Large Extra Dimensions and Black Hole Searches using CMS RunII Data

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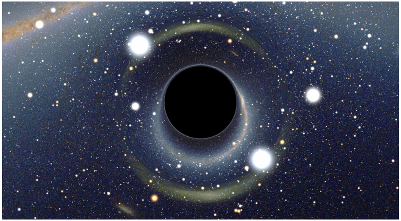
Black Holes

Astronomical Black Holes

A spacetime region with sufficiently compact mass produces an immense gravitational pull to prevent everything including light, from escaping. Classically, an event horizon is a surface around the a Black Hole which is called **point of no return**. Anything that touches event horizon, will be trapped and won't go back.

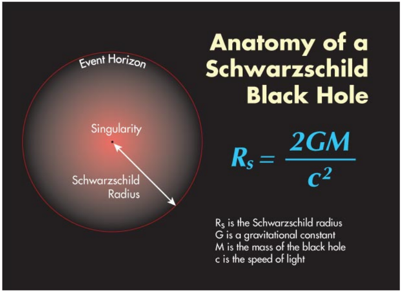
Microscopic Black Holes

In high energy particle collider, mini Black Holes can be produced if there is a strong gravity at small scales. Microscopic Black Holes will evaporate **quickly** unlike astronomical Black Holes.



Event Horizon

It is the surface around a black hole beyond which nothing even light can escape. Assume horizon radius R_H.



Schwarzschild Radius

The radius of black hole in which all the mass of black hole is packed. Assume Schwarzschild radius R_s.

Schwarzchild Black Hole

It is an uncharged, spherically symmetric and non-rotating black hole, for this case

$R_H = R_s \equiv r_s$

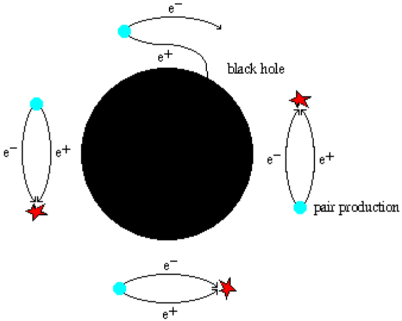
If Earth becomes a black hole, its all mass would be pressed in r_s=8.7 mm

Black Holes

Why A Micro Black Hole Evaporates ?

In 1974, Stephen Hawking predicted that

- Quantum/Vacuum fluctuations produce virtual pairs of particle-antiparticle near horizon
- Gravitational field of black hole converts them into real particles at expense of its mass
- One member falls into horizon and other escapes
- It seems the escaped particle is emitted from black hole

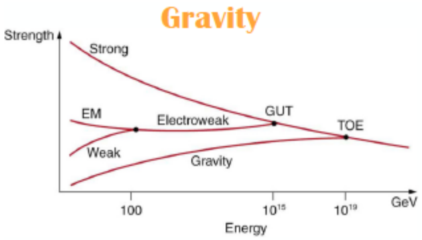


- Black hole loses its mass and quickly evaporates by emitting Hawking radiation

Smaller the mass of black hole quickly it evaporates, as $T_{BH} \propto \frac{1}{M_{BH}}$

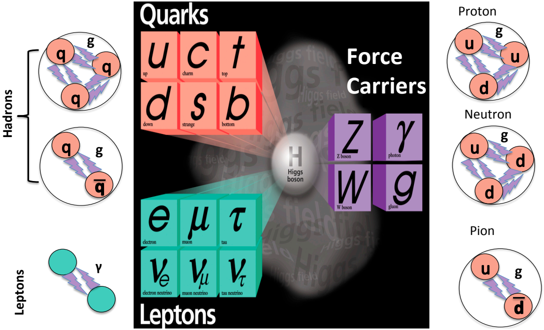
As energy and length are related: $E = \frac{hc}{\ell}$

Scales	Energy (GeV)	Length (m)	Experimentally Probed
Strong Scale	1	10^{-15}	Yes
Electroweak Scale (Fundamental scale)	10^{2}	10^{-18}	Yes
Grand Unification Theory (GUT) Scale	10^{15}	10^{-31}	No
Planck Scale -Theory of Everything (TOE) Scale	10^{19}	10^{-35}	No



How the Micro Black Hole can remove/fix this desert ? Stay tuned ☻

Fundamental Particles

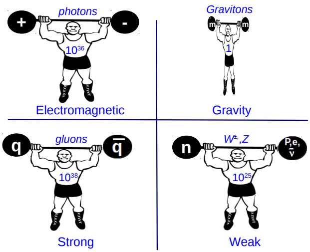


- Normally quarks exist in bound state, called Hadrons; Baryons (qqq) and Mesons ($q\bar{q}$)
- Quarks and Gluons are collectively called partons.

How do these fundamental particles interact?

Fundamental Forces

- All the particles interact via **four fundamental forces** in nature
- Standard Model of particle physics incorporates Electromagnetic, Weak and Strong forces but not gravity.

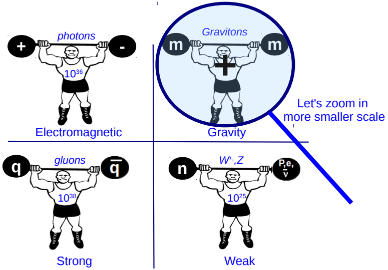


- Gravity appears to be much weaker than other force.

Is gravity really a very weak force?

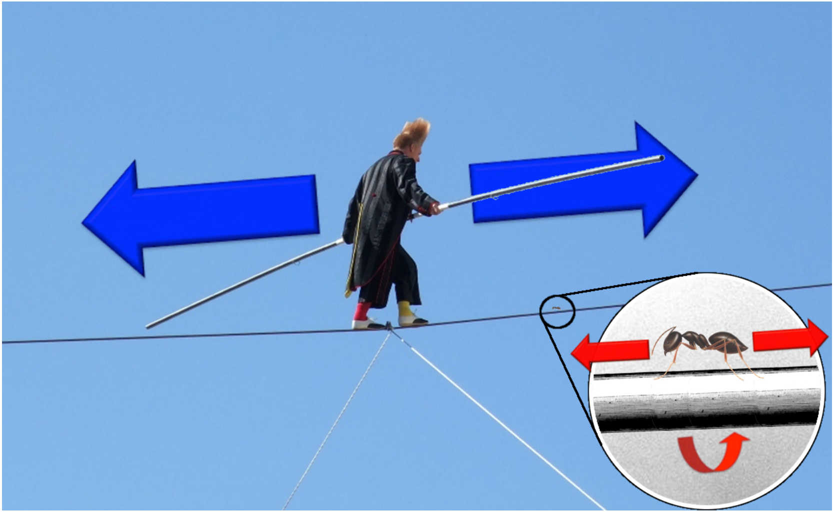
Extra-dimensions and Strong Gravity

- Gravity is the only force that can propagate in **extra dimensions** and most of its strength goes into extra dimension.
- At current fundamental scale 10^{-18} m we are not able to see extra–dimensions that's why gravity appears to be very weak.



- If go to more smaller scale than 10^{-18} m then we can see **extra dimensioned** and **strong gravity**
- **Microscopic Black Holes** are possible to produce in high energy colliders like **LHC**

Scales are important to explore extra-dimensions



Motivation for Searching Mini Black Holes

Hierarchy Problem

Why is there a large difference between the Electroweak scale (M_{EW} ~O(TeV)) and the Planck scale (M_P ~10^{16} TeV)

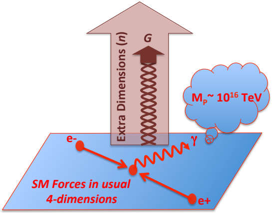
or

Why gravity appears weaker as compared to the SM forces ?

Low-scale gravity models propose a solution to this problem with the concept of extra spatial dimensions.

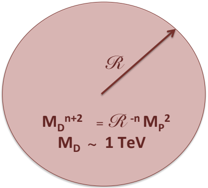
Low-scale Gravity

- **In ADD model**, there are large extra dimensions and only gravity can propagate in extra spatial dimensions (n).
- The extra dimensions are compactified in a sphere of radius $\mathscr{R}$, e.g., $\mathscr{R} \sim$ submillimeter scale for $n \geq 3$.
- At such a low scale ($\sim \mathscr{R}$), gravity will appear as strong as other forces, i.e., the apparent Plank scale (M_P) reduces to the true Planck scale (M_D[1]).
- As a consequence of strong gravity at low-scale, **production of microscopic black holes** (MBH) is possible in a high energy collision under certain conditions.



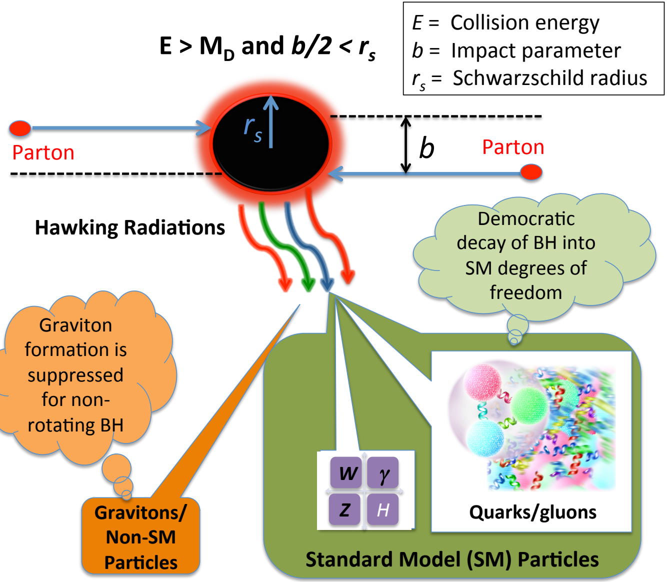
ADD Model of large extra dimensions

Extra dimensions (n) are compactified in a sphere



[1] where $D = n + 4$, total number of dimension

MBH Formation and Decay



Available SM Degrees of Freedom

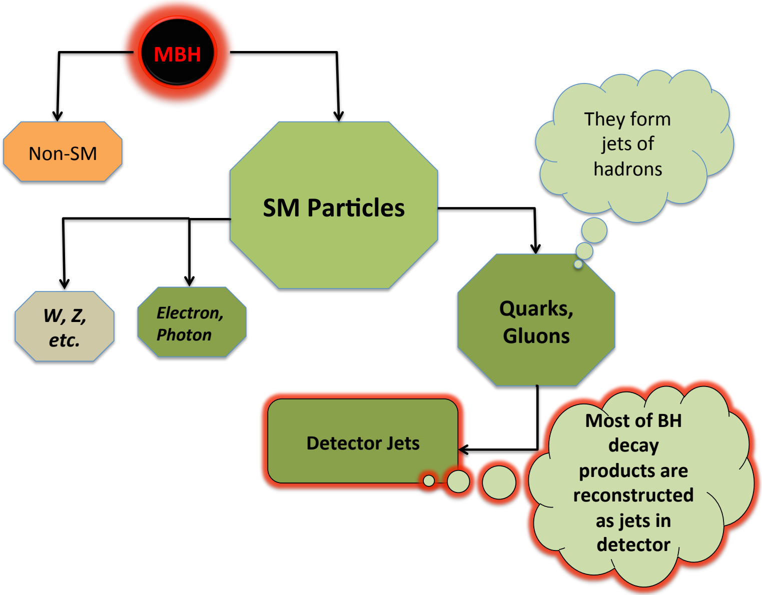
$dof = n_Q \times n_S \times n_F \times n_C$

Particle Type	Charge State (n_Q)	Spin State (n_S)	Flavour State (n_F)	Colour State (n_C)	dof
Quarks	2	2	6	3	72
Charged leptons	2	2	3		12
Neutrinos	2	1	3		6
Gluons	1	2		8	16
Photon	1	2			2
Z boson	1	3			3
W bosons	2	3			6
Higgs boson	1				1

Table : *Number of degrees of freedom (dof) of the Standard Model particles*

Quarks and Gluons are dominant in MBH decay

MBH Decay


MBH
Non-SM
SM Particles
They form jets of hadrons
W, Z, etc.
Electron, Photon
Quarks, Gluons
Detector Jets
Most of BH decay products are reconstructed as jets in detector

Signatures at the LHC

- Mini black holes (MBH) may be produced in high energy proton-proton (pp) collisions at the Large Hadron Collider (LHC).

- Once produced, MBH may be distinguished by
  - high number of SM particles in final states, i.e. multiplicity (N),
  - democratic (with equal probabilities) and
  - highly isotropic (same in all directions) decays

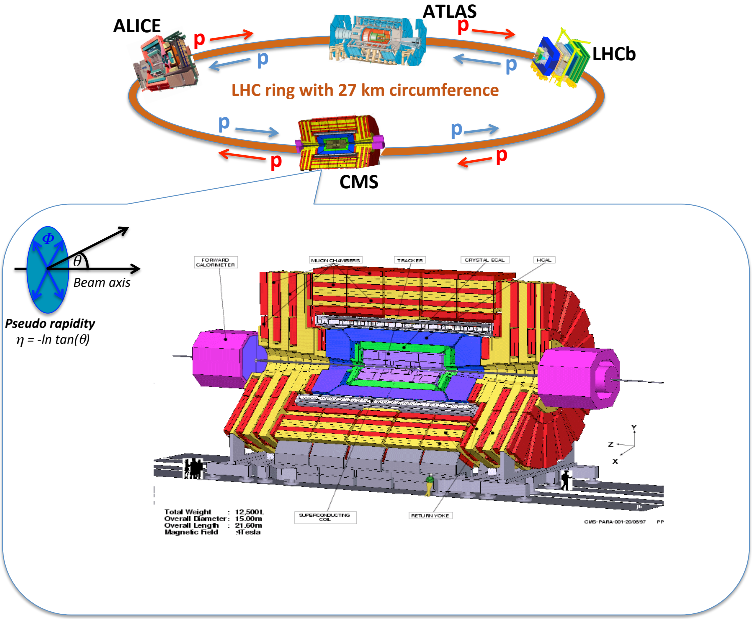
  with the final state particles carrying **several hundreds of GeV energy**.

- Hence,
  - high-N, and
  - high-E_T (transverse energy)

  in the detector coverage are the key signatures of MBH.

Therefore, we select **high multiplicities with high** $S_T = \sum E_T$ *in the data recorded by the CMS detector at the LHC.*

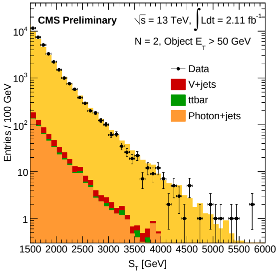
CMS Detector at the LHC

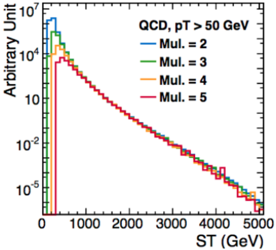


Major Backgrounds

Backgrounds considered are:

- $\gamma + jets$
- $V(W,Z) + jets$
- $t\bar{t}$
- QCD - **The dominant one**
  - S_T shape is invariant for all N
  - The shape of $N = 2$ is used to extract background for $N > 2$
  - The $N = 2$ shape is extracted from Ansatz fitting method

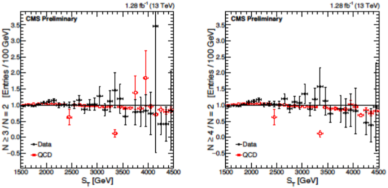




S_T shape invariance with different multiplicities is investigated further

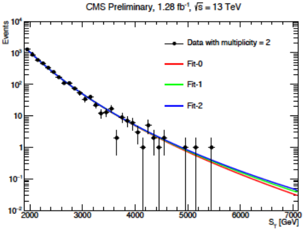
S_T Shape Invariance

The S_T ratio of $N > 2$ to $N = 2$ is computed and many tests are performed



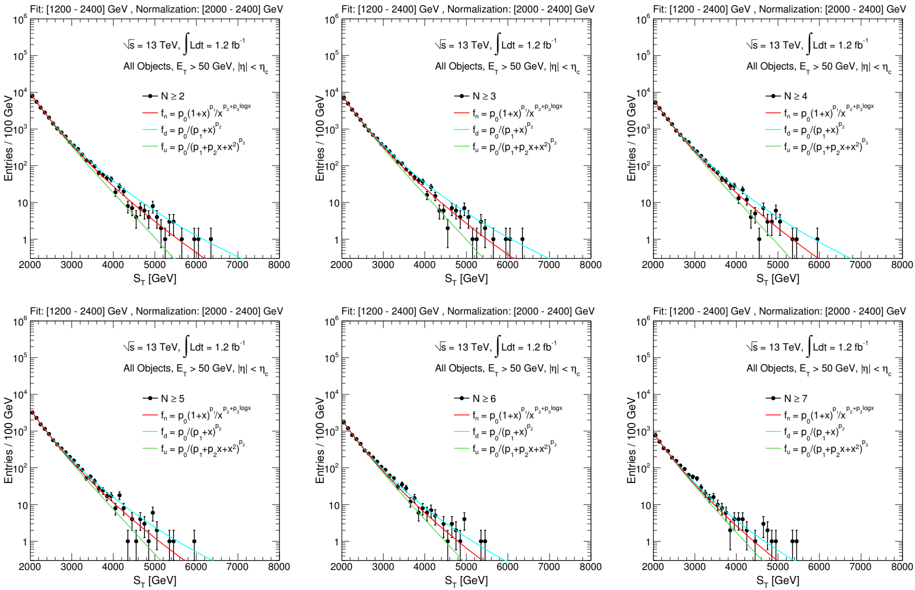
Functions are fit to $N = 2$ because:

- The dominant dijet case is well-studied, and
- it has no new physics

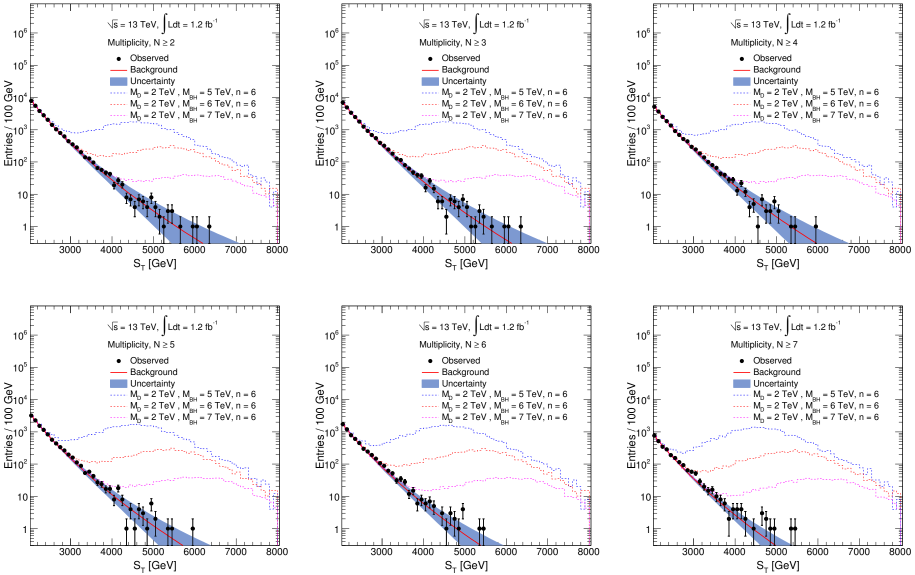


The shape of $N = 2$ is used to extract background for $N > 2$ by shape invariance assumption

Background Estimation for $N > 2$



Everything for $N > 2$



Systematic Uncertainties

In a physics data analysis, beside statistical uncertainties, there are also systematic uncertainties involved that depend on analysis techniques.

No.	Uncertainties	Range
1	Function Fitting	5-100%
2	Choice of kinematic Regions	2-10%
3	Parton Distribution Functions (PDF)	~6%
4	Jet Energy Uncertainties	~5%

Example of a Candidate Event for Black Hole Searches

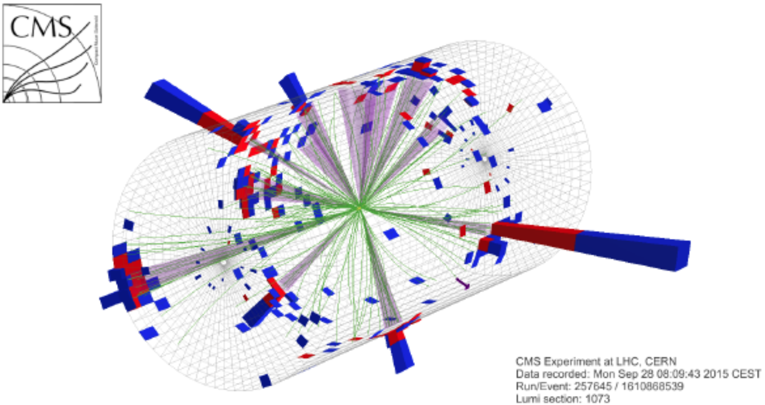
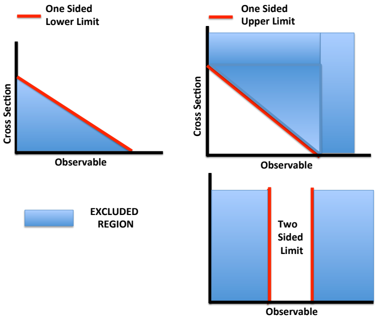


Figure : *Event display for a black hole candidate collected in Run 257645, Event 1610868539. This event has 12 jets, E_T^{miss} of 120 GeV, and the multiplicity N = 12*

What if there is no Signal found?

If there is no new physics (such as black hole) found then

- Exclusion Limits are drawn by model-dependent or model independent way
- A fake signal is added on top of estimated background in the signal region up to the level of 95% Confidence Level (CL) and cross section is recomputed.



Model-independent and Model-dependent Limits

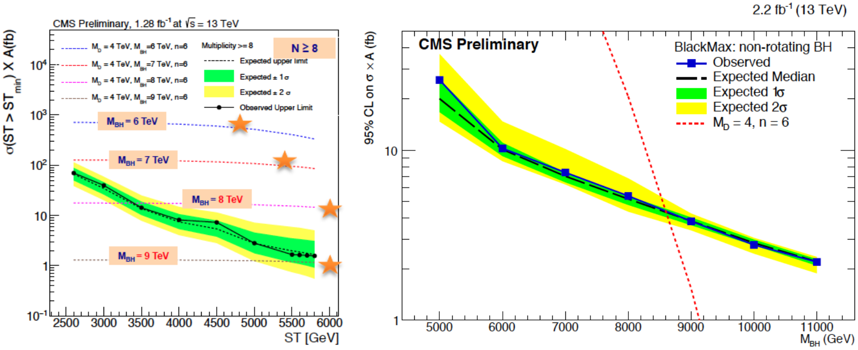


Figure : *The observed (black solid line) and expected (black dotted line) model independent upper limits along with one sigma (green) and two sigma (yellow) bands. The model dependent limits (colored dotted lines) are also shown for multiplicity $N \geq 8$ with 95% confidence.*

Summary

- Background Estimation
  - QCD is the main background estimated purely from data
  - Background is estimated using S_T shape invariance
  - Background is estimated using $N = 2$ multiplicity as a baseline
- New Physics
  - All the data were consistent with the background
  - No new physics was found
  - Exclusion limits are computed
- Exclusion Limit
  - Upper limits with 95% CL are shown on the production of new physics
  - Many BH models were checked for the exclusion limits

Thanks