It is important to note that the star mass will decrease when it undergoes gravitational collapse. The decrease in mass is caused by the fact that matter in the star will release gravitational potential energy during gravitational collapse, causing increased energy in the outer layers of the star, giving them enough energy to escape the star. This process is called a type 1 supernova.[3]

If the remnant of the star exceeds 3-4 solar masses which is called the Tolman-Oppenheimer-Volkoff limit not even the neutron degeneracy will prevent the gravitational collapse into a black hole. It is thought that during the early ages of the universe there existed stars that were 10^3 heavier than the sun. The black holes created from the gravitational collapse of these stars could be the super-massive black holes situated in the middle of many of the galaxies like the milky way.[15][17][18]

Even though energy released during a gravitational collapse has a very high velocity and is released during a short period of time the end of the collapse can never be seen by an outside observer. The observer will see the in-falling material slow down and eventually stop when it reaches the black hole's event horizon due to the gravitational time dilation explained by general relativity.[19]

The other dominant way of forming a black hole is through bunches of matter with extremely high density. In the current universe there is no such places where the density of matter is high except in stars where black holes form in a different way, but in the early universe right after big bang the density was extremely high. Even though high density in itself is not enough for black hole formation, since a uniform distribution of matter will prevent matter to bunch up, an initial density perturbation that would later grow due to its own gravity could create black holes. These types of black holes are often called primordial black holes. Due to that they are very old and could potentially have been very heavy during creation these black holes could be the super-massive black holes in the middle of many galaxies.[20]

Event horizon:

One of the most defining features of a black hole is the existence of an event horizon. The event horizon is the sphere at which the gravitational forces are so strong that the only paths which light and matter can take is towards the centre of the black hole. This means if an event happens inside the bulk of the black hole there is no way for an outside observer to get any information from that event.[21]

It is the radius of the event horizon, called Schwarzschild radius, that determines the size of the black hole. The Schwarzschild radius is dependent on mass M through $R_s = \frac{2GM}{c^2}$, and is only exact for black holes with zero charge and angular momentum. For a more general black hole the relation can differ by a factor of 2.[22]

Due to the effect of gravitational time dilation, i.e. information getting slowed down due to gravitational pulling, objects travelling towards a black hole will seem to slow down the closer they come to the event horizon. In addition, information will be less energetic and more scarce, leading to light waves in the visible region becoming redder and dimmer. When the object reaches the event horizon the information will become so scarce that the object will become invisible to an outside observer.[23][24]

Observer travelling towards a black hole will not feel these effects, though. In fact, an observer will not even notice when he has crossed the event horizon since there is no local signs of it.[25]

The shape of the event horizon is completely spherical if the black hole is non-rotating and slightly oblated if the black hole is rotating.[26]

Singularity:

In the centre of the black hole there is a region which is called the gravitational singularity and is the point where the space-time curvature becomes infinite in the black hole. For a non-rotating black hole the singularity is point-like, where as if the black hole is rotating the singularity will be smeared out into a ring. In a black hole all mass resides in the singularity and since the singularity has a volume of zero one can say that its density is infinite.[27][28][29]

In general relativity a singularity is the point were all physical laws break down since parameters become infinite. This is of course a big problem for general relativity, but by combining quantum mechanics and general relativity physicists think this problem will be solved. The reason for this is that quantum mechanics should describe the big amount of particle interactions due to the high density. When forming quantum gravity in a convenient way physicists hope that black holes without a singularity will arise.[30][31][32]

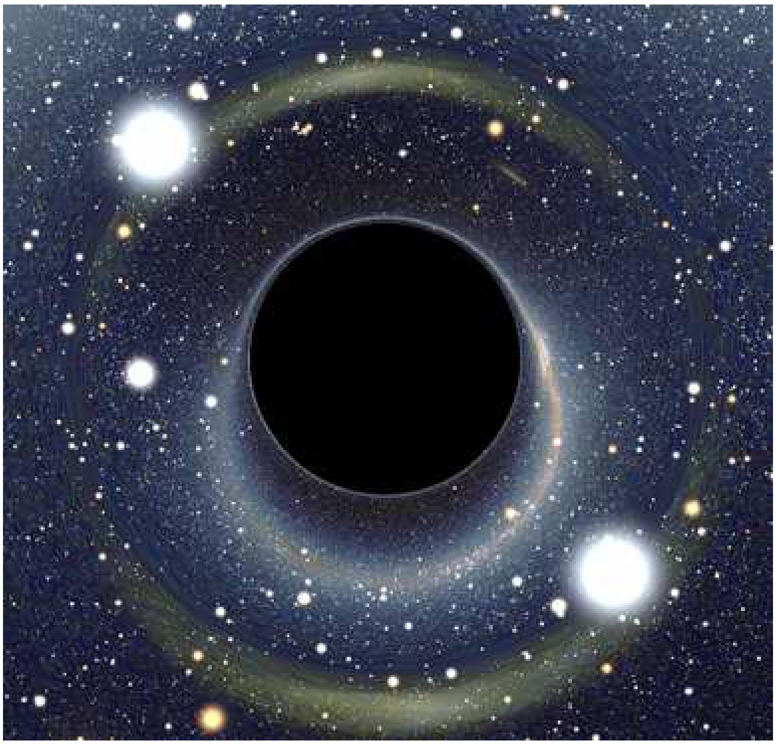

Figure 1: Simulated image of how a black hole would look like in space. The event horizon is located at the edge of the black ring and the singularity is located in the middle.[1]

General relativity:

General relativity is the geometric theory which incorporates gravity with special relativity. Special relativity is the theory of systems motion that has a uniform motion with respect to each other. General relativity generalizes special relativity and Newton's law of universal gravitation, describing gravity as a geometric property in space-time. The curvature of space-time, for example, relates directly to the four-momentum of any system present. General relativity was first published in 1916 where the curvature of space-time is described in the Einstein field equations which is a set of 10 equations.[4]

The predictions of General relativity's differ from those of classical mechanics, especially passage of time, the geometry of space, bodies motion in free fall and the propagation of light. For example some predictions are: gravitational time dilation (the closer you are a body of mass the slower time passes), gravitational lensing (light is bent around a body of mass since space-time is curved around it creating magnified distorted images) and gravitational red-shift (when light from a body of mass its wavelength becomes longer since gravitation becomes weaker). All observations and experiments to date have confirmed the predictions of general relativity and even though general relativity isn't the only relativistic theory of gravity, it is the simplest one consistent with observations.[4]

Gauge theory:

To explain what gauge theory is, it is important to state that in modern physics the universe is described in terms of fields, for example the electromagnetic field, gravitational field and even fields for all elementary particles. None of these fundamental fields, which are the fields that change under a gauge transformation (change of the field's configurations), can be directly measured. However, the observable quantities like electric charge, energy and velocity, is invariant under a gauge transformation, even though the quantities are derived from the fundamental fields. Invariance under gauge transformation is called gauge symmetry. For example, in classical electromagnetism the observable quantities electric field, E, and magnetic field, B, are invariant under a gauge transformation, in contrast to the corresponding fundamental fields of potentials V and A which change under a gauge transformation.[33][34][35]

Gauge theories introduce constraints to the laws of physics since all changes in the fundamental fields induced by a gauge transformation must cancel out when written in terms of observable quantities. Fundamental interactions (weak, strong, gravitation and electromagnetism) come from constraints imposed by local symmetry, i.e. gauge transformations vary from point to point in space-time. Perturbative quantum field theory describes the fundamental interactions in terms of force mediating particles called gauge bosons where the nature of these particles is described by the nature of the gauge transformations. The standard model of particle physics is a quantum field theory which explains all of the fundamental interactions except gravitation, unifying electromagnetism and the weak interaction.[5]

Main theme:

Extra dimensions:

The reason why physicists want a unified theory for all of the natural forces is that there are reasons to believe that the electroweak theory (the electro magnetic and weak force) and Quantum chromodynamics (the strong force) can be unified (there are very elaborate theories, such as the grand unified theory, though they have yet to be confirmed). Since it would be more logical that all four natural forces are equally strong at a certain energy, physicists have long been trying to find theories which predict this behaviour.[8]

One way of forming a unified theory for the four natural forces is by including extra dimensions to the four-dimensional space-time.[8]

According to general relativity gravitation is provided by fluctuations of the space-time curvature, and experiments have shown that the general relativity is very accurate at long distances. But, due to the weak nature of the gravitational force there is yet no evidence that this theory holds up at small distances. I.e. if a perturbation is applied to the general relativity which does not affect it at long ranges, it could make a big impact on the microscopic level.[8]

As early as the 1910s and 20s Nordström, Kaluza and Klein proposed that gravity and electromagnetism could be unified by extending space-time to a five-dimensional manifold if the fields would not depend on the extra dimension. Although this proposition was discarded since no experimental implications or quantum description of gravitation was available at the time the idea of extra spatial dimensions was awoken.[8]

Nowadays theories have encountered theoretical phenomenon such as the microscopic black hole which relate the physics of extra dimensions to observables in many physics experiments.[8]

Basic concepts:

The general idea of why the number of extra dimensions are hidden is that the visible three-dimensional space is a 3-brane, just like the membrane of a cell. This 3-brane is then a part of the higher D-dimensional space-time $D = 3 + \delta + 1$, where δ are the extra dimensions which are orthogonal to the 3-brane. This D-dimension space-time is called the bulk, and the extra dimensions are hidden due to the fact that an observer trapped on the 3-brane can not directly probe the extra dimensions without overcoming the brane tension. According to the theory the 3-brane carries the standard-model gauge charges. Therefore, the fields which carry gauge charges are stuck on the brane and represent the standard model fields. Fields, such as gravitons, which don't carry gauge charges will be free though to propagate throughout the full D-dimensional bulk. With gauge charges it is meant that all the three standard model forces has a property, called charge, associated to their gauge theory, electric charge for electromagnetism and colour charge for strong interaction, while all standard model forces carry weak charge. A charge associated with gravity is missing, therefore the graviton which is supposed to be the gauge boson of gravity does not carry gauge charges.[8]

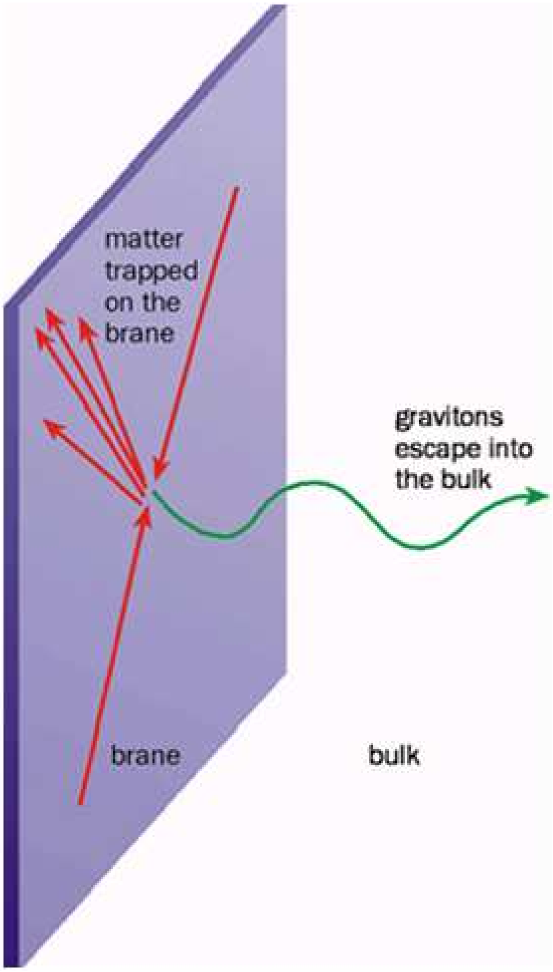

Figure 2: Image of the three standard model fields propagating only in the 3-brane, while the graviton is able to escape the 3-brane and propagate in the bulk.[10]

This means that matter and the standard model forces will be stuck on the 3-brane and only propagate on our three-dimensional space, whereas gravity will propagate in a D-dimensional volume. In order not to predict unacceptably large deviations from Newtonian gravity, most extra dimensional model builders have made the extra dimensions finite. It is important to note that not all theories have finite extra dimensions, and some have suppression of gravitational deviations from other phenomena.[8]

If the extra dimensions are small enough propagation of standard-model fields are in fact allowed in the bulk. As a result of the finite extra dimensions propagating fields in the bulk will expand into a series of states known as a Kaluza-Klein (KK) tower, individual KK excitations are labelled by mode numbers. Since the bulk is finite the momentum in the bulk will be quantized and for an observer in the brane, each quantum of momentum in the bulk appears as a KK excited state with mass $m^2 = \vec{p}_\delta{}^2$. This builds a KK tower of states, where each state will carry identical spin and gauge quantum numbers, but with different masses.[8]

A generalized calculation of the action for linearised gravity in D dimensions can be used to compute the effective four-dimensional theory, i.e. using the KK-towers one can compute a more precise four-dimensional theory than the one used today. The spin-2 KK-tower couples to the standard-model fields on the brane via the conserved symmetric stress-energy tensor. The stress-energy tensor is a tensor quantity that describes the density and flux of energy and momentum in space-time, it is the source of the gravitational field in the Einstein field equations of general relativity.[2] The spin-1 KK-tower does not interact with fields on the 3-brane. The scalar KK-tower couples to the standard-model fields on the brane via the trace of the stress-energy tensor.[8]

Large extra dimensions:
One model which uses the theory of extra dimensions is the Arkani-Hamed, Dimopoulos and Divali (ADD) model.[8] In this model Gauss's law relates Planck scale of the effective four-dimensional theory, M_{Pl}, to the scale where gravity becomes strong in the $4+\delta$-dimensional space-time, M_D. This is done by using the volume of the compactified dimensions V_δ via $M_{Pl}^2 = V_\delta M_D^{2+\delta}$. Making M_D of the order of 1 TeV will subsequently eliminating the hierarchy problem between M_{Pl} and the electroweak scale. i.e. M_{Pl} is not the fundamental scale of gravity but is generated by the volume of the higher-dimensional space. This means that the hierarchy problem is transferred to a perhaps easier to answer question of why the compactification scale of the extra dimensions is large.[8]

If M_D is of order of $1TeV$, the radius R_c of the extra dimensions will be between a fraction of a millimetre to $\sim 10 fm$ for δ between 2 and 6. The case of 1 extra dimension is not included since R_c would become $\approx 10^{11} m$ which would directly affect Newton's law at solar-system distances.[8]

Since the coupling constant for gravity is so weak one may think that possible observables would drown in the background, which is a valid point. In the ADD model, there are $(ER_c)^\delta$ KK modes that have enough kinematic energy to be detected in a collider with energy E. If $\delta = 2$ and $E = 1TeV$, the amount of graviton KK states will be 10^{30} individual contributers to the process. It is the sum of all these contributions that later will remove the Planck-scale suppression in a process and replaces it with the fundamental scale M_D of order a TeV.[8]

Microscopic black hole formation:

In the LHC two proton beams collide at a maximum energy of $14TeV$, a black hole of this collision would be formed if two partons interacted with an impact parameter smaller than twice the Schwarzchild radius of the system. The cross section for this process would then be the cross section of the event horizon of a black hole with mass equal to the centre of mass energy of the collision $\sigma_{mbh} = \pi R_s^{\ 2}$.[12]

Unfortunately, $R_s = \dfrac{2GM}{c^2} \equiv \dfrac{2M}{M_{Pl}^{\ 2}}$ show that the Schwartzchild radius is inversely proportional to the Planck mass squared, which means that $\sigma_{mbh} = \dfrac{4\pi M^2}{M_{Pl}^{\ 4}}$. This in turn means that microscopic black hole productions has a cross section too low to be relevant when using classical general relativity. But, as discussed before, in models with extra dimensions it is possible to reduce the value of M_{Pl}. As seen in $\sigma_{mbh} = \dfrac{4\pi M^2}{M_{Pl}^{\ 4}}$ the cross section of microscopic black holes is increasing with the centre of mass squared. This behaviour is very unique in particle physics where most cross sections fall with energy, i.e. with higher collider energies the possibility of finding microscopic black holes will probably be higher.[12]

Hawking radiation:

Hawking radiation is thought to be the main source of decay for microscopic black holes. The derivation of this radiation is based on propagating a quantum mechanical wave equation near a collapsing body which will form a black hole. The result is that black holes will emit particles and gravitational waves not only during creation but during their whole existence.[12]

The Hawking temperature T_H of a black hole characterises the energy spectrum of the particles it emits and as I've written before the behaviour of a black hole can be explained by the laws of thermodynamics. The expression for the Hawking temperature of a Schwarzschild black hole is $T_H = \frac{\hbar c^3}{8\pi G M k_B}$, where c is the speed of light, G Newton's gravitational constant, M the mass of the black hole and k_B is Boltzmann's constant.[12]

As this Hawking temperature is assuming a universe with 3+1 dimensions, and as concluded before the energy in the LHC will be insufficient for black hole formations with these conditions. In general T_H can be applied to Schwarzschild black holes in any number of dimensions. The dependence on n means that the more extra dimensions there exists the hotter the black hole will be. The hotter the black hole is the fewer particles the black hole will emit, but the particles will be more energetic. $T_H = \frac{1+n}{4\pi R_{BH}} \equiv \frac{1+n}{M_{BH}^{1/1+n}}$ where M_{BH} is the mass of the black hole, R_{BH} its radius and n number of dimensions.[12]

The microscopic black hole emission spectrum is not only influenced by its Hawking temperature. It is influenced by the electrical charge of the black hole which will influence the emission of charged particles, leading to a higher count of particles with the same sign as the microscopic black hole. The black hole angular momentum will affect the type of particle emitted, leading to an increased amount of particles with large spin which in turn would have an impact of the number of gravitons produced in decaying black holes. Coupling between the spin of an emitted particle and the gravitational field of the black hole will also affect the emission spectrum. All these properties affecting the emission spectrum are called the grey body factors. The lifetime of the microscopic black hole depends on the environment surrounding it, i.e. how the extra dimensions look like. In the ADD-model the lifetime of the microscopic black hole is about $10^{-26} s$.[12]

One of the flaws when using the derivation of Hawking radiation for microscopic black holes is that the derivation relies on the forming black holes event horizon becoming an infinite future horizon. This assumes that the black hole will exist for an infinite amount of time which isn't a good assumption when microscopic black holes are expected to live $\sim 10^{-26} s$. Another flaw is that the gravitational collapse of the black hole is assumed to be quasi-static. This assumption is also bad since microscopic black hole (MBH) formation will probably be violent producing MBH's with very large angular momentum and complex multi-pole moments in the event horizon.[12]

Even though Hawking radiation is a rather accepted part of theoretical physics, it has actually never been experimentally observed. This is expected however since black holes with a high mass have a very low temperature and therefore remain stable since they devour more matter than they radiate. Super massive black holes have such a low temperature that their radiation can't even be detected, whereas low mass black holes are not abundant enough, if they exist, to be observed since they decay so fast.[12]

Experiments:

In order to confirm the theories of extra dimensions and the production of microscopic black holes there needs to be experimental evidence. This is a bit of a problem since the only field particle thought to propagate in the extra dimensions is the graviton which has never been found and since it only interacts through gravitation it's hard to detect. Moreover, since microscopic black holes have such a short lifetime they are impossible to be detected directly.

At the newly built LHC in Switzerland, with a maximum beam energy of $14TeV$, physicist are trying to find evidence of both the extra dimensions and the microscopic black hole. One of these searches, which I will explain in detail later on is the search of microscopic black holes from $7TeV \;\; pp$ collisions using the compact muon solenoid CMS. What the physicists do in this experiment is looking at the transverse energy E_T of events with multiple jets, leptons and photons with signals similar to that expected of microscopic black hole using a high energy trigger. Transverse energy is the energy component of an object in the plane perpendicular to the beam line, $E_T = E\sin\theta$ where E is the total deposited energy and θ is the angle between the beam line and the path of the object. A jet is a hadronic shower created after a quark, gluon or an anti-quark is liberated and violates the no colour charge rule creating multiple hadrons. In the LHC the number of collisions is up to 40 million per second and therefore a set of software and hardware algorithms, called triggers, is introduced to reduce the rate to a manageable level. I.e. the triggers are used to make the measurement more efficient and to give the physicists raw data with events that could be interesting to look further into. The amount of data collected is measured in terms of integrated luminosity, i.e. the intensity of the beams summed over a specified amount of time.[6][7]

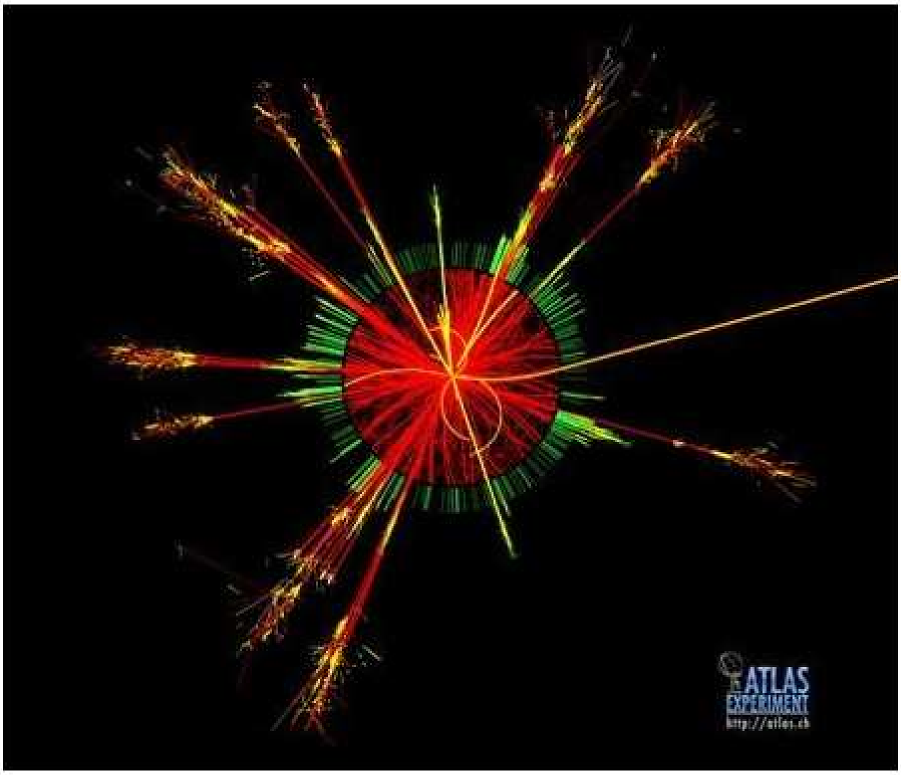

Figure 3: Simulated event of a black hole decay. The multiple long red cones of tracks are the multiple high energetic objects produced by the black hole.[11]

Later, I will also present an experiment done from data from $1.8TeV \quad p\overline{p}$ collisions at Tevatron in USA taken between 1994 and 95. In the experiment physicists are trying to find signals of gravitons looking at events with final states with high missing transverse energy and one or two high energy jets. Missing transverse energy is defined as the negative vector sum of the transverse energy, $E_{Tmiss} = -\sum_i (E_i \sin\theta_i)\hat{n}_i$ where E_i is the energy of the i-th jet, $\hat{n}_i$ is a transverse unit vector pointing to the centre of each jet and θ_i is the polar angle of the jet.[7]

Microscopic black holes:

Microscopic black holes produced in the LHC would be distinguished by high multiplicity and by radiating with the same intensity in all directions where the final particles would carry several hundred GeV. Since most of the radiated particles are expected to be quarks and gluons the results is expected to be mostly jets of hadrons. Observations of these signatures would give a direct measurement of the nature of microscopic black and the dimensions as well as the structure of space-time.[6]

In the "Search for Microscopic Black Hole Signatures at the Large Hadron Collider" the CMS collaboration look at the $\sqrt{s} = 7TeV \quad pp$ collision recorded between March and October 2010 using the Compact Muon Solenoid (CMS) at the LHC, which correspond to an integrated luminosity of $34.7 \pm 3.8 pb^{-1}$. The main parts of the CMS are the $3.8T$ superconducting solenoid enclosing the silicon pixel and strip tracker, the electromagnetic calorimeter (ECAL), the brass-scintilator hadronic calorimeter (HCAL) and a muon spectrometer.[6]

The CMS trigger system consists of two levels. The first level (L1) uses coarse granularity information from the calorimeters and the muon detectors to select the most interesting events to be stored for more refined selection and analysis as fast as $80kHz$. The second level, the software-based High Level Trigger (HLT) further the decreases the selection rate to about $300Hz$ for data storage. The luminosity is measured using forward hadronic calorimeters.[6]

The CMS collaboration use the data collected with a dedicated trigger on the total jet activity, H_T, where H_T is the scalar sum of the transverse energies, E_T, of the jets above the preprogrammed threshold. At L1 the threshold for E_T was $10GeV$ and $50GeV$ for H_T. The thresholds at HLT varied between 20 and $30GeV$ for E_T, and 100 to $200GeV$ for H_T. Energetic electrons and photons can also be reconstructed as jets at the trigger level and are thus included in H_T.[6]

Jets are reconstructed using energy deposits in HCAL and ECAL, clustered using a collinear and infra-red safe anti-k_T algorithm with a distance parameter of 0.5.[6] The jet energy resolution is $\Delta E / E \approx 100\% / \sqrt{E} \oplus 5\%$. Jets are moreover required to certain quality requirements to exclude those consistent with noise. Missing energy E_{Tmiss} is reconstructed as the negative of the vector sum of transverse energy in the calorimeter towers.[6]

Electrons and photon are identified by isolated energy deposits in the ECAL, with a shape consistent of that of electromagnetic showers. Electrons are required to have a matching track in the inner pixel layers, while photons are required to have no track in this region.[6]

Muons are required to have matching tracks in the central tracker and the muon spectrometer, to be within pseudo-rapidity $|\eta| = \left|-\ln(\tan\frac{\theta}{2})\right| < 2.1$ where θ is the polar angle with respect to the counter-clockwise beam, be consistent with the interaction vertex to suppress contribution from cosmic rays and have the transverse momentum p_T above $20GeV$.[6]

The separation between two tracks (jet, lepton, photon) has to be $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.3$, where ϕ is the azimuthal angle.[6]

As said before there are more parameters governing black hole production and decay than M_D and n. For each value of M_D the CMS collaboration considers a range of minimum black hole masses $M_{BH}^{\min}$, between M_D and the energetic limit of the beam at the LHC. They assume that no collision energy is from gravitational shock waves when forming the black hole and graviton radiation by the black hole is not considered. For most of the sample signals the CMS collaboration consider a full Hawking evaporation without a stable non-interacting remnant.[6]

The CMS collaboration employ a selection based on transverse energy to seperate black hole candidates from background noise. The variable S_T is defined as the scalar sum of E_T of the N individual particles (jets, electrons, photons and muons) passing the former selections. Only particles above $E_T > 50GeV$ are included in S_T, in order to suppress the standard-model background and to be insensitive to jets from pile-up (two events occurring within a period of time which shorter than the time resolution of the electronics). Also, the missing transverse energy is added to S_T, if the transverse energy exceeds $50GeV$. It is important to note that while E_{Tmiss} is added to S_T, it is not considered in the determination of N.[6]

The main background in black hole signals comes from QCD multijet events. Background from direct photons, W/Z jets and $t\bar{t}$ production were estimated from Monte Carlo simulations and were found negligible at high S_T contributing less then 1% after the final selection. Further splitting of the jets from final-state radiation and additional jets arising from initial-state radiation does not change S_T considerably. Therefore, the shape of the S_T distribution is expected to be independent of the multiplicity N if S_T much higher than $N*50GeV$.[6]

The assumption of S_T shape invariance from N is confirmed using Monte Carlo (MC) generators able to simulate multijet final-states using either matrix elements or parton showers, which offers a direct way of extracting the expected number of background events in the search for black hole production.[6]

The CMS collaboration fit the S_T distributions between 600 and $1100GeV$, where no black hole production is expected, for data events with $N=2$ and $N=3$ using an ansatz function $\frac{P_0(1+x)^{P_1}}{x^{P_2+P_3\log(x)}}$, shown as a solid line in Figure 3. The systematic uncertainty of the fit is checked using two additional ansatz functions, $\frac{P_0}{(P_1+P_2x+x^2)^{P_3}}$ and $\frac{P_0}{(P_1+x)^{P_2}}$, shown as the upper and lower boundaries of the shaded band. The ansatz function was chosen based on the best-fit to the S_T distribution for $N=2$. Systematic uncertainties arise from the difference in the best-fit shapes of $N=2$ and $N=3$. The fits for these two exclusive multiplicities agree, despite the systematic uncertainties, with each other within the uncertainties, which shows that the shape of the S_T distribution is independent of the final state multiplicity.[6]

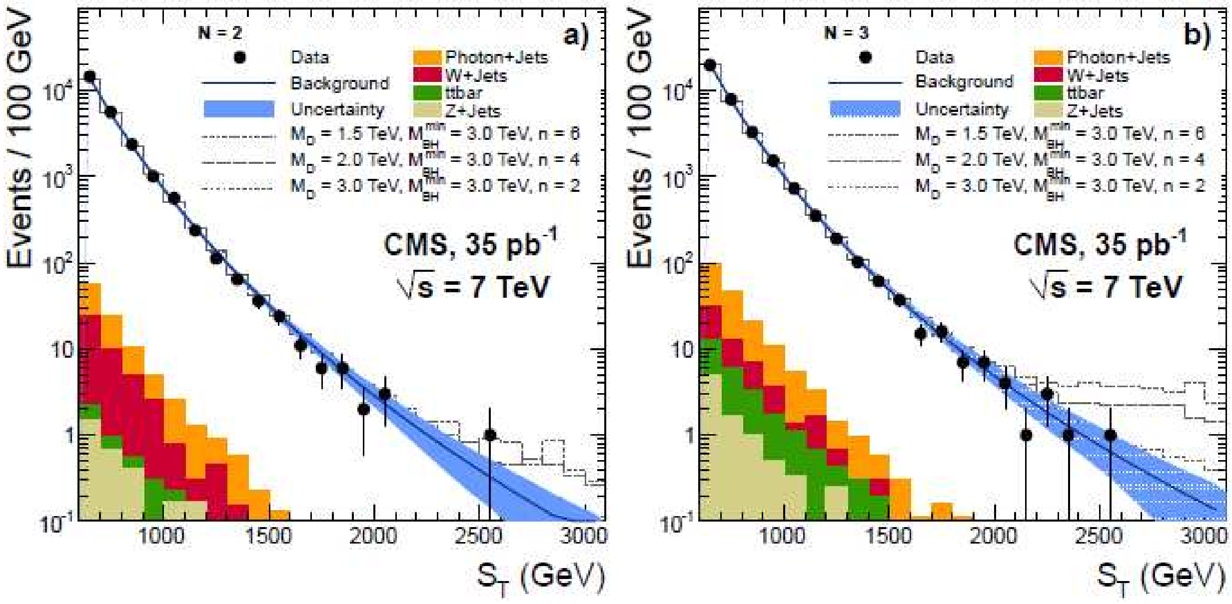

Figure 3: Total transverse energy S_T, for events with the multiplicities of a) $N = 2$ and b) $N = 3$ objects in the final state. Data is shown as solid circles with error bars, while the shaded band is the background prediction obtained from data (solid line) with its uncertainty. Background from non-multijets are shown as coloured histograms. Finally, predicted black hole signal for three different parameter sets is shown.[6]

The CMS collaboration set limits on the black hole production with optimized S_T and N selections by counting events with $S_T > S_T^{\min}$ and $N > N^{\min}$. They set upper limits of the black hole production cross section, and the upper limits at the 95% confidence level (CL) is shown in Fig. 4, as a function of $M_{BH}^{\min}$. For the three different assumptions shown in the figure, the observed lower limits on the black hole mass are 3.5, 4.2 and 4.5, respectively.[6]

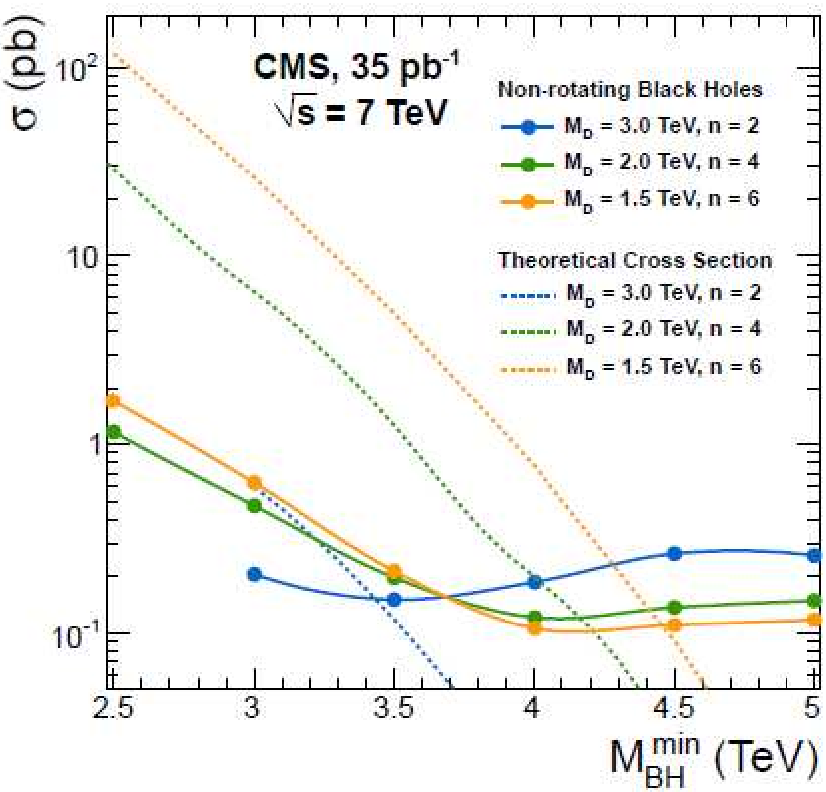

Figure 4: The upper limits, with 95% CL, of black hole production cross section (solid lines) and three theoretical predictions for the cross section (dotted lines), as a function of the black hole mass. Limits on $M_{BH}^{\min}$ are set looking at the crossing of the respective theoretical and experimental curves.[6]

Using these upper limits as lower limits on the parameters in the ADD model, the CMS collaboration can exclude the production of black holes with minimum mass of $3.5 - 4.5 TeV$ for values of M_D up to $3.5 TeV$ at 95% CL. These limits, shown in Fig. 5, don't look like they depend on the details of the production and evaporation model.[6]

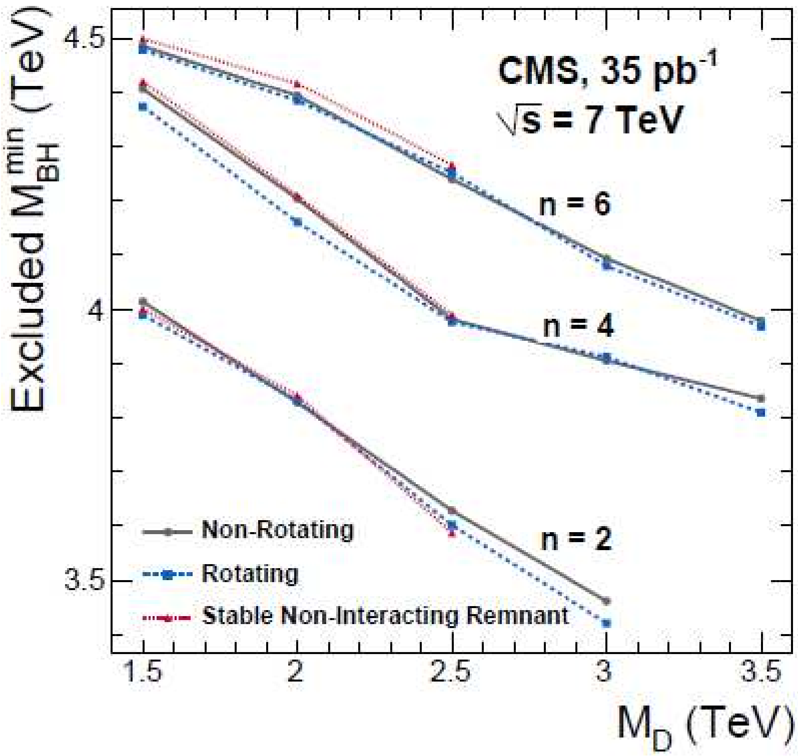

Figure 5: The limits of the black hole mass, with a 95% CL, as a function of the multidimensional Planck scale M_D for several benchmark scenarios.[6]

At last, the CMS collaboration produce model-independent upper limits on the cross section times the acceptance for new physics production in high-S_T inclusive final states for $N \geq 3$, 4 and 5. Fig. 6 shows 95% CL upper limits from counting experiments for $S_T > S_T^{\min}$ as a function of $S_T^{\min}$. This can be used to test models of new physics that results in these final states. An example of such a model is the production of high-mass $t\bar{t}$ resonances, in the six-jet and lepton + jet final states. These limits can also be used to constrain black hole production for additional regions of the parameter space of the model, and set limits on the existence of string balls, which are the quantum precursors of black holes in some string models.[6]

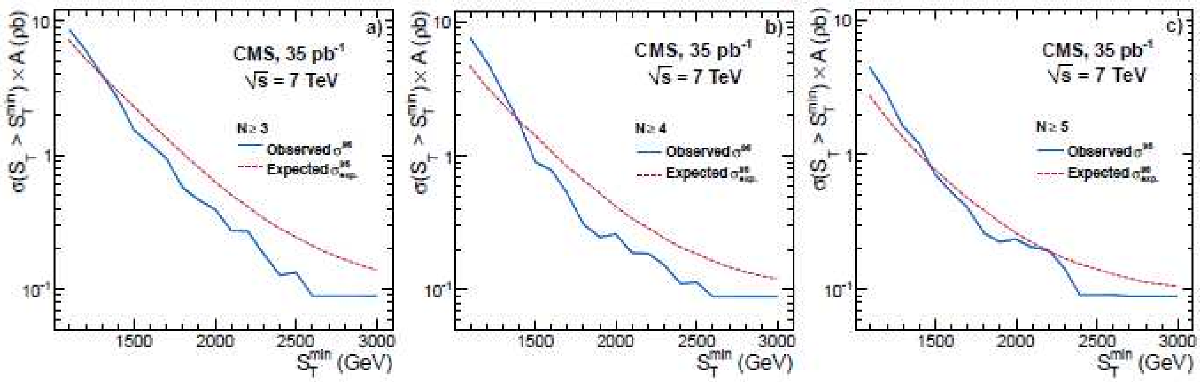

Figure 6: Model-independent 95% CL upper limits on a signal cross section times acceptance for counting experiments with $S_T > S_T^{\min}$ as a function of $S_T^{\min}$ for (a) $N \geq 3$, (b) $N \geq 4$ and (c) $N \geq 5$. The blue (red) line corresponds to observed (expected) limits for nominal signal acceptance uncertainty of 5%.[6]

Graviton emission:

In $p\bar{p}$ collisions there are three processes that can result in a hadronic jet and a graviton: $q\bar{q} \to gG$, $qg \to qG$ and $gg \to gG$, where q, g and G are quarks, gluons and gravitons respectively, shown in Figure 7. The calculation of graviton emission is based on the effective low-energy which is reliable at energies below M_D. Since the graviton interacts through gravity only it will not give rise to a signal in the detector and is therefore seen as missing transverse energy E_{Tmiss} from the jet created from a quark or gluon in the process.[7]

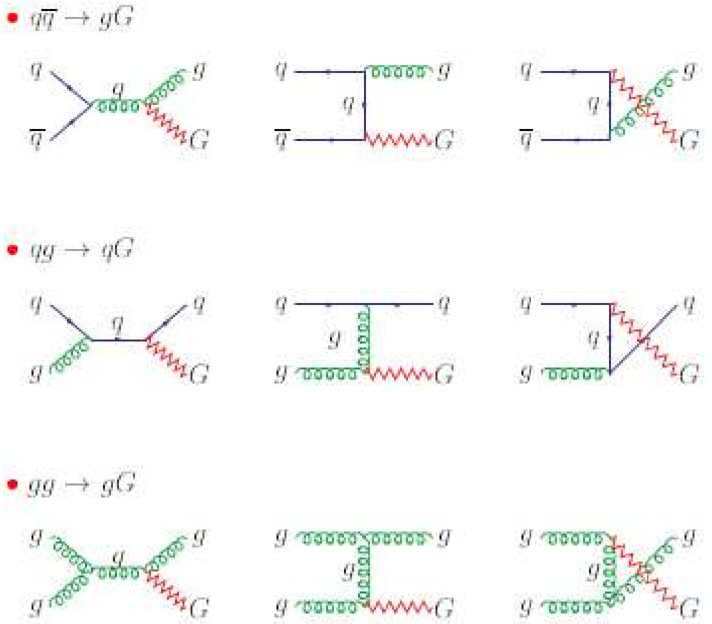

Figure 7: The lowest-order Feynman diagrams emitting real gravitons in $p\overline{p}$ collisions.[7]

In this particular experiment the CDF collaboration searches for the direct production of KK graviton modes using the rate of events with one or two energetic jets and large E_{Tmiss} at the Collider Detector at Fermilab (CDF). The integrated luminosity during the search was $84 \pm 4 pb^{-1}$ recorded with the CDF detector during the 1994-95 Tevatron run.[7]

To measure the momenta of charged particles the central tracking chamber (CTC) is used, which sits inside a 1.4 T superconducting solenodial magnet. Outside the magnet electromagnetic and hadronic calorimeters are used to identify jets, covering the pseudo-rapidity region $|\eta| < 4.2$ and arranged in a projective tower geometry. Jets are reconstructed using a iterative clustering algorithm with a fixed cone of radius $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$ in $\eta - \phi$ space. For this analysis, the threshold for jets are $E_T \geq 15GeV$ to be considered.[7]

The data sample is selected with an online trigger that requires $E_{Tmiss} \equiv \left|\vec{E}_{Tmiss}\right| > 30GeV$. The sample is dominated by instrumental backgrounds and by multijet events, where the observed missing energy is mostly a result of insufficient detector resolution and mismeasurements.[7]

The CDF collaboration remove events where the missing energy is due to energy flow from a jet to a region of the detector which is uninstrumented by requiring that the second highest E_T jet does not point in η to a detector gap if it is within 0.5 radians in ϕ of the missing energy direction. They reduce the residual mismeasured multijet backgrounds by setting a threshold that the minimum $\delta\phi$ between the E_{Tmiss} vector and any jet in the event ($\delta\phi_{\min}$) is greater than 0.3 radians and the z position of the event vertex is within 60 cm of the nominal interaction point.[7]

To reduce the background contribution from electroweak processes with leptons in the final state the CDF collaboration set a requirement that the two highest energy jets are not allowed to purely be electromagnetic ($f_{em} \equiv E_{em} / E_{Tot} \leq 0.9$) and the isolated track multiplicity is zero. For the final sample, $E_{Tmiss} \geq 80GeV$, $E_T \geq 80GeV$ for the leading jet and $E_T \geq 30GeV$ for the secondary jet if there is any. Reliable normalizations of the background predictions from QCD simulations can be achieved by accepting events with an energetic second jet, as well as controlling the systematic uncertainty on the signal due to initial/final state radiation (ISR/FSR). An interpretation of the results with a K-factor (the ratio of the cross section at leading-order (LO) and next-to-leading-order (NLO)) can also be achieved by accepting the before mentioned events and which is included in the estimated signal cross section. The selection thresholds and the number of accepted events at each threshold is summarized in table 1.[7]

Table 1: The data requirements for the E_{Tmiss} (sometimes noted as E_T with a slash) plus one or two jets and the number of events accepted in all the consecutive steps.[7]

Selection Requirement	Events Passing
Pre-Selection	300945
$1 \leq \text{N}_{jet} \leq 2$ (cone 0.7, $E_T \geq 15$ GeV) $\lvert\eta\rvert(1$ *or* $2) < 1.1$	157035
2nd jet gap veto $\delta\phi_{min} \geq 0.3$ $\lvert z_{vertex}\rvert \leq 60$ cm	50938
$f_{em}(1),\ f_{em}(2) \leq 0.9$	21012
N_{trk}^{iso}=0	16459
$E_T(1) \geq 80$ GeV If $\text{N}_{jet} = 2$, $E_T(2) \geq 30$ GeV	897
$\not{E}_T \geq 80$ GeV	284

Background events with missing energy (and one or two jets) that are from standard model particles are predominantly $Z(\rightarrow \upsilon\overline{\upsilon})$+jets, $W(\rightarrow l\upsilon)$+jets and residual QCD production. While $Z(\rightarrow \upsilon\overline{\upsilon})$+jets directly produces E_{Tmiss}+jets events, $W(\rightarrow l\upsilon)$+jets will produce a similar signal if the lepton doesn't interact with the detectors or is not identified to the right event. To estimate the background level uncertainties of the final samples for these two different events the CDF collaboration normalize Monte Carlo (MC) predictions using the observed $Z(\rightarrow e^+e^-)$+jets data sample. QCD dijet events will look like the wanted signal if one of the jets is measured very badly, which results in large E_{Tmiss}. For the QCD predictions the CDF collaboration uses a different MC program and normalizes to the high statistics jet data samples using well-balanced dijet events. They estimate additional backgrounds from $t\bar{t}$, single top and diboson when using MC predictions, which is normalized using theoretical cross section calculations for each of the processes.[7]

The predicted backgrounds from standard model processes are presented in table 2. Since the MC predictions have been normalized to high statistics data samples the dominant uncertainty on the W+jets and Z+jets is the 4% luminosity uncertainty, while the QCD prediction has an additional 14% uncertainty due to jet energy resolution. In Fig. 8 a comparison between the predicted standard model E_{Tmiss} distribution and the distribution the CDF collaboration observe in the data. In Fig. 9 same comparison is shown for other kinematic distributions. As seen, both figures show that the data is consistent with the expected background. If there would be an additional contribution from graviton production there be an evident excess over the background in nearly all kinematic distributions, shown in Fig. 10 for E_{Tmiss}.[7]

Table 2: The predicted number of events in the final sample from standard model sources and the number of observed events in the data.[7]

Background Source	Predicted Events
$Z(\rightarrow \nu\bar{\nu})$+jets	160.2 ± 11.5
$W(\rightarrow \tau\nu)$+jets	46.6 ± 5.5
$W(\rightarrow \mu\nu)$+jets	23.8 ± 5.0
$W(\rightarrow e\nu)$+jets	18.1 ± 4.3
QCD	21.7 ± 6.7
$t\bar{t}$, single t, dibosons	3.9 ± 0.3
Total predicted	274.1 ± 15.9
Observed	284

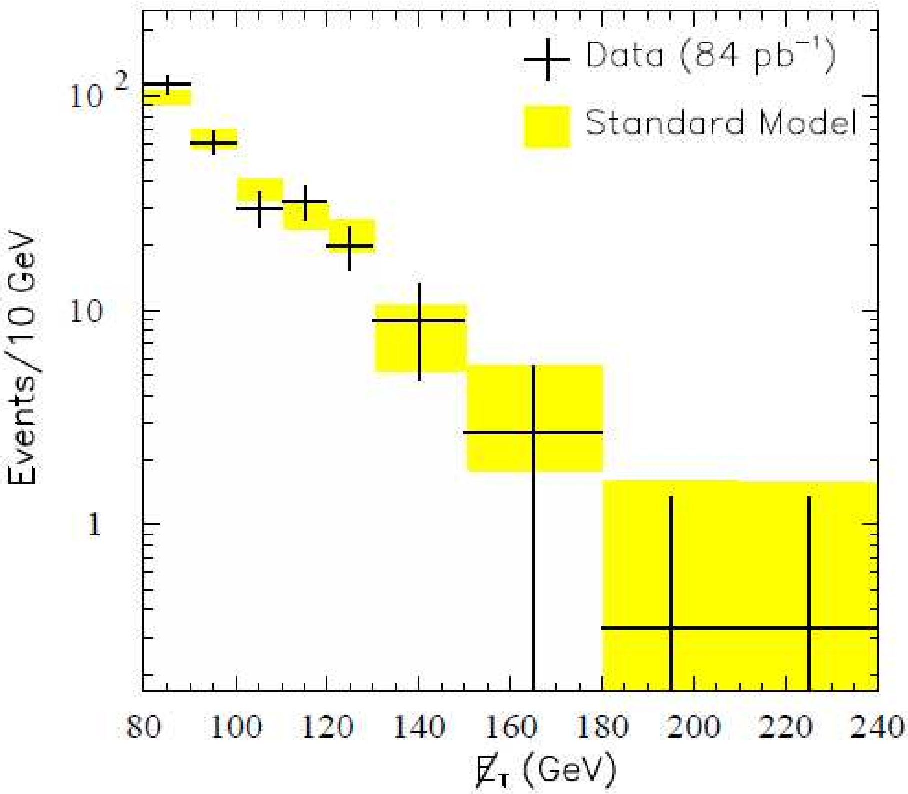

Figure 8: Comparison between data (points) and standard model predictions (boxes) of the E_{Tmiss} distribution. The height of the boxes shows the uncertainty on the standard model predictions.[7]

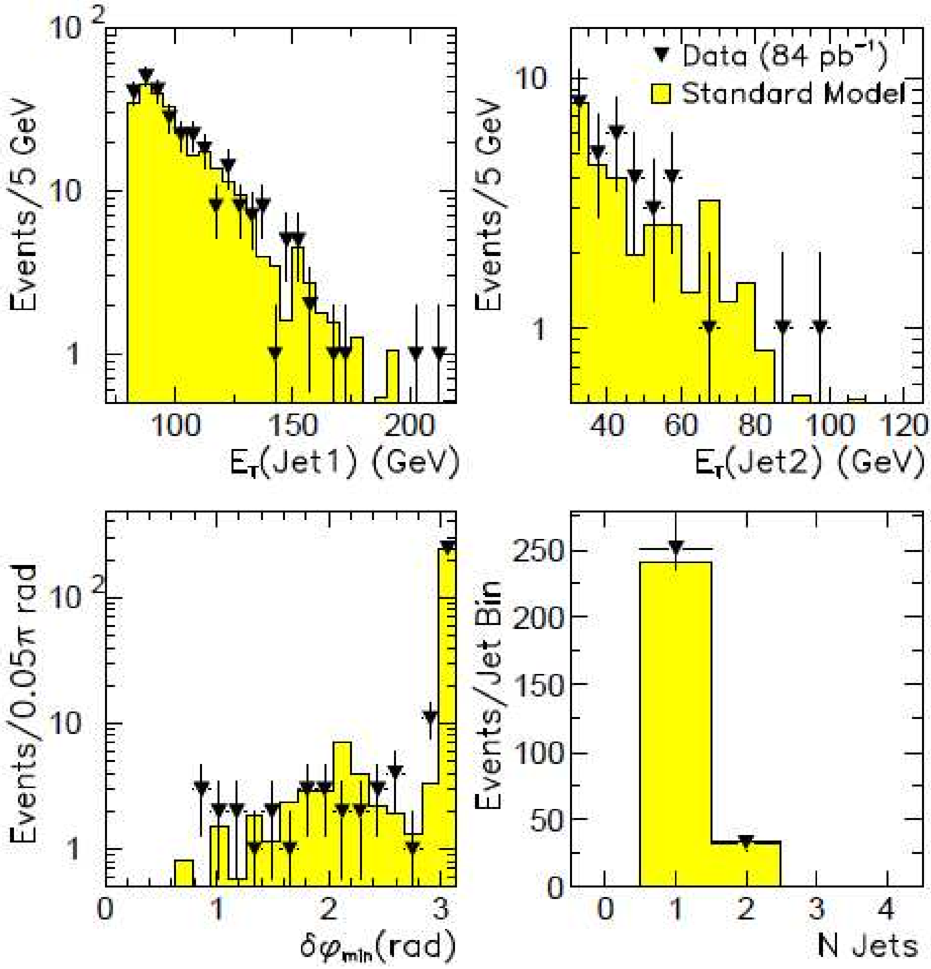

Figure 9: Comparison between data (points) and standard model predictions (histogram) of the the first and second leading jet E_T, $\delta\phi_{\min}$ and N_{jet} distributions.[7]

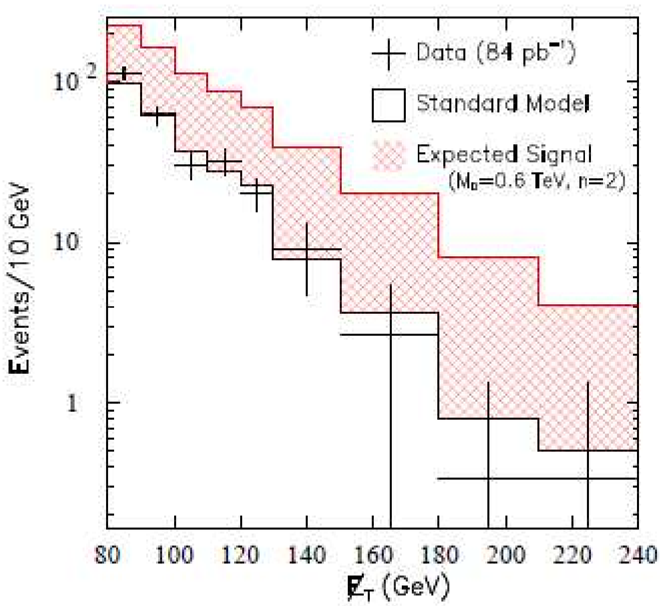

Figure 10: The predicted E_{Tmiss} distribution from standard model processes (histogram) and the one from the expected graviton signal (for $n = 2$, $M_D = 0.6TeV$ and a K-factor of 1.0) added to the standard model (hatched).[7]

The CDF collaboration use a MC program to generate a dataset of graviton emission, using a leading-order production cross section calculated before. The signal processes are simulated for $n = 2$, 4 and 6 extra dimensions, and for different values of M_D.[7]

With the use of a Monte Carlo technique to convolute the uncertainty on the background estimate with the relative systematic uncertainty on the signal efficiency, the 95% confidence level upper limit on the number of signal events is 62. For $K = 1.0$ the CDF collaboration exclude an effective Planck scale less than $1.00TeV$ for $n = 2$, less than $0.77TeV$ for $n = 4$ and less than $0.71TeV$ for $n = 6$, this is shown in Fig. 11. It is reported that another research group had gotten a similar result but using $K = 1.3$. To compare, using the same $K = 1.3$ with the CDF collaboration data their corresponding lower limits on M_D are $1.06TeV$ for $n = 2$, $0.80TeV$ for $n = 4$ and $0.73TeV$ for $n = 6$.[7]

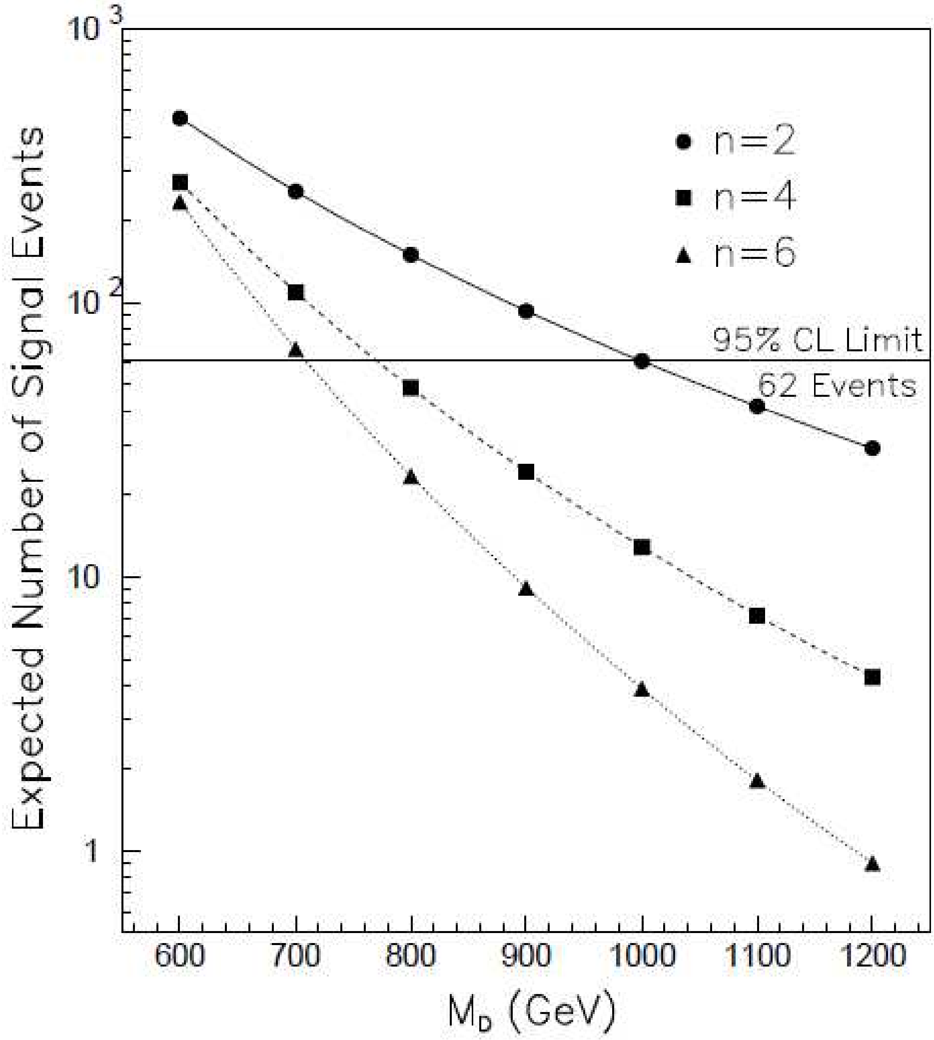

Figure 11: The three curves are the expected signal events for $n = 2$, 4 and 6 extra dimensions as a function of M_D for $K = 1.0$. The straight line in the figure is the 95% CL upper limit on the number of signal events.[7]

Assuming the compactification of the extra dimensions described in the ADD model, the corresponding limits on the compactification radius would be $R < 0.48mm$ for $n = 2$, $R < 0.014nm$ for $n = 4$ and $R < 42fm$ for $n = 6$.[7]

Conclusion:

As can be seen from the experiments there has not yet been any data confirming the existence of microscopic black holes or extra dimensions. It is important to understand that these experiments has been conducted on particle collisions with energies that are relatively low compared to the postulated M_D, and the lack of evidence is actually partly expected by the

ADD-model. When LHC operates at its maximum $14TeV$ collision energy there will be a higher possibility to confirm the ADD-model if it is indeed true.

Lastly, also the ATLAS collaboration has been simulating events thought to occur in the LHC, trying to look for the possibilities to find black holes using the maximum beam energy for the LHC.

The two key parameters for black hole production is the Planck scale M_D and the number of extra dimensions n, and the ATLAS collaboration has been working on finding methods to extract these parameters from data taken from a black hole. There has already been a proposed method for extracting M_D from cross-section data, which will fix the Planck scale, and from high energy object emissions.[36]

As I have shown before T_H does depend on n. If events with emissions near $M_{BH}/2$, the energy of those emissions is a measure of the initial T_H. Therefore, the probability of such emissions is a measure of the characteristic temperature of the black hole, and can be used to extract n. It should be noted that this measurement requires knowledge of M_D, and if this cannot be determined by the black hole production cross-section, black hole threshold behaviour near the Planck scale will probably give indications of the value of M_D.[36]

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