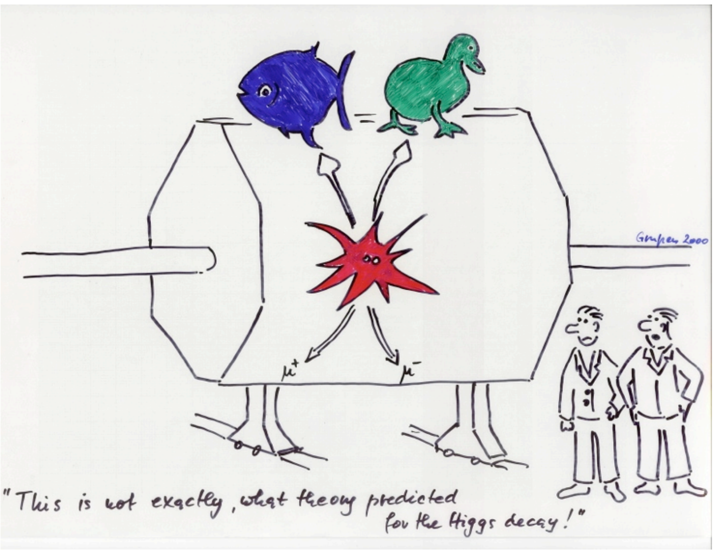
Subatomic Physics:

Particle Physics Handout 9

Physics at the LHC



- LHC collisions
- Higgs boson
- Supersymmetry
- Extra dimensions
- Force Unification

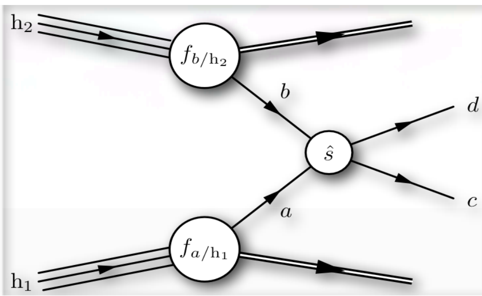
LHC Collision Energy

Proton - proton collision at centre of mass energy, $\sqrt{s} = 14$ TeV

From handout 7: **parton model**

A high-energy proton consists of partons (quarks **and** gluons **and** anti-quarks) - interacting independently

- The interactions of two partons - one from each colliding quark - is called **hard scatter**
- The hard scatter can be: quark–quark, quark–anti-quark, quark–gluon, gluon–gluon etc.
- Key parameter for describing partons is Feynman x: fraction of proton momentum carried by parton
- The effective energy of the collision is $\sqrt{\hat{s}}$, defined as: $\hat{s} = (\underline{\underline{p}}_1 + \underline{\underline{p}}_2)^2$
  - $\underline{\underline{p}}_1$, $\underline{\underline{p}}_2$: four-momenta of the interacting partons



$$
\begin{aligned}
\hat{s} &= (\underline{\underline{p}}_1 + \underline{\underline{p}}_2)^2 = ((x_1 E_p/c, 0, 0, x_1\, p_p) + (x_2\, E_p/c, x_2\, 0, 0, -x_2\, p_p))^2 \\
&= m_1^2 + m_2^2 + 2(x_1\, x_2 E_p^2/c^2 + x_1\, x_2\, p_p^2) \\
&= 4\, x_1\, x_2\, p_p = x_1\, x_2\, s
\end{aligned}
$$

- Effective collision energy **not known** on event-by event: always less proton-proton energy of $\sqrt{s} = 14$ TeV

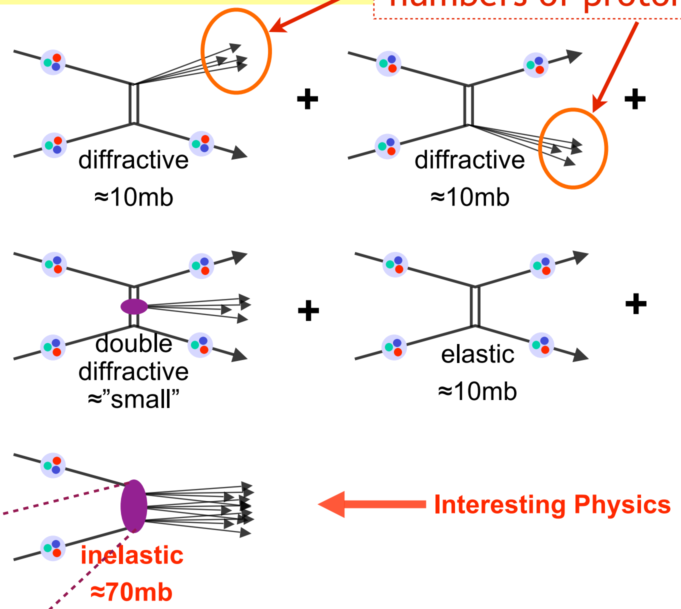
LHC Collisions

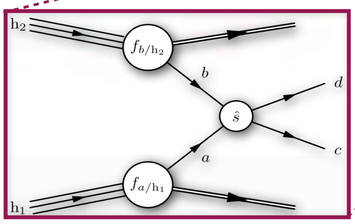
state with quantum numbers of proton

At LHC collisions:

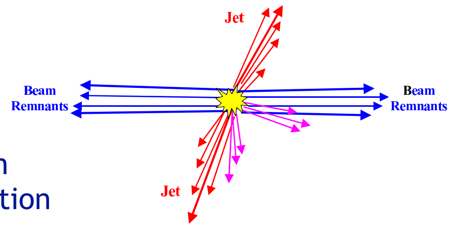
- protons can just exchange momentum (elastic scattering)
- one or both protons can remain as a proton (diffractive scattering)
- both protons destroyed: a parton from each proton undergoes hard scattering (inelastic scattering)

σ_{tot} = ≈100mb





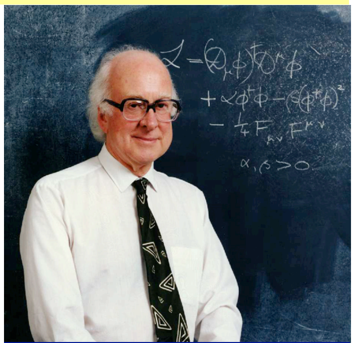
After collision: the proton remnants remain travelling in roughly same direction



The Higgs Boson

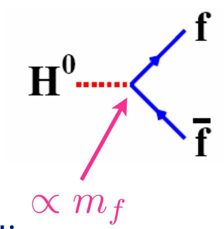
The Higgs boson: missing piece of the Standard Model.

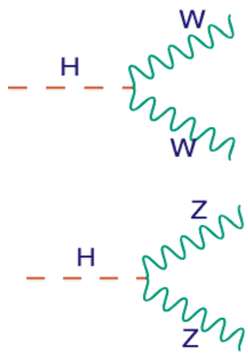
- The theoretical framework for the Standard Model only works for massless bosons and massless fermions.
- Introducing Higgs field give masses to the W and Z bosons
- Two key consequences:
  - The fermions also get a mass!
  - The existence of an additional massive, neutral boson: **the Higgs boson**
- Mass of the Higgs is not predicted in Standard Model, we have to search for it.



Peter Higgs emeritus professor in the School of Physics

Higgs interacts with W and Z bosons, and all massive fermions.





Interaction strength between Higgs and fermions ∝ fermion mass, m_f

The Higgs Mechanism

The Higgs exists at all places in space and time even in a vacuum. This is in contrast to the electromagnetic field (photons) and QCD field (gluons) which do not exist in a vacuum.

1. Physicists (representing the Higgs field evenly distributed throughout space) are at a conference reception; all free to move around the room.

2. In comes a noble prize winner; everyone wants to speak to him. physicists crowd around him. The noble laureate is not free to move around; he has gained inertia by interacting with the crowd.

This is analogous to how the particles acquire mass: by interacting with the Higgs field. Laureates of different popularity gain different masses.

The Higgs Boson

3. The next evening; physicists enjoying another drink.

A rumour enters the room: the keynote speaker tomorrow will announce the discovery of a new particle!

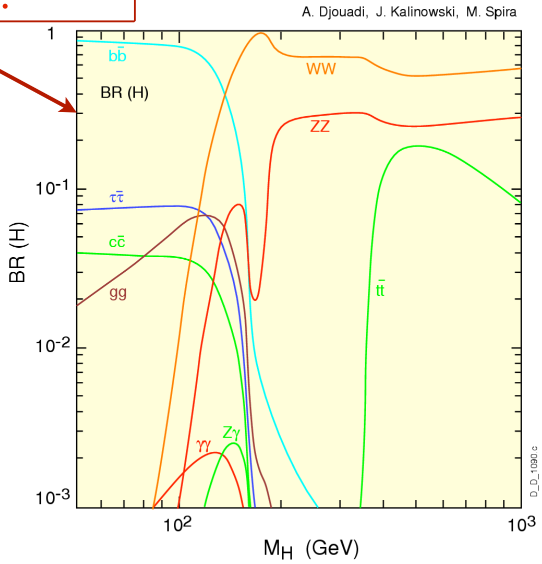
4. The physicists gather together to spread the rumour. The group of physicist acquire inertia.

The clustering of the field of physicists is as if a new massive particle has formed. This is the Higgs boson.

The Search for the Higgs

Higgs boson has been searched for at LEP, is being searched for at the Tevatron and will be search for at the LHC.

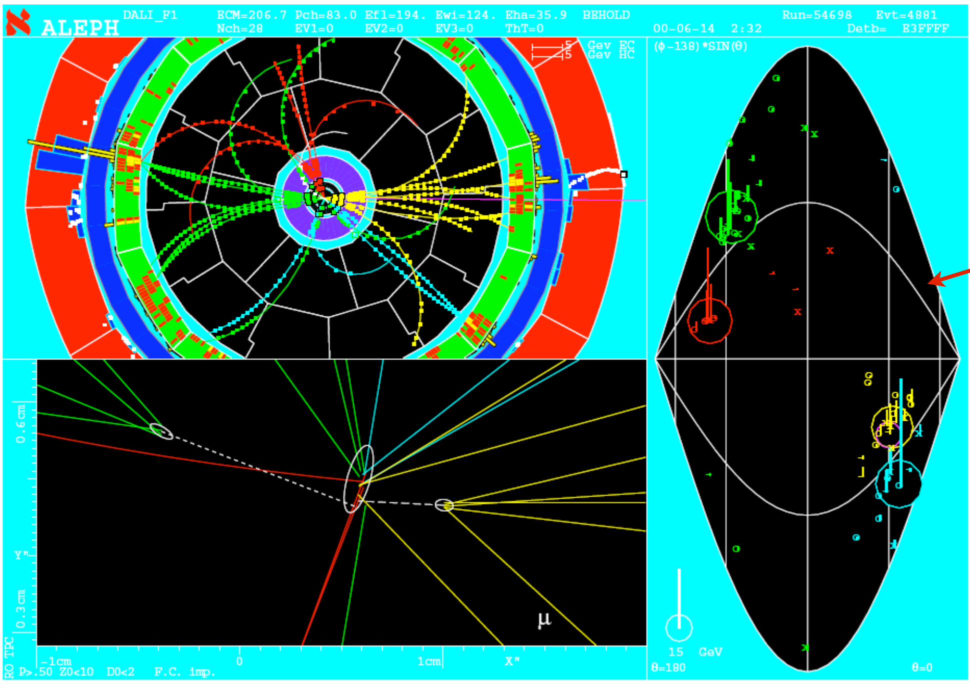
Predicated branching ratio of the Higgs boson **BR(*H*)**, as a function of Higgs boson mass, m_H.

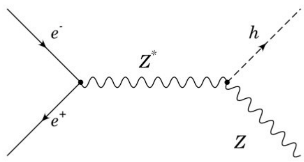


- Higgs coupling proportional to mass ⇒ Higgs *generally* decays to heaviest particles possible
- $m_H <$ ~135 GeV search for $H \to b\bar{b}$ decay.
- $m_H >$ ~135 GeV search for $H \to W^+W^-$, $H \to Z^0Z^0$ decays. (1 boson may be virtual)

Lots of other events look similar to events will Higgs decays. The challenge is to separate background events from Higgs events.

Higgs Event at LEP?





Four “jets” from hadronisation of quarks

Two jets originate outside of collision point: signature of the b-quark

Picture from ALEPH detector at LEP, found during search for $e^+e^- \to Z \to ZH$

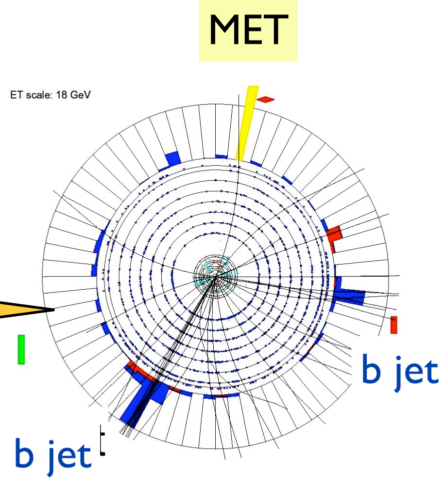
Event looks like: $e^+e^- \to Z \to ZH$ where $Z \to q\bar{q}$ and $H \to b\bar{b}$

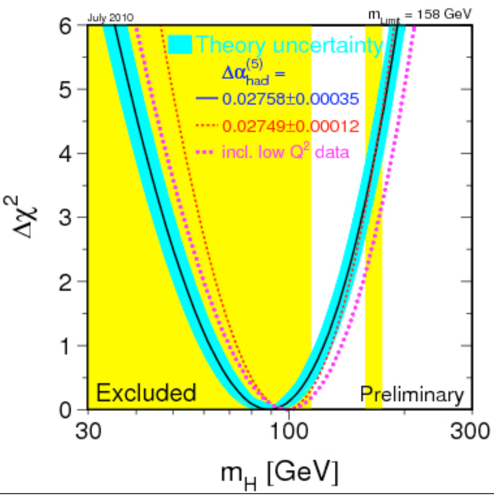
(but could also be a background event, *e.g.* $e^+e^- \to W^+W^-$ where $W^+ \to q\bar{b}$ $W^- \to b\bar{q}$)

Current Limits on Higgs Boson Mass

As the Higgs boson can interact with most other bosons and fermions, many measurements (cross sections, W, Z mass and width) are slightly sensitive to Higgs mass.

Picture of event at Tevatron which looks like $ZH \rightarrow \nu\bar{\nu}b\bar{b}$ (could also be background)

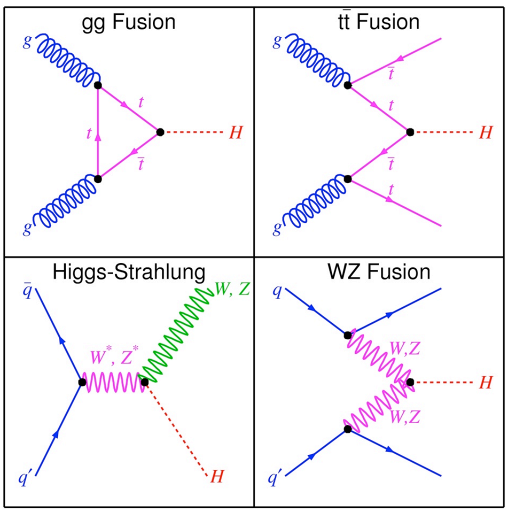


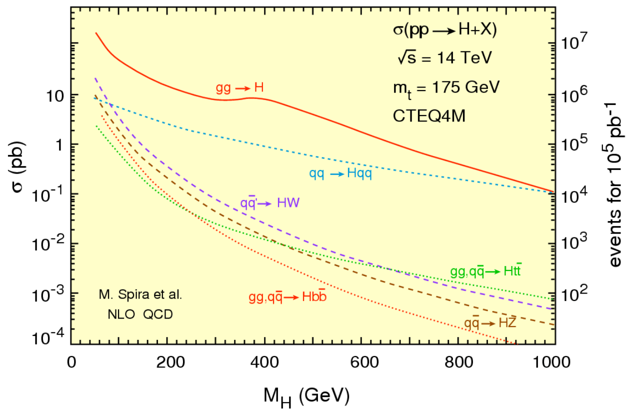


- "Blue band" shows the χ^2 of a fit to measurements of electroweak model parameters as a function of Higgs mass.
- Yellow is LEP and Tevatron excluded regions
- Best fit $m_H = 89^{+35}_{-26}$ GeV/c^2.
- All evidence suggests that (if the Standard Model is correct) $m_H < 200$ GeV /c^2

Higgs Production at LHC

At the LHC Higgs boson is produced alone, in association with a W or Z boson or with two jets (Hqq).





- σ ~ **1pb** to **30pb** (depending on m_H)
- With planned integrated luminosity of **100 fb^{-1}** per year make 10,000 to 300,000 Higgs bosons per year!

Higgs searches:

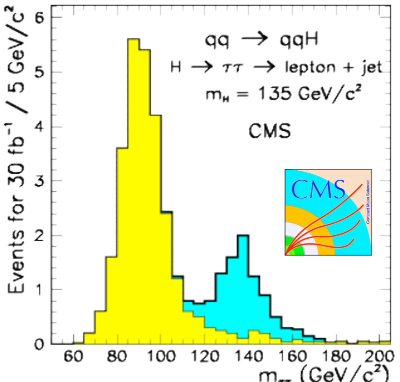
- For decays similar to background use HW, HZ, or Hqq events - which have smaller background.
- For higher masses use single H production - higher cross section.

Higgs Searches at LHC

Many studies of Higgs bosons searches at LHC have been made…

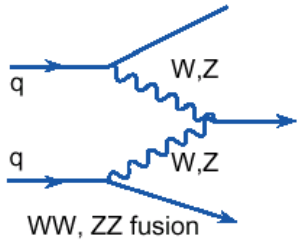
Using 2 years of data at √s=14 TeV with full luminosity, if $m_H < 1$ TeV the LHC should find the Higgs.

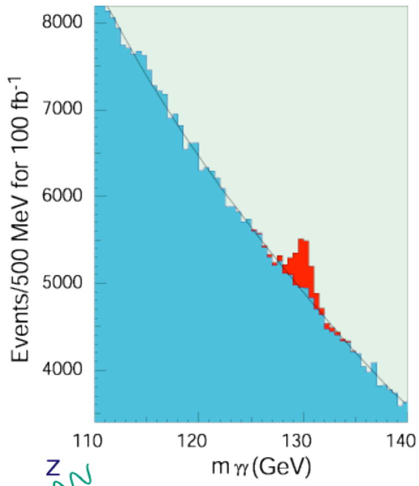
… otherwise Standard Model is in trouble!



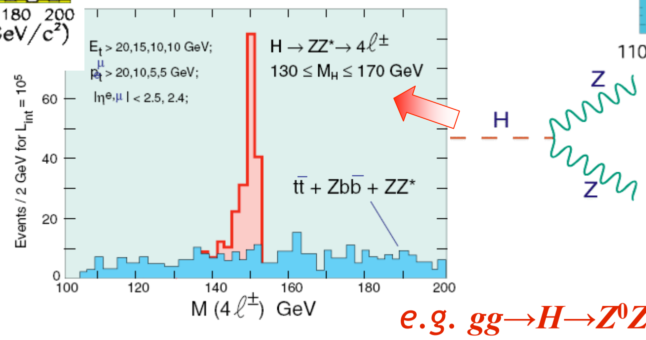
Phys. Rev. **D59**(1999) 014037

e.g. $qq \to qqH \to \tau^+\tau^-$+2 jets





e.g. $gg \to H \to \gamma\gamma$

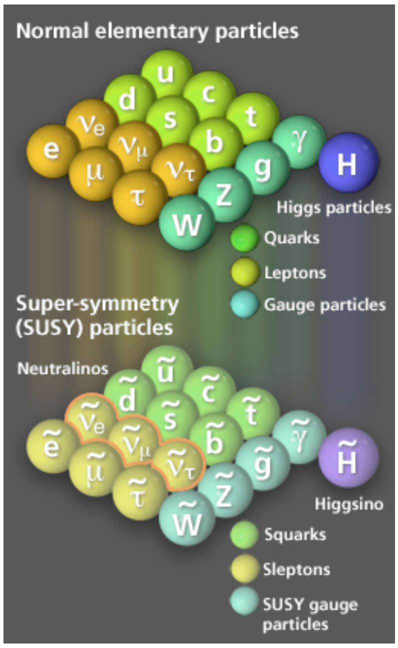


e.g. $gg \to H \to Z^0Z^0 \to$ 4 charged leptons

Supersymmetry (SUSY)

Adding the Higgs mass into the Standard Model has some theoretical problems.

An extra symmetry - **supersymmetry** - would solve this problem. It would also result in **new** (as yet undiscovered) **fundamental particles.**



Supersymmetry is symmetry between fermions & bosons:

- Every fundamental fermion has a boson partner. *e.g.:*

  $u \leftrightarrow \tilde{u}$ — up-quark ↔ up squark

  $\tau \leftrightarrow \tilde{\tau}$ — tau-lepton ↔ tau-slepton

- Every boson (W, Z, γ, **Higgs**) has a fermion partner *e.g.:*

  $W \leftrightarrow \widetilde{W}$ — W-boson ↔ Wino

  $H \leftrightarrow \widetilde{H}$ — Higgs ↔ Higgsino

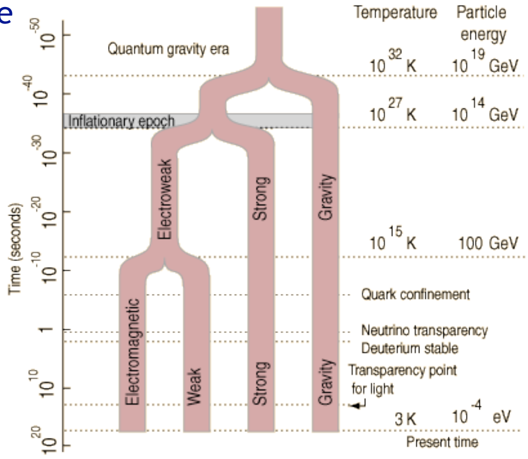
- The lightest supersymmetric particle (LSP) is probably neutral and stable. Supersymmetric particles will decay, eventually producing the LSP. It will leave the detector without interacting too much - similar to an neutrino.
- LSP is a candidate for dark matter

And what about gravity?

The ultimate unification of the forces should include gravity.

- But gravity is very much weaker than the other forces...

Many ideas proposed to explain this.



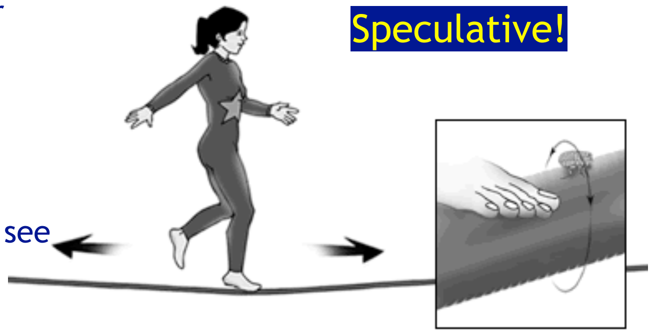
e.g. **Extra dimensions**

- Most particles (and us) can only travel in the regular 3 space + 1 time dimensions
- Gravitions - the bosons which propagate gravity - can travel in the extra dimensions.
- Strength of gravity is natural weaker in our dimensions

$$F(r) = G\frac{m_1 m_2}{r^2} \to G_{\text{new}}\frac{m_1 m_2}{r^4}$$

- They have to be small extra dimensions, otherwise we'd have seen them already.
- If the dimensions are big enough we might see their effects at the LHC!

Speculative!



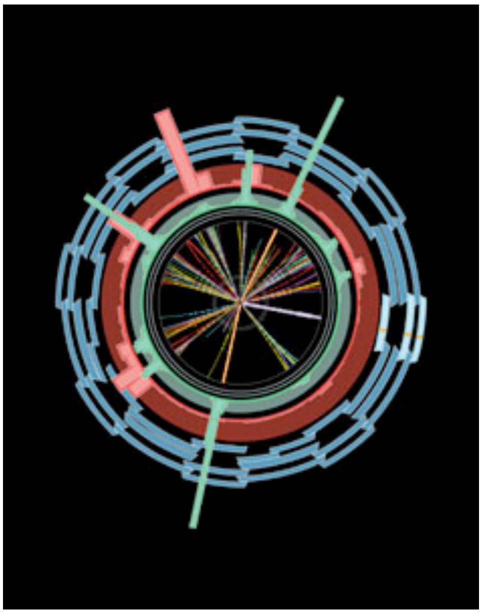
Mini black holes

From: http://cerncourier.com/cws/article/cern/29199

- Mini black hole production at the LHC would be an observable consequence of extra space-time dimensions.
- Key parameter: size of extra dimension, R_H. Limit on $R_H < \sim 1$ mm.
- With a extra dimension the **real** gravitational constant, G_{new}, is larger than the effective one we see: allows us to make a small black hole.
- Schwarzschild black hole radius: $R_S = 2\, G_{new} M / c^2$
- The LHC can probe distances:

$$R \approx \frac{\hbar c}{E} \sim \frac{197\ \text{MeV} \cdot \text{fm}}{2\ \text{TeV}} \sim 10^{-4}\ \text{fm}$$

- Can explore any black holes with radius $R_S > 10^{-4}$ fm.
- Cross section for making black holes could be $\sigma \sim \pi R_H^2$: as large as 1 per minute for R_H ~ mm.
- Black hole will decay very quickly ($\tau \sim 10^{-26}$ s) via Hawking radiation: particles emitted isotropically.



Simulation of a mini black hole decay in the ATLAS detector

LHC Physics Summary

The Standard Model is a beautiful theory of (almost) all the measurements we see in particle physics.... But it isn't the whole picture. "We can explain everything, but we understand (at a fundamental level) almost nothing!"		Interesting LHC collisions are due to the hard scattering of one parton from each proton.
Higgs boson is the missing particle in the Standard Model. The LHC has a good chance to see it.	Higgs boson couples to the fermions proportionally to fermion mass.	Effective collision energy is: $\sqrt{\hat{s}} = \sqrt{x_1 \, x_2 \, s}$
Ultimately we think the electroweak, strong and gravitational forces should be described by one underlying interaction. Extra dimensions could be explain some of this … may provide mini black holes at LHC		Supersymmetry is one popular theory for physics beyond the Standard Model. Supersymmetry provides a candidate particle for dark matter.

Notes