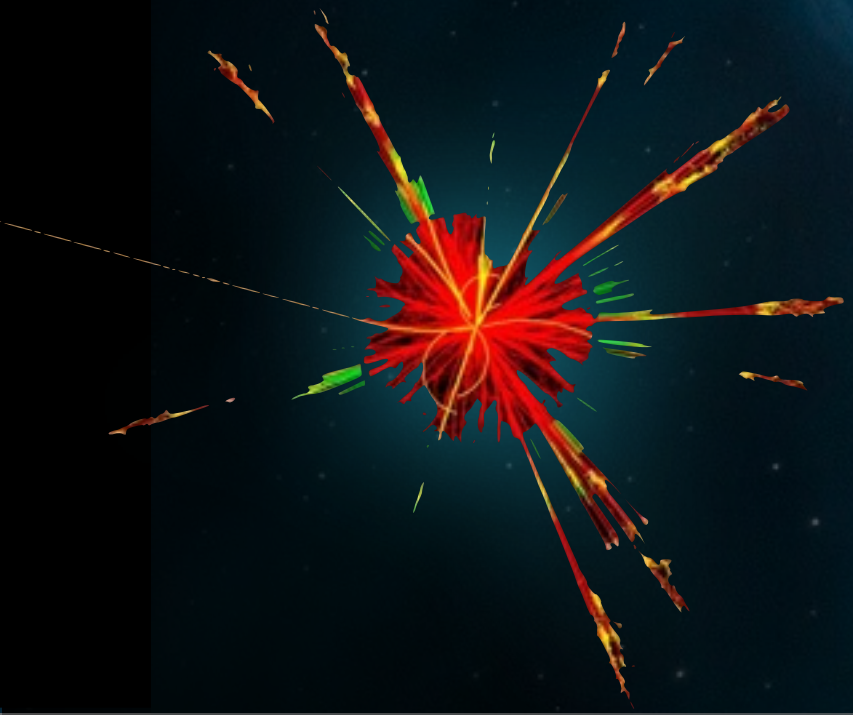
From Quarks to Haystacks

Plan: Start Here (Elementary Particles) End Here (Jets & more)



Dr. Peter Skands
School of Physics and Astronomy - Monash University
& ARC Centre of Excellence for Particle Physics at the Terascale

Why do Science?

Scientia potentia est - knowledge is power

Hobbes *Leviathan (1651)*

We can improve our lives with it

We can build new things with it

We can go further with it (even to the Moon!)

The Real Reasons:

Curiosity and **Fascination**

The Universe is vast, beautiful, and full of mysteries

+ I believe that science is a force for civilisation, without which ...

"no knowledge of the face of the earth; no account of time, no arts, no letters, no society, and, which is worst of all, continual fear and danger of violent death, and the life of man solitary, poor, nasty, brutish, and short."

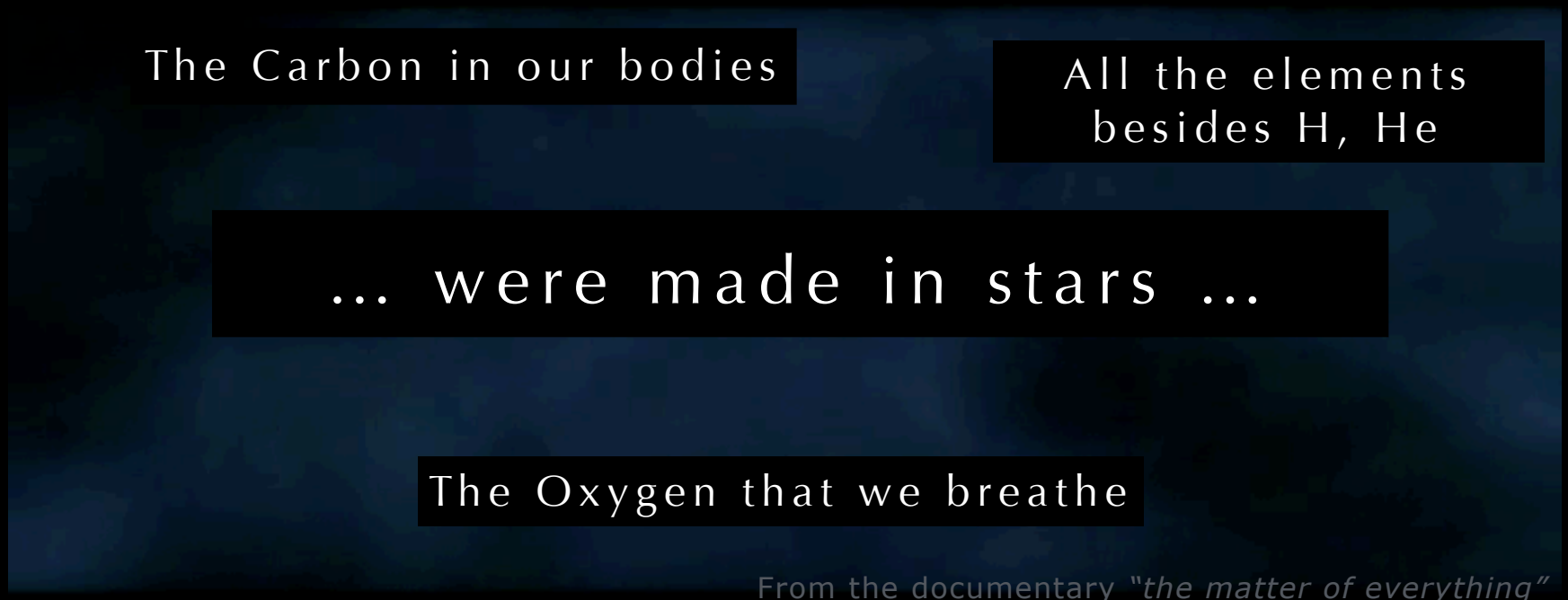
On mankind's state without civilisation; Hobbes *Leviathan (1651)*

Superstition ain't the way

S. Wonder; *Superstition (1974)*

If you want to be more philosophical

We are children of **stardust**



Nature is a fantastic **work of art**
It inspires us to think beyond ourselves

Who am I?

So I thought I wanted to be an **astronomer** …

Studied physics & astronomy at Copenhagen Uni (Denmark)
(Masters degree: 5 years)

Learned **Quantum Mechanics**
(and didn't understand it)

UNIVERSITY OF COPENHAGEN

➜ *Got interested in Particle Physics*
the study of matter and force at the most fundamental level

→ Lund University (Sweden):
Theoretical (high-energy) Physics
(PhD: 3 years; Graduated 2004)

Monte Carlo : computer simulations of the fundamental laws based on random numbers (chosen according to Q.M. probabilities)

Who am I?

After the PhD, you typically spend a number of years as a "post doc"
- preferably abroad at great centres of learning

→ Fermilab (Chicago)
(Theoretical Physics Dept.)

Became an expert on Monte Carlo simulations of **proton-antiproton** collisions at the Tevatron

(+ met my wife)

I had thought physics = books, maths, experiments, maybe computers …
It was a (nice) surprise that it turned out to mean traveling the globe, and meeting all kinds of interesting people, at the top of their profession

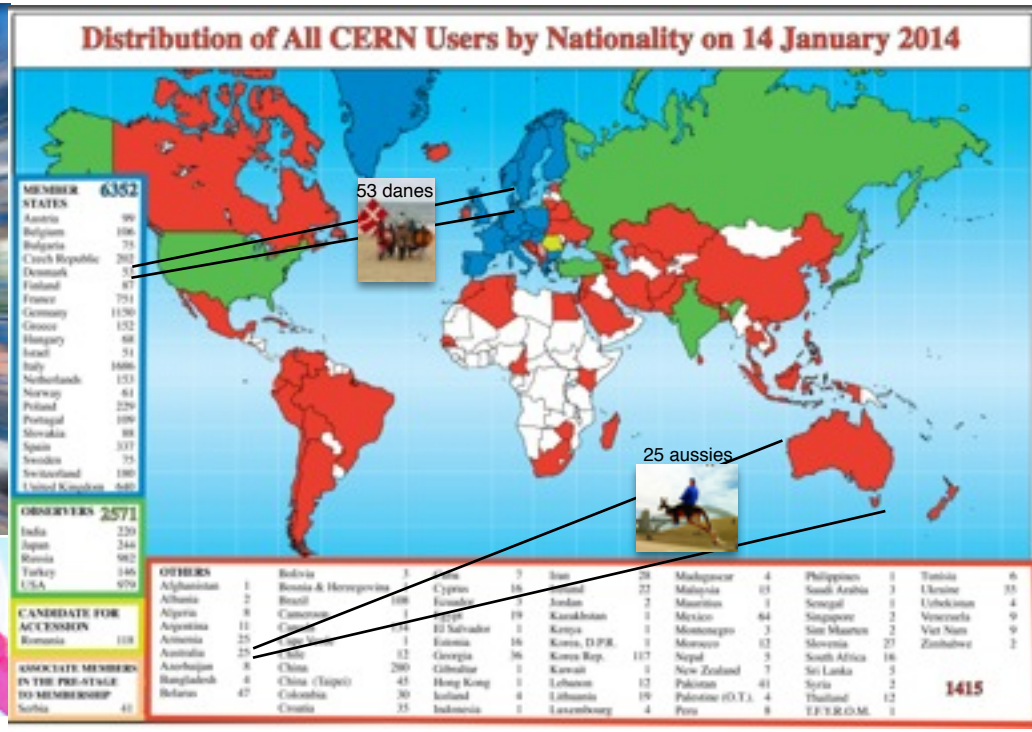
I was very happy at Fermilab. But after 5 years there, I got an offer I couldn't refuse

CERN: European Organization for Nuclear Research

20 European Member States and around 60 other countries

~ 10 000 scientists work at CERN

Flags of CERN's Member States



Founded in 1954; located in Geneva, Switzerland

Yearly budget ~ 1 billion CHF ~ 1.4 billion AUD

High Energy Physics

How do we see, in the quantum world?

To see something small, we scatter waves off it

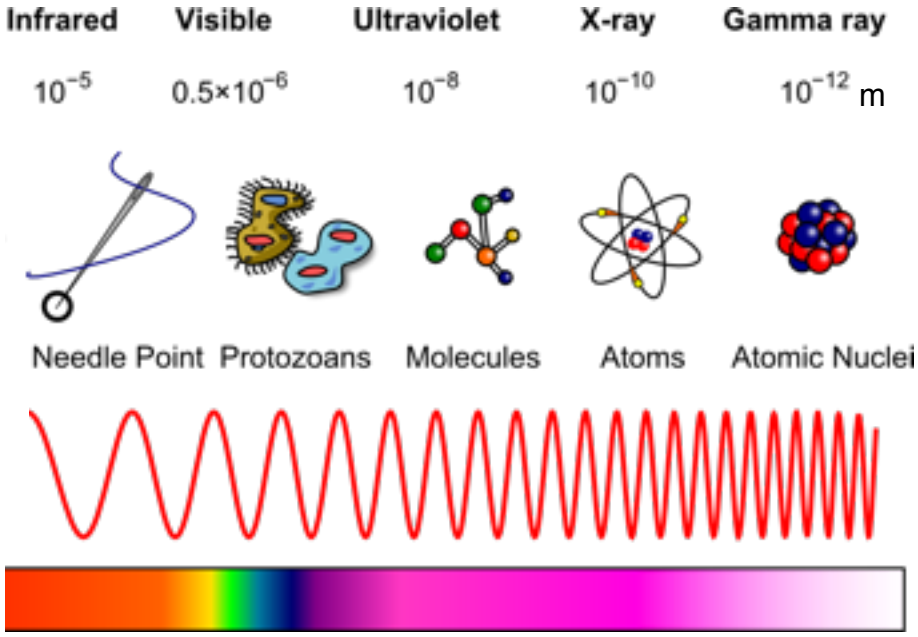
E: Energy

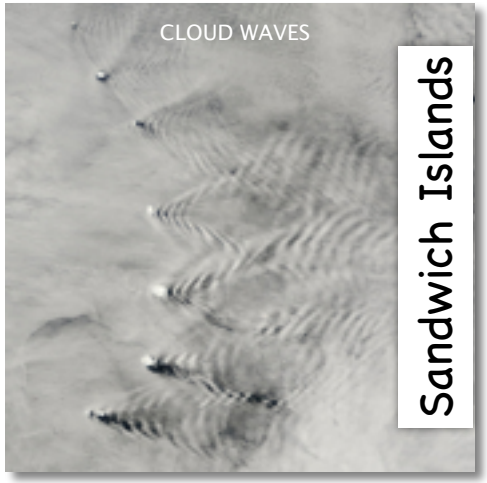
$$E = h\nu = hc / \lambda$$

"Planck-Einstein" relation

h: Planck's const
c: speed of light
ν: frequency
λ: wavelength

➜ Heisenberg's uncertainty principle.





NASA – MODIS

To resolve "a point", we would need infinitely short wavelengths

(Heisenberg would then give it an infinitely hard kick)

In the real world: kick as hard as we can → particle accelerators

So what is "High" Energy ?

Relative to combustion of 1 kg of octane molecules (gasoline) :

100m **Waterfall** : 0.000 025

Burning wood : 0.3

Burning sugar (metabolism) : 0.5

Burning ethanol or coal : 0.75

Burning Beryllium : 1.5

So what is "High" Energy ?

Relative to combustion of 1 kg of octane molecules (gasoline) :

100m **Waterfall** : 0.000 025

Burning wood : 0.3

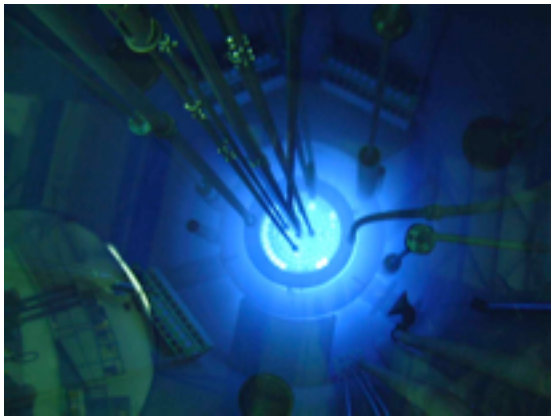
Burning sugar (metabolism) : 0.5

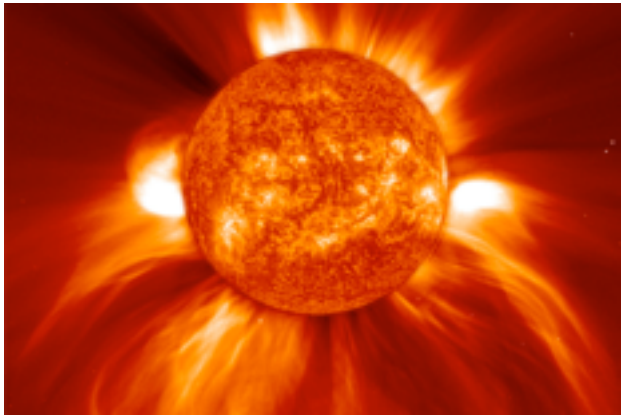
Burning ethanol or coal : 0.75

Burning Beryllium : 1.5

Uranium-235 **Fission** : 2 000 000

Deuterium-Tritium **Fusion** : 10 000 000





So what is "High" Energy ?

Relative to combustion of 1 kg of octane molecules (gasoline) :

100m **Waterfall** : 0.000 025

Burning wood : 0.3

Burning sugar (metabolism) : 0.5

Burning ethanol or coal : 0.75

Burning Beryllium : 1.5

Uranium-235 **Fission** : 2 000 000

Deuterium-Tritium **Fusion** : 10 000 000

Matter-Antimatter **Annihilation** : 2 000 000 000

So what is "High" Energy ?

Relative to combustion of 1 kg of octane molecules (gasoline) :

100m **Waterfall** : 0.000 025

Burning wood : 0.3

Burning sugar (metabolism) : 0.5

Burning ethanol or coal : 0.75

Burning Beryllium : 1.5

Uranium-235 **Fission** : 2 000 000

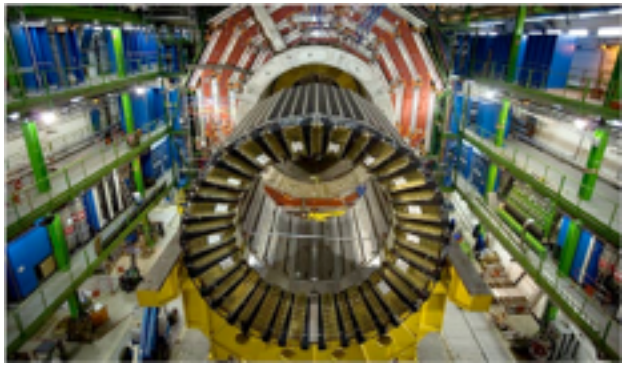
Deuterium-Tritium **Fusion** : 10 000 000

Matter-Antimatter **Annihilation** : 2 000 000 000

Tevatron collisions : 2 000 000 000 000

LHC collisions: 13 000 000 000 000 (in run 2)

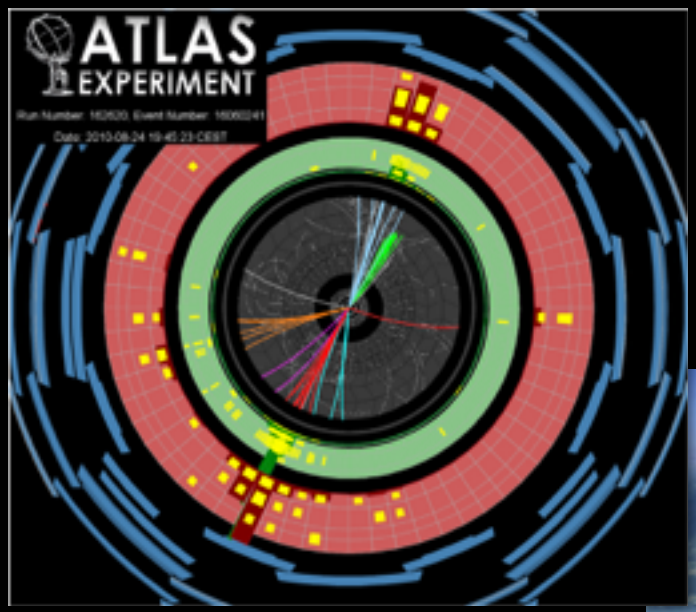
FCC collisions: 100 000 000 000 000



Still, Dan Brown exaggerated a bit in "Angels & Demons" …

"If all of the antimatter ever produced at Fermilab had been collected, we would have a couple of nanogrammes …" *Dave Vandermeulen, antimatter expert, Fermilab*

The Large Hadron Collider

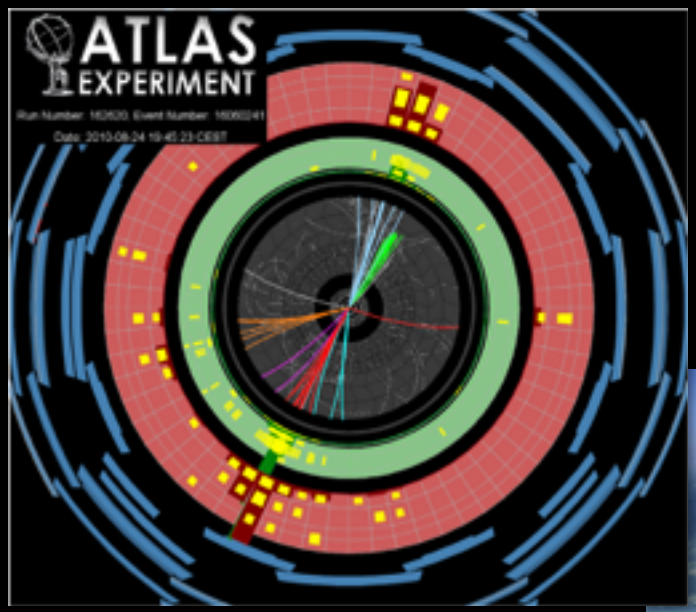


The LHC at CERN currently produces the highest energies we can create in lab conditions

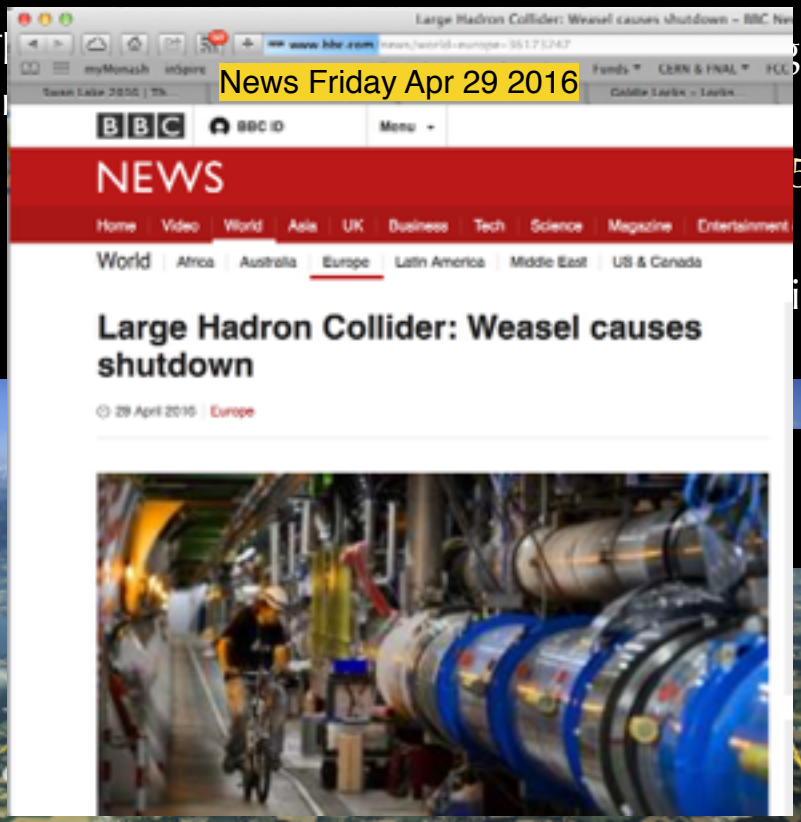
"Stable beams" for run 2: June 3rd, 2015

Collision Energy: 13 Tera-eV
(~ 1 million times higher than nuclear fusion)

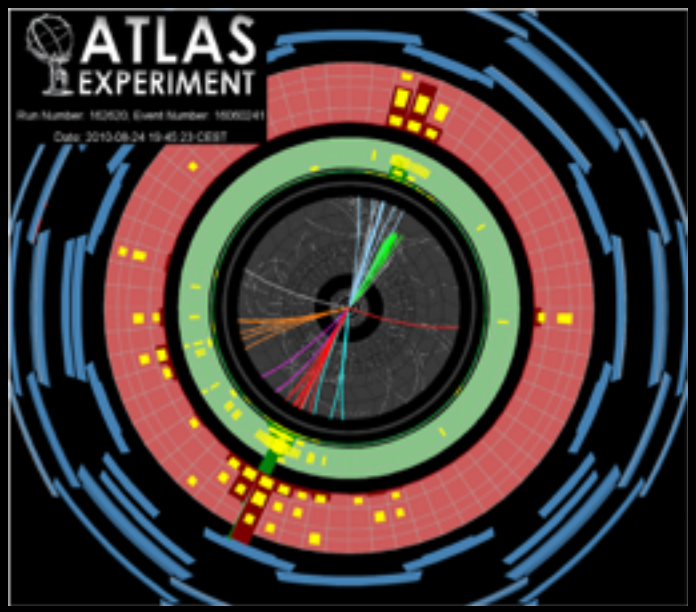
The Large Hadron Collider



T… …ghest
e… …5
…ion)



Experiment



What goes on at CERN?

LHC Collision from Run 1
7000 billion electron-Volts
ATLAS, March 2010

The ATLAS Experiment at the LHC

ATLAS collision event at 7 TeV from March 2010

http://atlas.ch

Colliding Protons

Combination of Q.M. + (special) Relativity: **Quantum Field Theory**

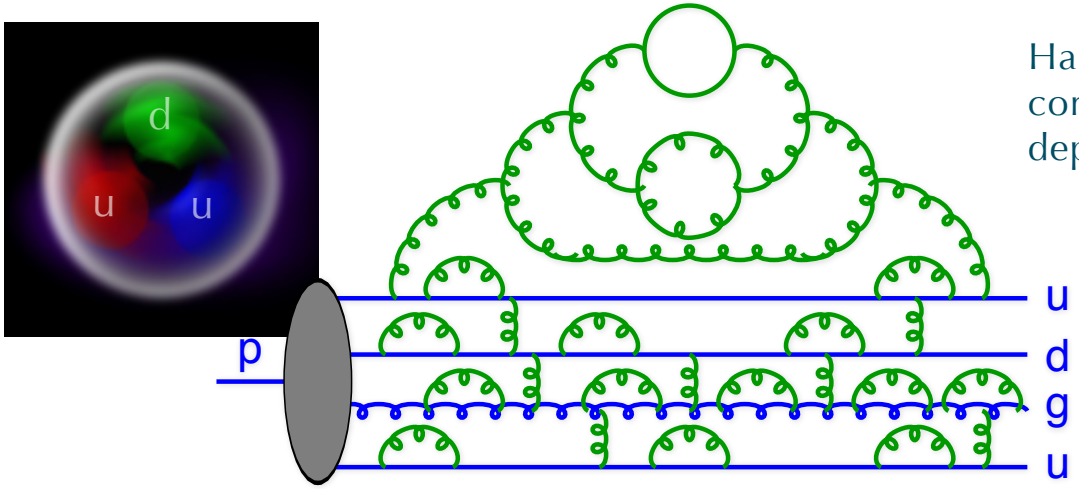
Quantum interactions can convert the kinetic energy of the beam particles into rest energy (mass) + momentum of outgoing particles

$$E = mc^2\sqrt{1 + p^2/(m^2c^2)}$$

E = energy
m = mass
p = momentum
c = speed of light

What are we really colliding?

Take a look at the quantum level



Hadrons are composite, with time-dependent structure

Colliding Protons

Combination of Q.M. + (special) Relativity: **Quantum Field Theory**

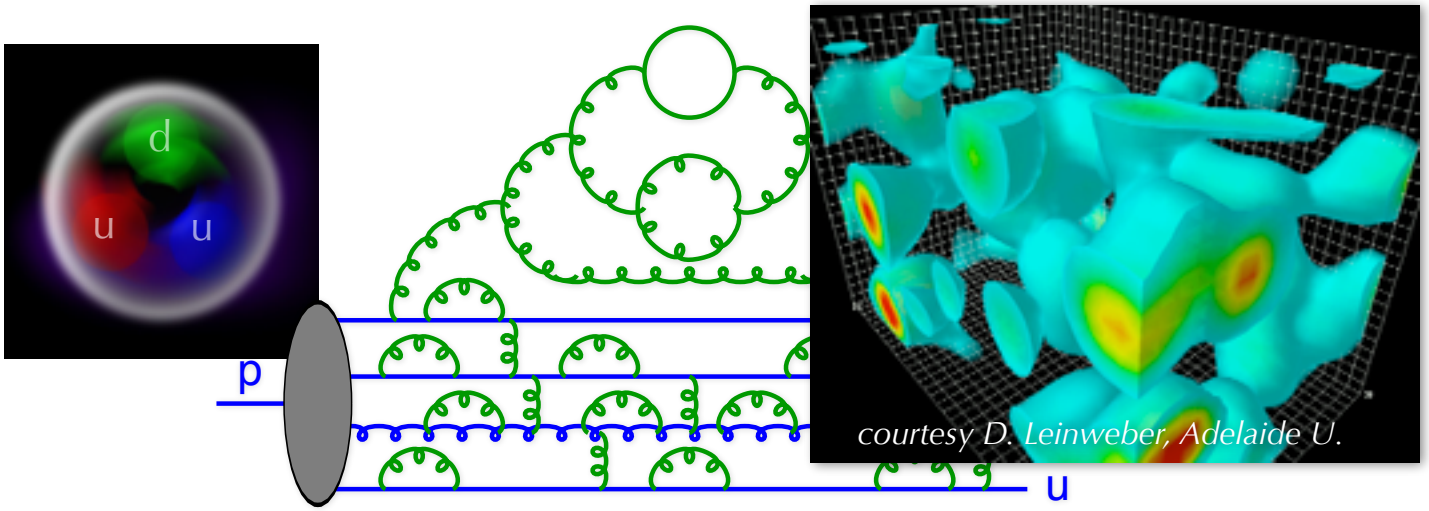
Quantum interactions can convert the kinetic energy of the beam particles into rest energy (mass) + momentum of outgoing particles

$$E = mc^2\sqrt{1 + p^2/(m^2c^2)}$$

E = energy
m = mass
p = momentum
c = speed of light

What are we really colliding?

Take a look at the quantum level



Such Stuff as Beams are Made Of

Lifetime of typical fluctuation ~ r_p/c (=time it takes light to cross a proton)

~ 10^{-23} s; Corresponds to a frequency of ~ 500 billion THz

To the LHC, that's slow! (reaches "shutter speeds" thousands of times faster)

Planck-Einstein: $E=h\nu$ ➜ ν_{LHC} = 13 TeV/h = 3.14 million billion THz

➜ Protons look "frozen" at moment of collision

But they have a lot more than just two "u" quarks and a "d" inside

Hard to calculate, so use statistics to parametrise the structure

Every so often I will pick a gluon, every so often a quark (antiquark)

Measured at previous colliders, as function of energy fraction

Then compute the probability for all possible quark and gluon reactions and compare with experiments …

→ Fundamental Science

July 4th 2012:

"Higgs-like" particle seen at CERN

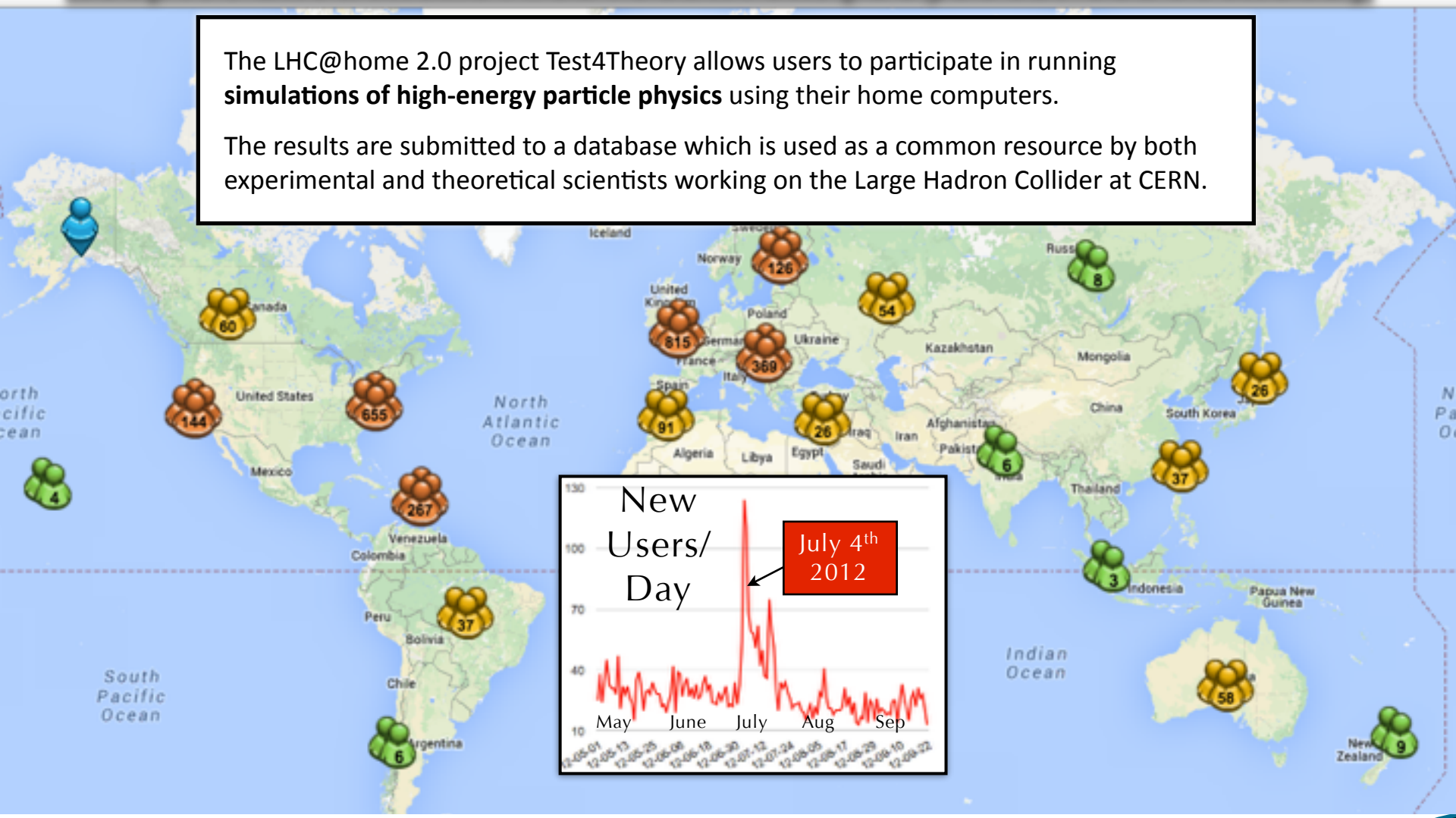
(+ over 1500 other published physics papers from LHC so far)

Excitement Everywhere (LHC@home)

http://lhcathome.web.cern.ch/projects/test4theory

The LHC@home 2.0 project Test4Theory allows users to participate in running **simulations of high-energy particle physics** using their home computers.

The results are submitted to a database which is used as a common resource by both experimental and theoretical scientists working on the Large Hadron Collider at CERN.



What is "Mass"?

Consider a 'field' distributed evenly across the Universe, of uniform strength (doesn't point in any direction: a 'scalar' field)

Suppose that different particles experience this 'field' as being more or less transparent

To a photon (light), the field is completely "translucent"

But an electron (or a proton), will interact with it

Suppose that this field **condenses** around the particles which couple to it, causing an increased energy density around those particles. **Looks like mass** ($E=mc^2$).

We call this field the "H" (or Brout-Englert-Higgs) Field

If correct, it should be possible to create waves in the Higgs field itself (though that may require a lot of energy)

The Higgs Particle

So the Higgs mechanism made **one spectacular prediction**:
it should be possible to excite a wave in the Higgs field itself

Made out of pure 'Higgs' stuff, in particle form this wave is known as the **'Higgs particle'** or 'Higgs boson'

This particle would quickly dissolve (decay) into other particles, but should be detectable via its decay products

The discovery of a particle consistent with these properties was announced at CERN on July 4, 2012

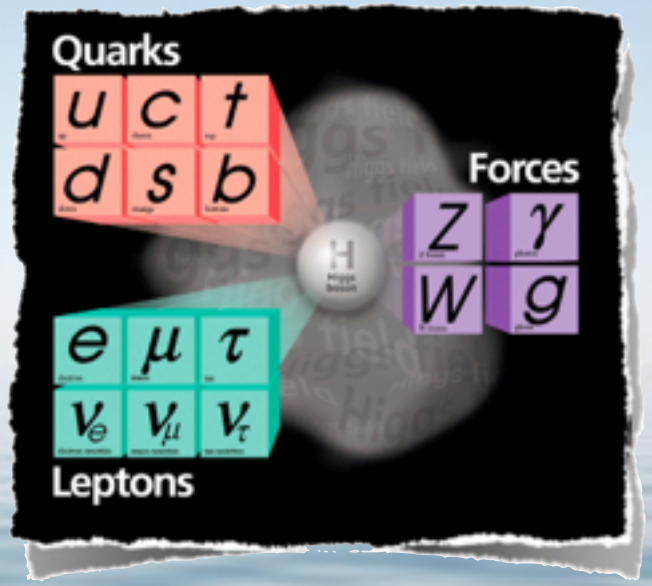
The coming years will see a huge activity trying to determine all the quantum properties of this new "H particle"

So far, no **major** deviations from Standard-Model predictions

➜ intense, high-precision studies required to reveal more …

the Last Piece of the puzzle?

Atoms
Neutrinos
Exotic matter
Antimatter



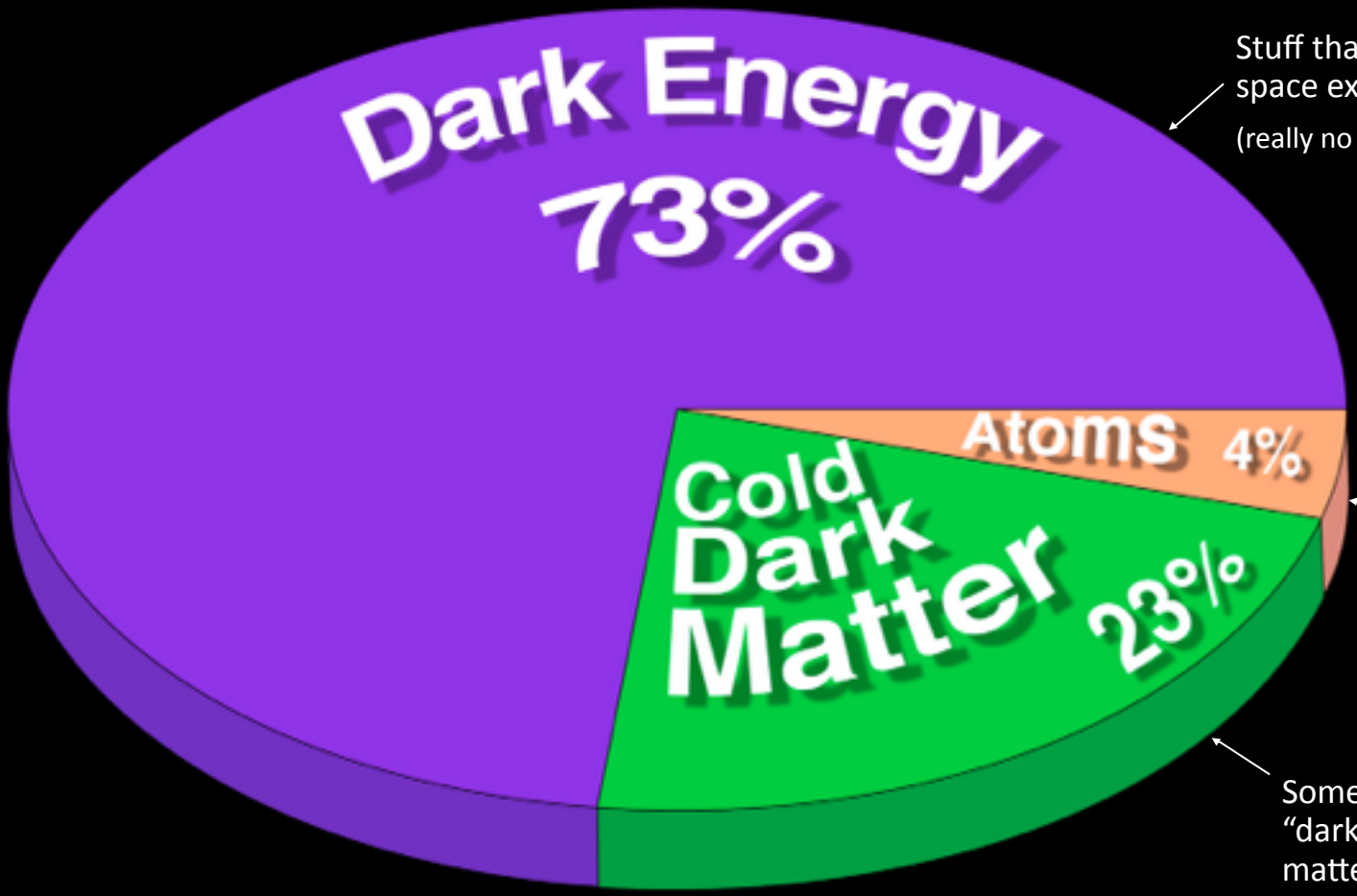
Electromagnetism
The nuclear forces
+ Gravity (Einstein)

+ Mass (Higgs)

Or is there something beyond?

Dark Matter, Higgs Origins, Grand Unification, Extra Dimensions, Quantum Gravity …

The Dark side of the Universe



Hopefully you have / will get another speaker on these exciting topics

Rates and Triggers

We get ~ 40 million collisions / sec.

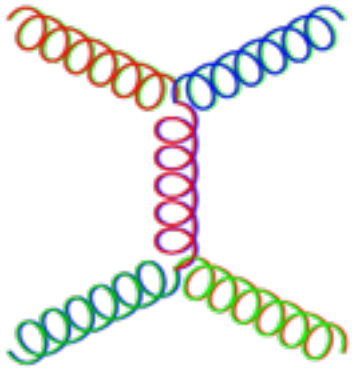
We can save ~ 100 / sec to disk.

WHICH ONES?

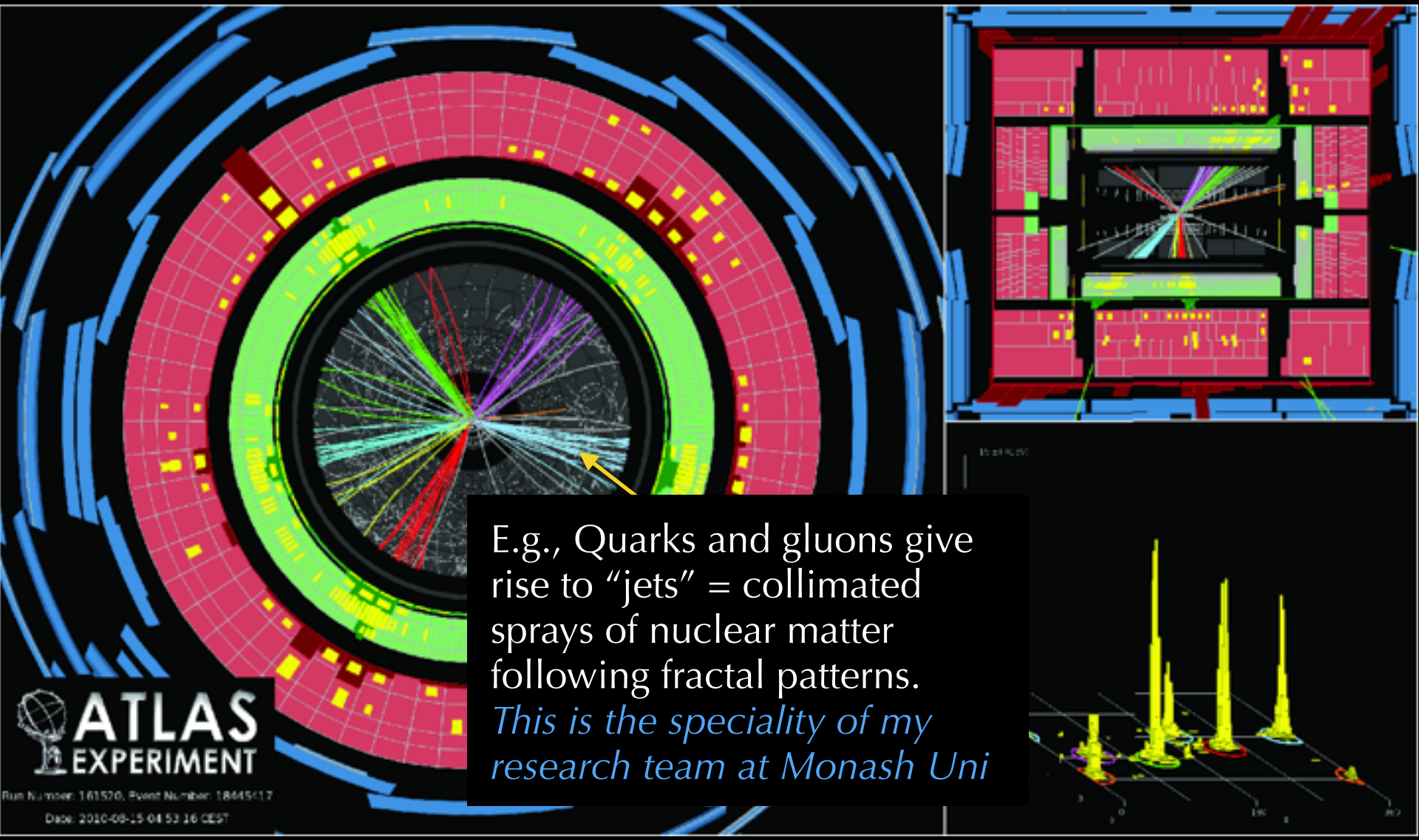
Automated "trigger" systems decide which collisions may be interesting

Not all reactions are created equally

- The most likely collision type is gg → gg
- The top quark is the heaviest elementary particle
  - Discovered in 1995 by Fermilab's Tevatron accelerator.
  - The LHC can make ~ 1 top quark / second.
- The reaction gg → Higgs will happen ~ 1 / minute
  - We don't want to loose too many of them …



+ Complications: *Bremsstrahlung radiation, confinement (quarks/gluons→**hadrons**), probabilities, …*



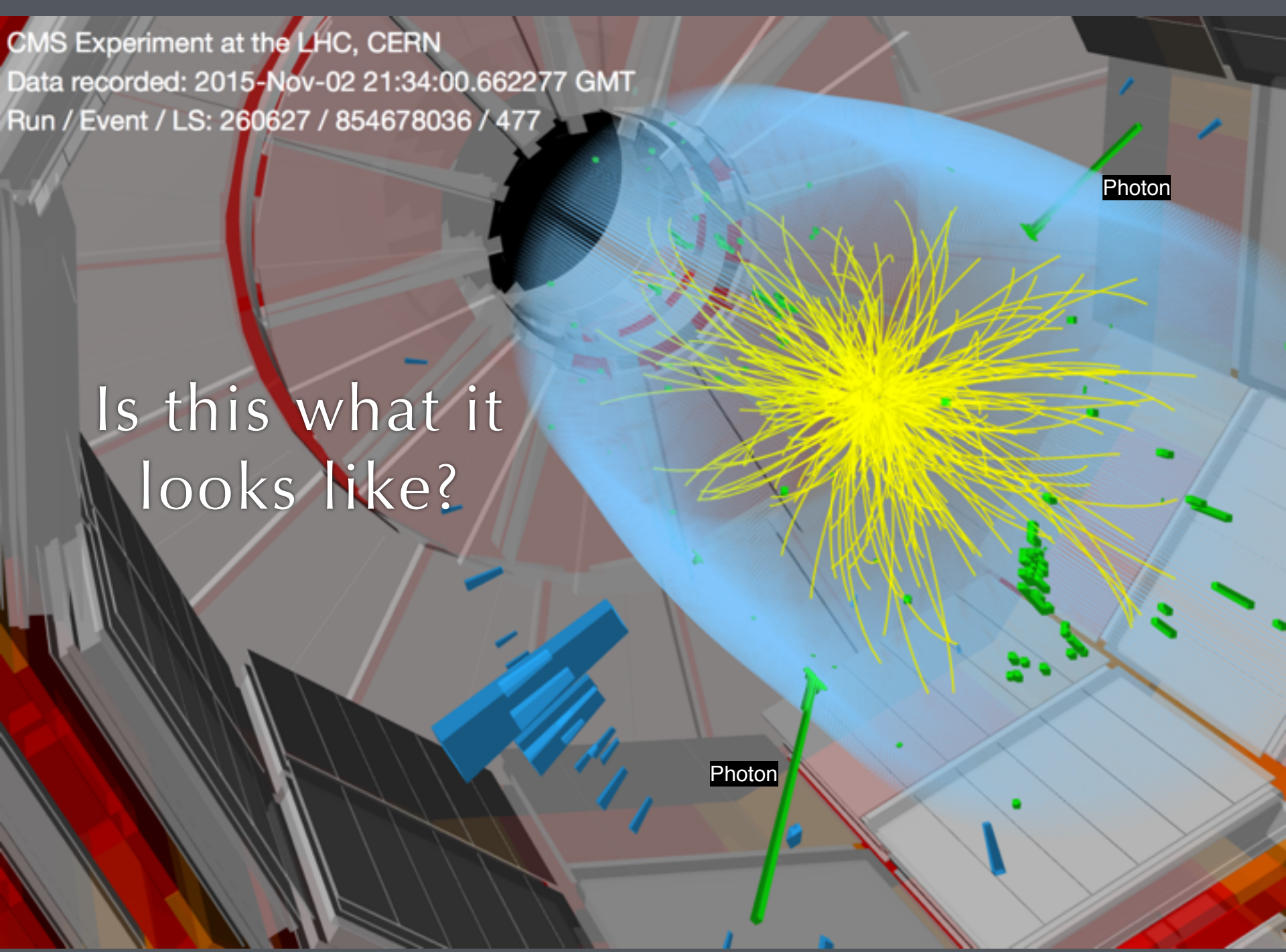
E.g., Quarks and gluons give rise to "jets" = collimated sprays of nuclear matter following fractal patterns.
This is the speciality of my research team at Monash Uni

The basic law of quantum mechanics: anything that ***can*** happen ***will*** happen

We found one needle

Are there more?

And what are they going to **look like?**



Is this what it looks like?

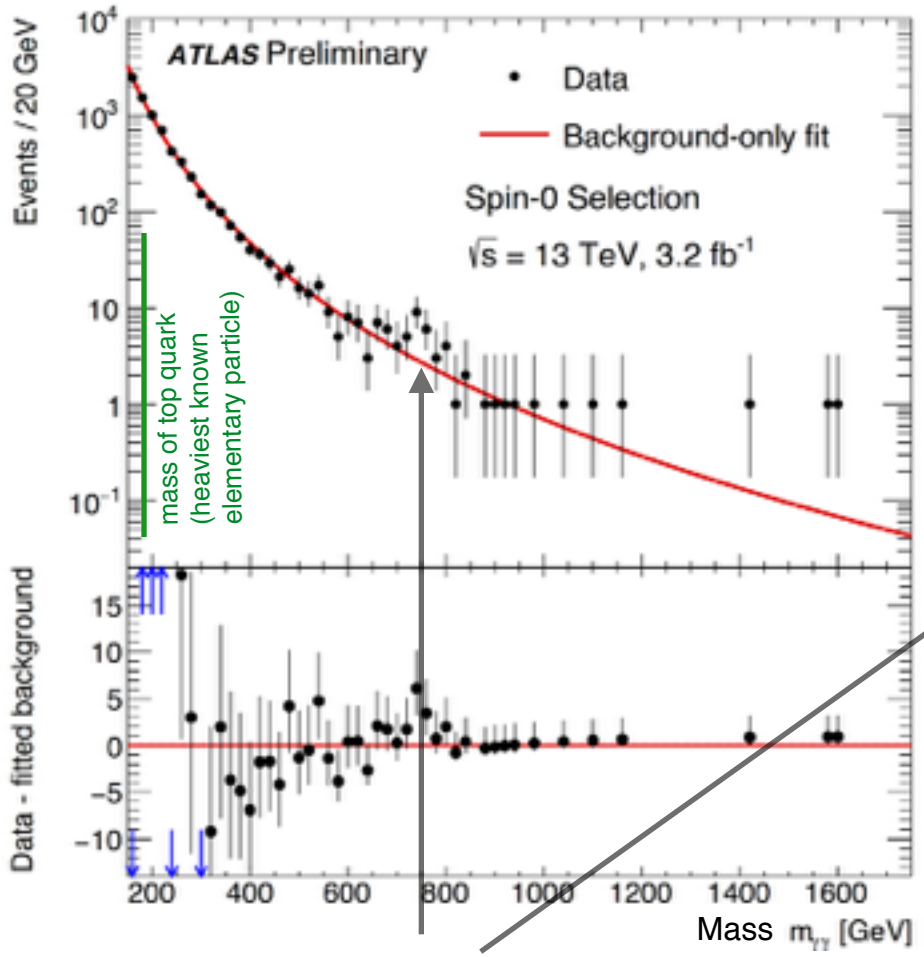
Moriond Conference,
February 2016
ATLAS Results

Bump Hunting / "ambulance chasing"

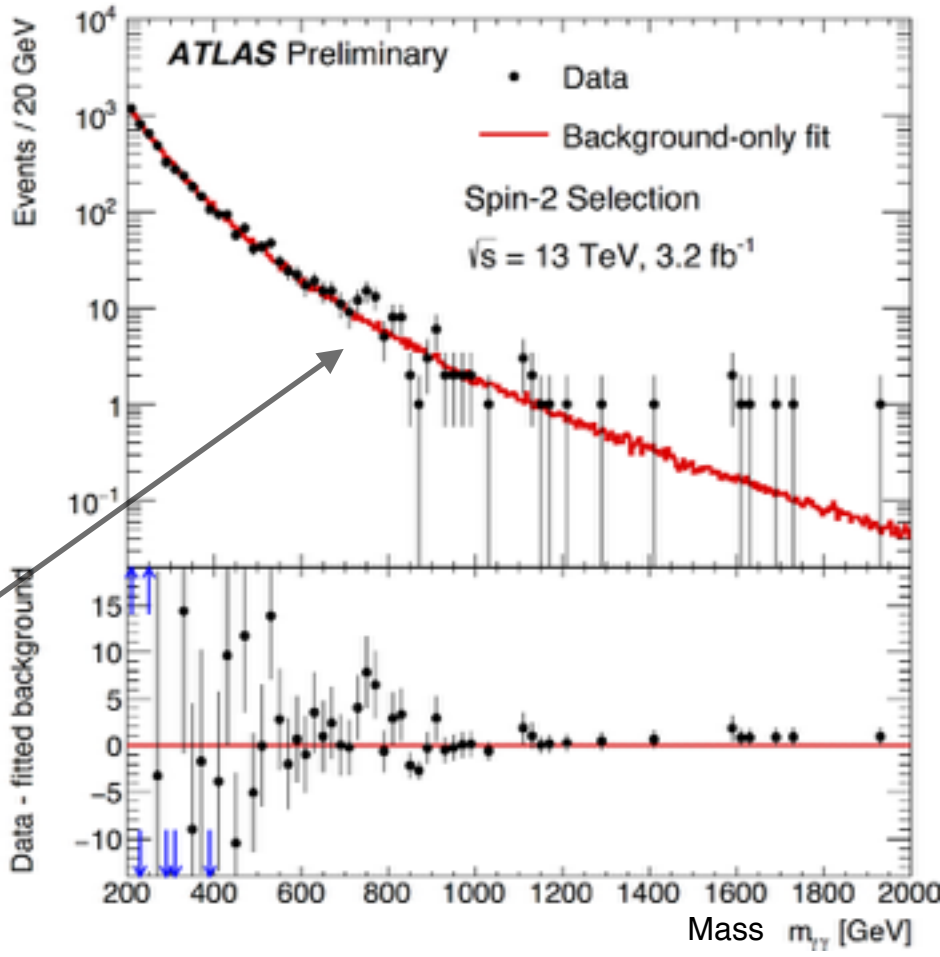
Update on the "diphoton" anomaly

SPIN-0 ANALYSIS ← Two different analyses of "two-photon" events → **SPIN-2 ANALYSIS**

background-only fit



background-only fit



Are these bumps real ???

Mass > 4 times higher than any known particle

Expect more news this summer (winter); (if the weasels allow)