RMIT UNIVERSITY

New Scientist live

Mysteries of matter: What the LHC will discover next

with

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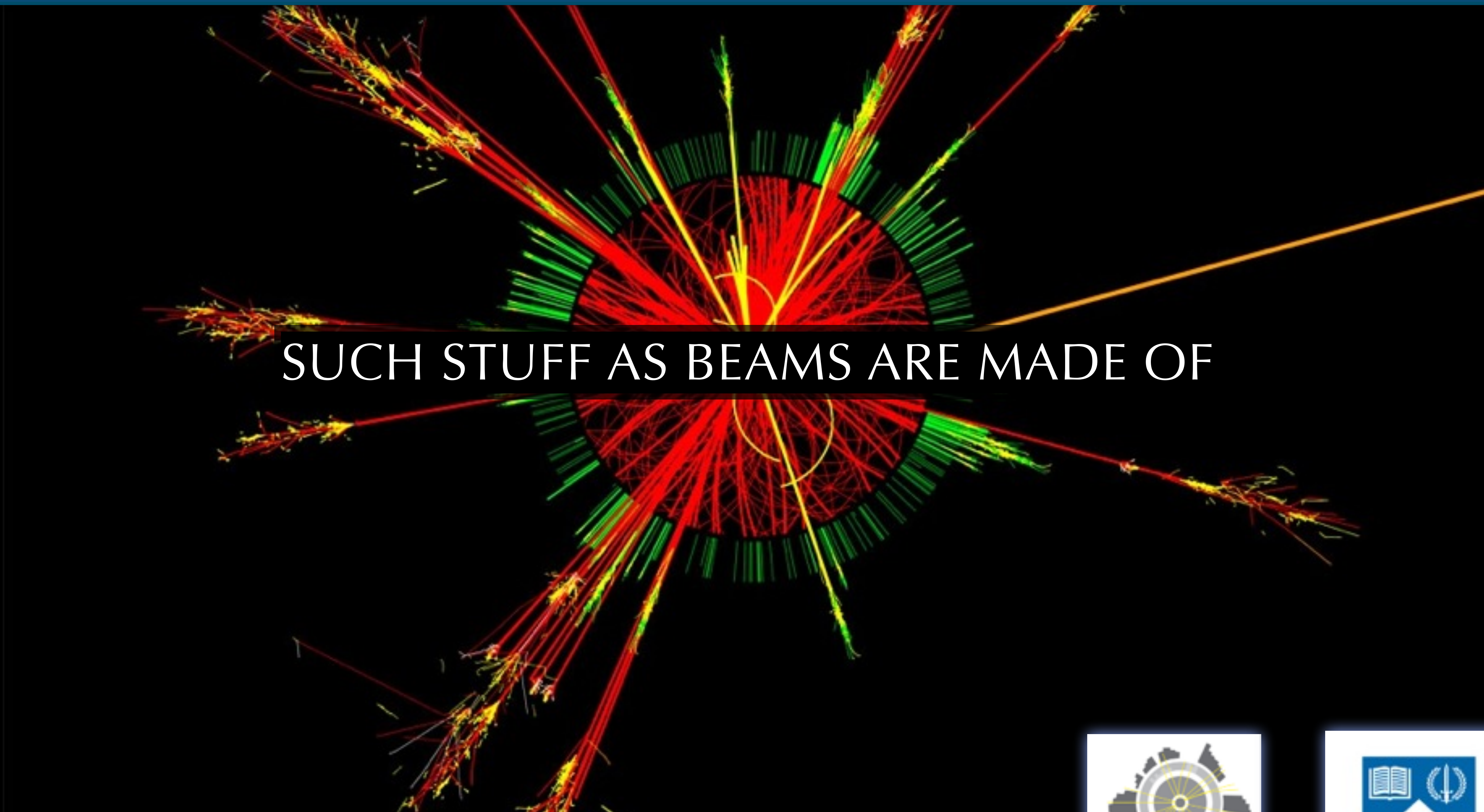
Raymond Volkas, University of Melbourne

#NSLive

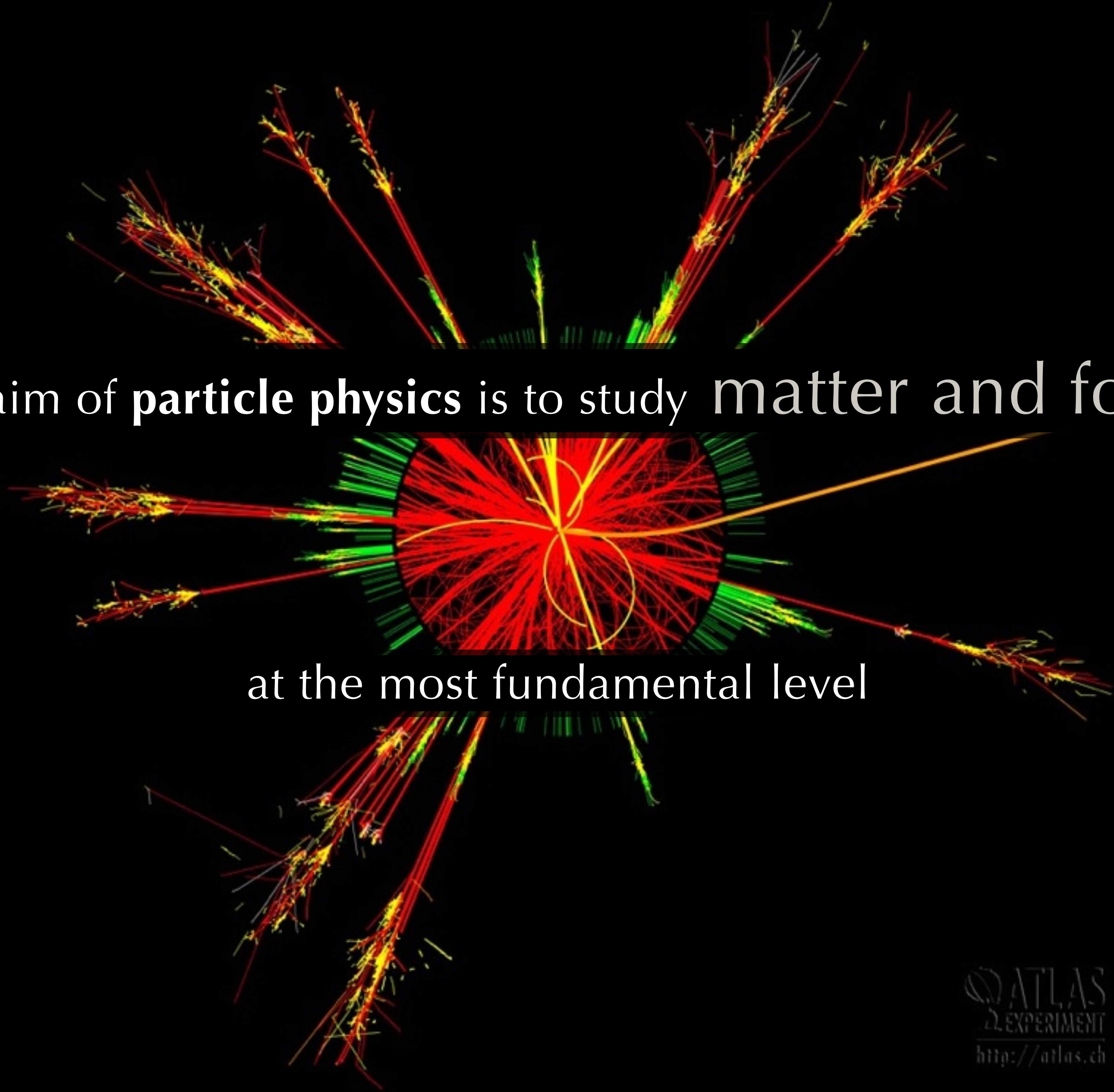
What's Next for the LHC?

Dr. Peter Skands, Monash U & ARC Centre of Excellence for physics at the Terascale



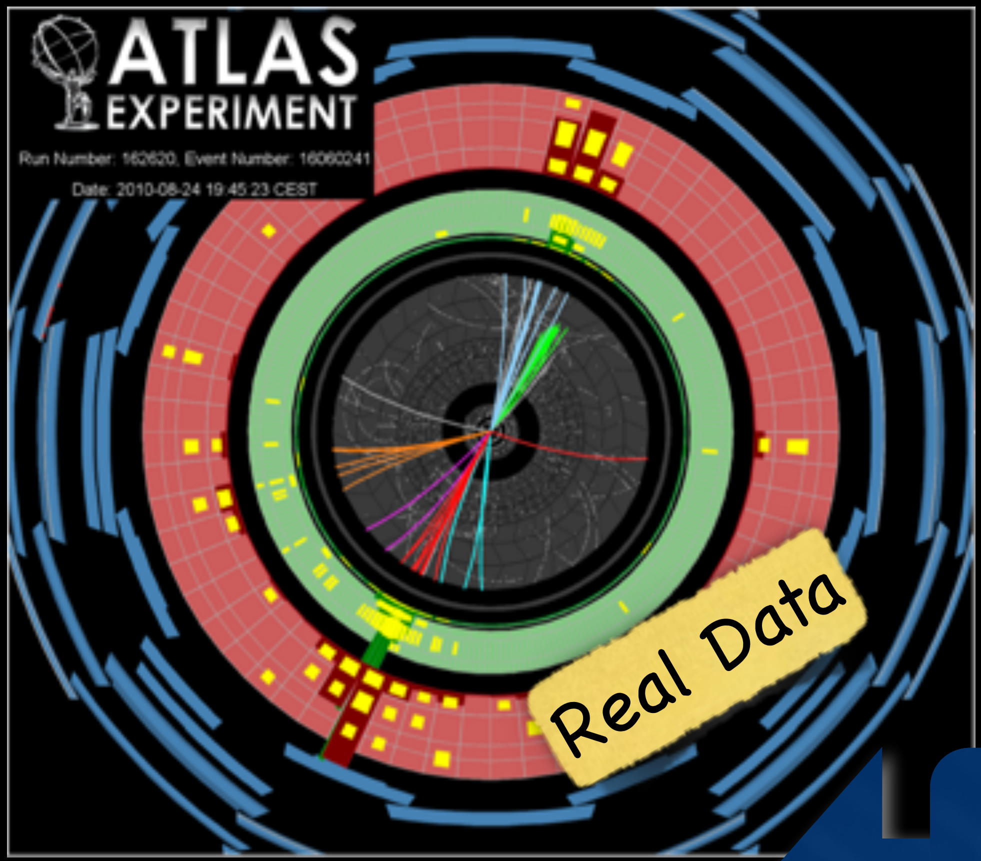
New Scientist Live
Melbourne, August 18, 2015

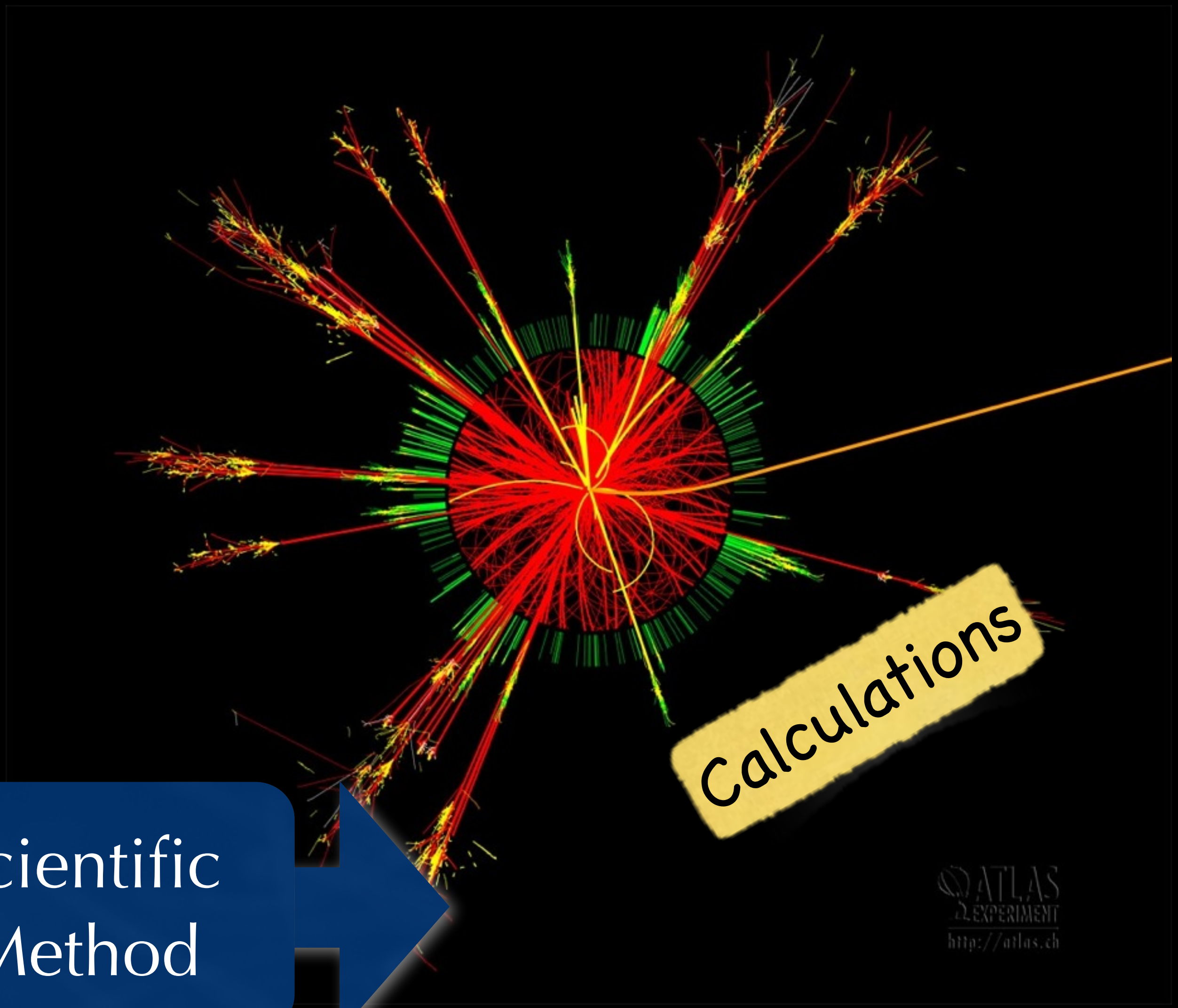
The aim of **particle physics** is to study matter and force



at the most fundamental level

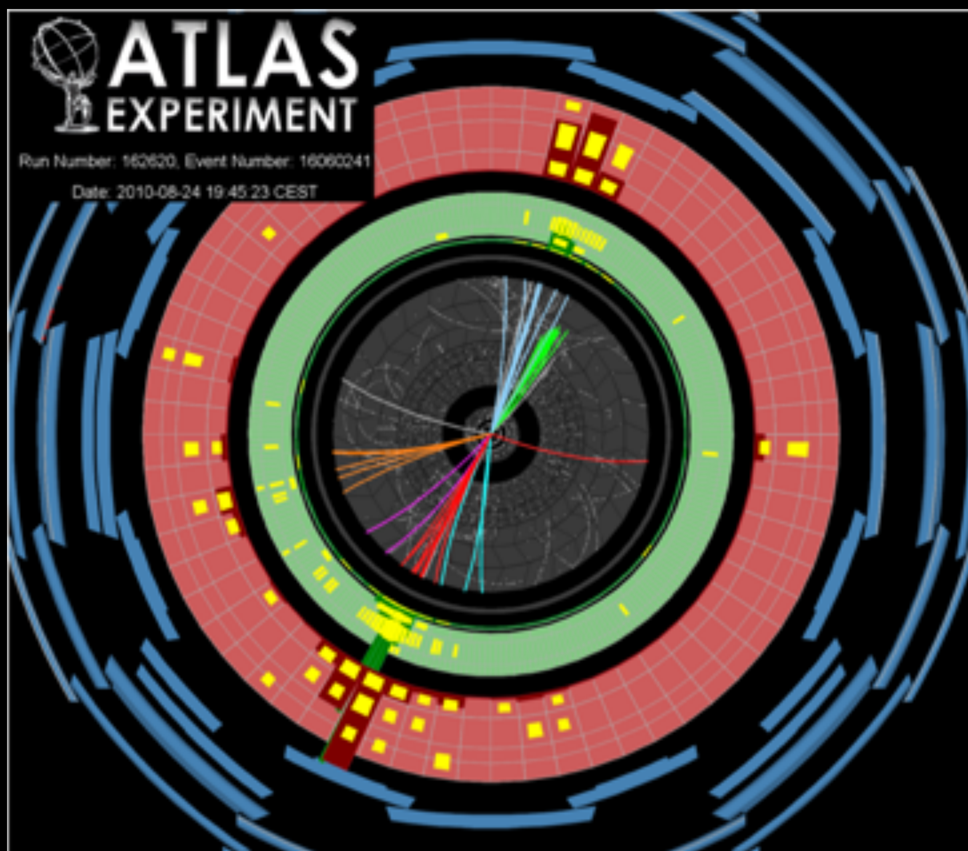
Theory vs Experiment





Scientific Method

The Large Hadron Collider

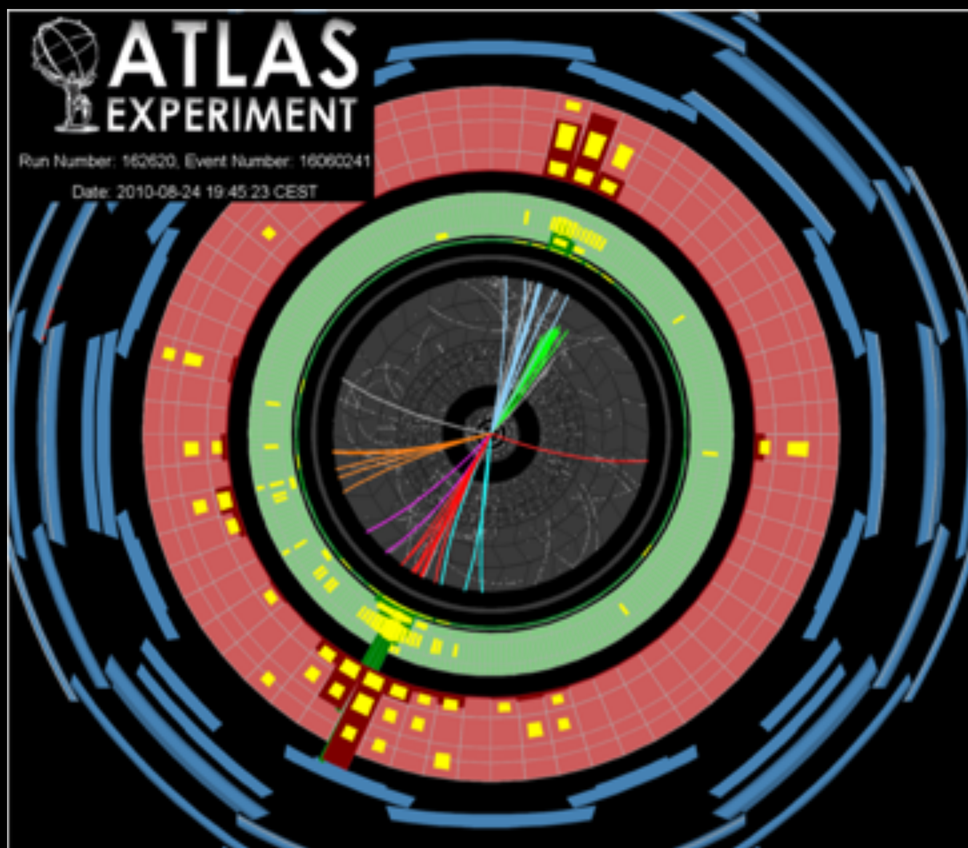


The LHC at CERN currently produces the highest energies we can create in lab conditions

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

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

Experiment



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

Many from One (well … from Two, really)

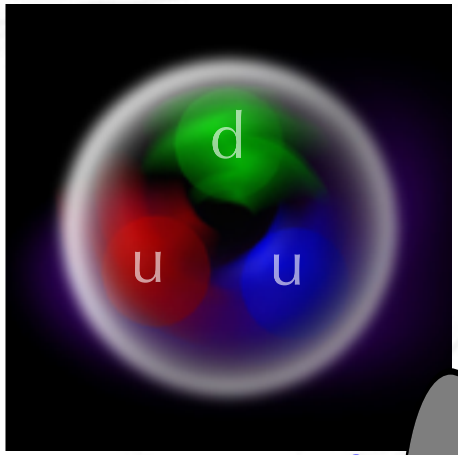
Quantum processes can convert the kinetic energy of the beam particles into rest energy (mass) + momentum of outgoing particles

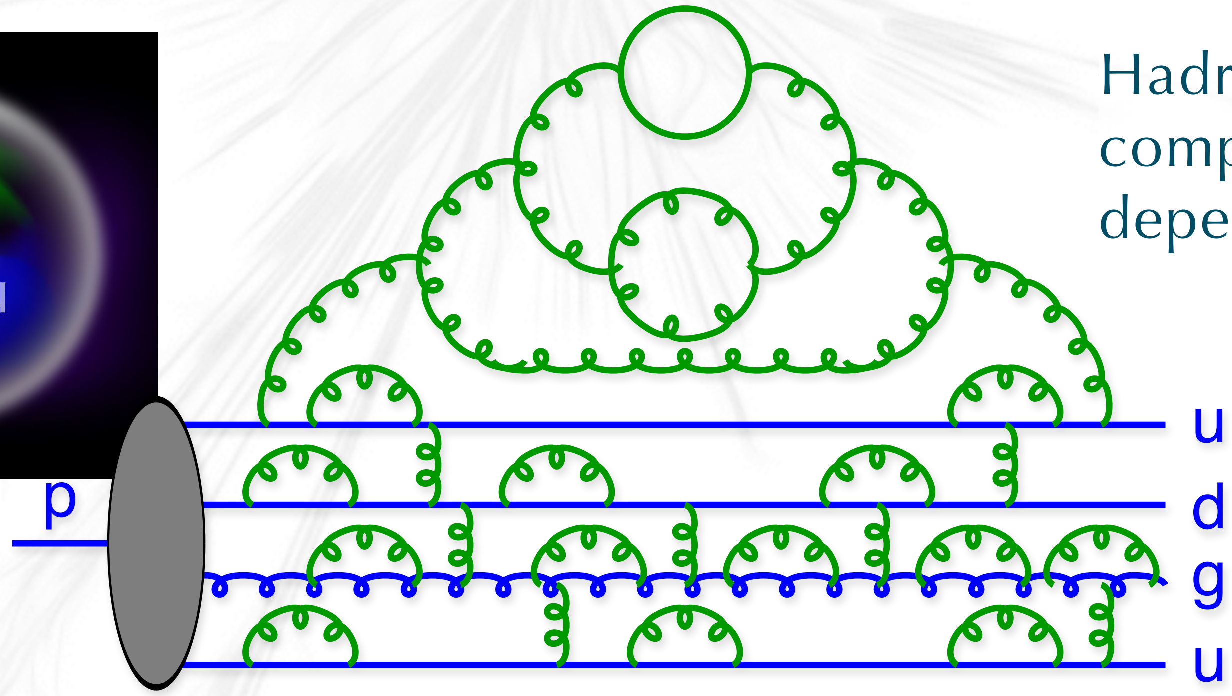
$$E = mc^2\sqrt{1 + p^2/(m^2c^2)}$$

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

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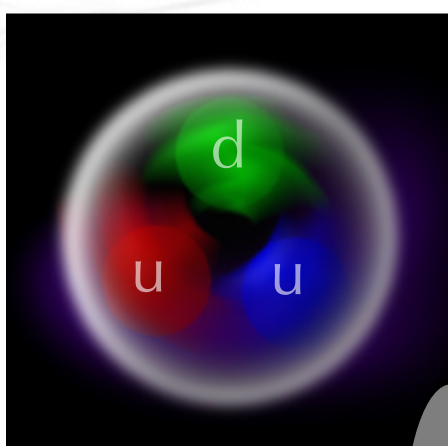
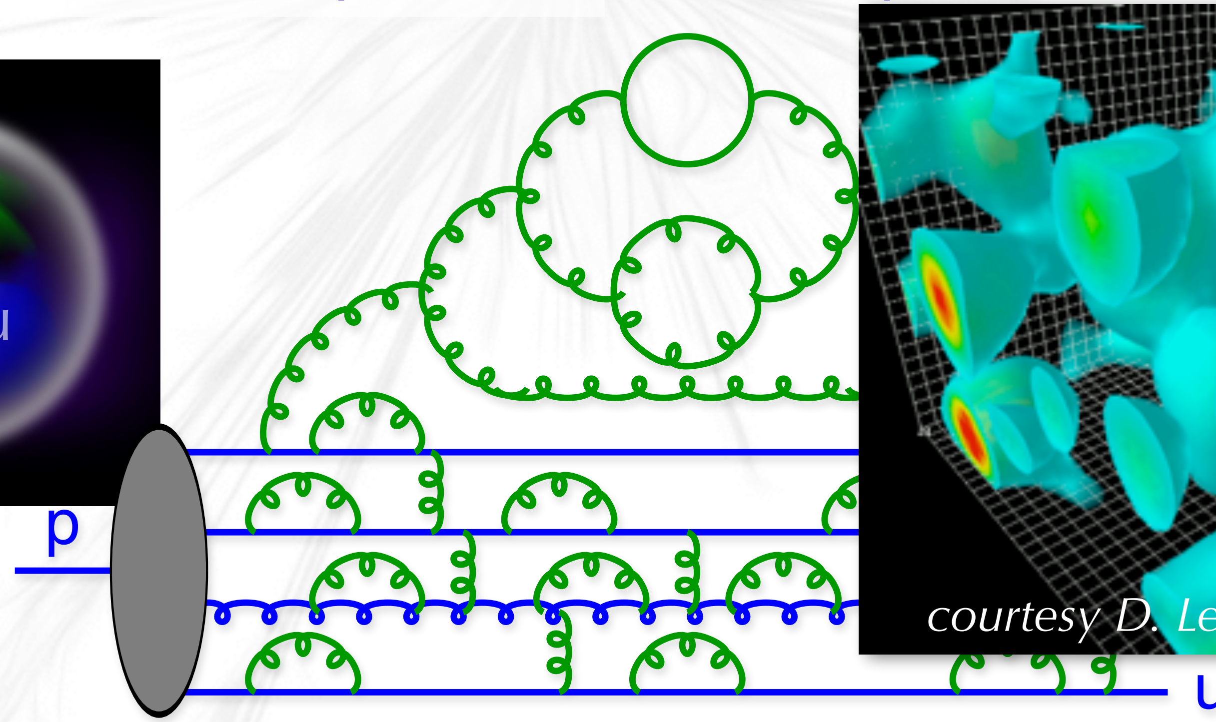
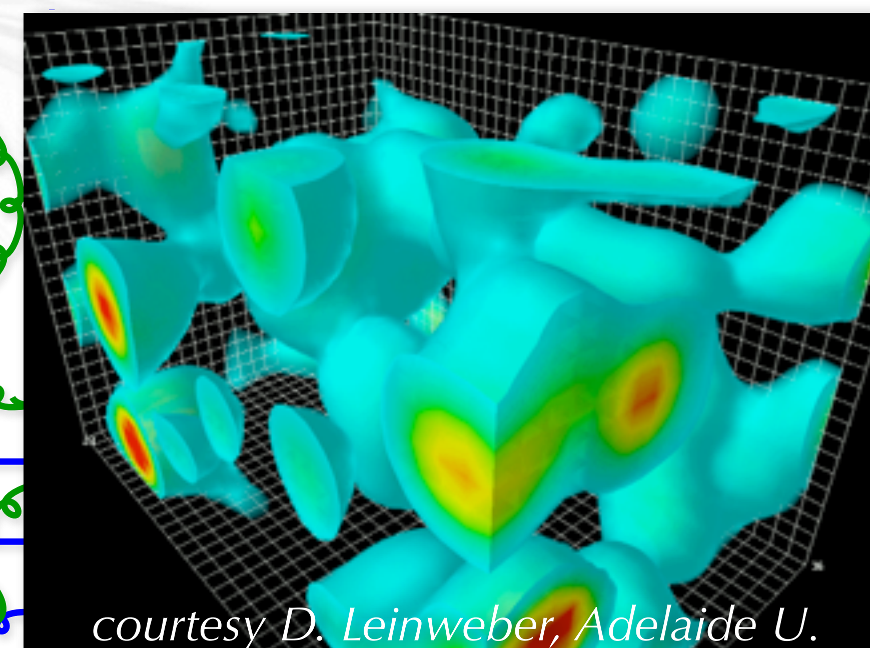






courtesy D. Leinweber, Adelaide U.

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 …

Rates and Triggers

We get ~ 40 million collisions / sec.

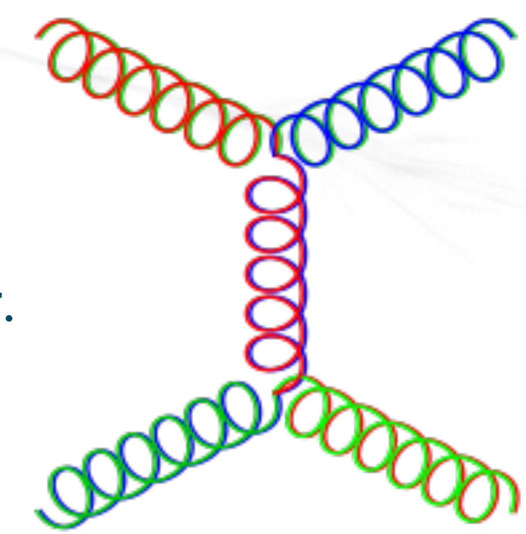
We can save ~ 100 / sec to disk.

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 …



Easy to collect millions of events of “high-cross-section-physics”

➜ Test models of “known physics” to high precision

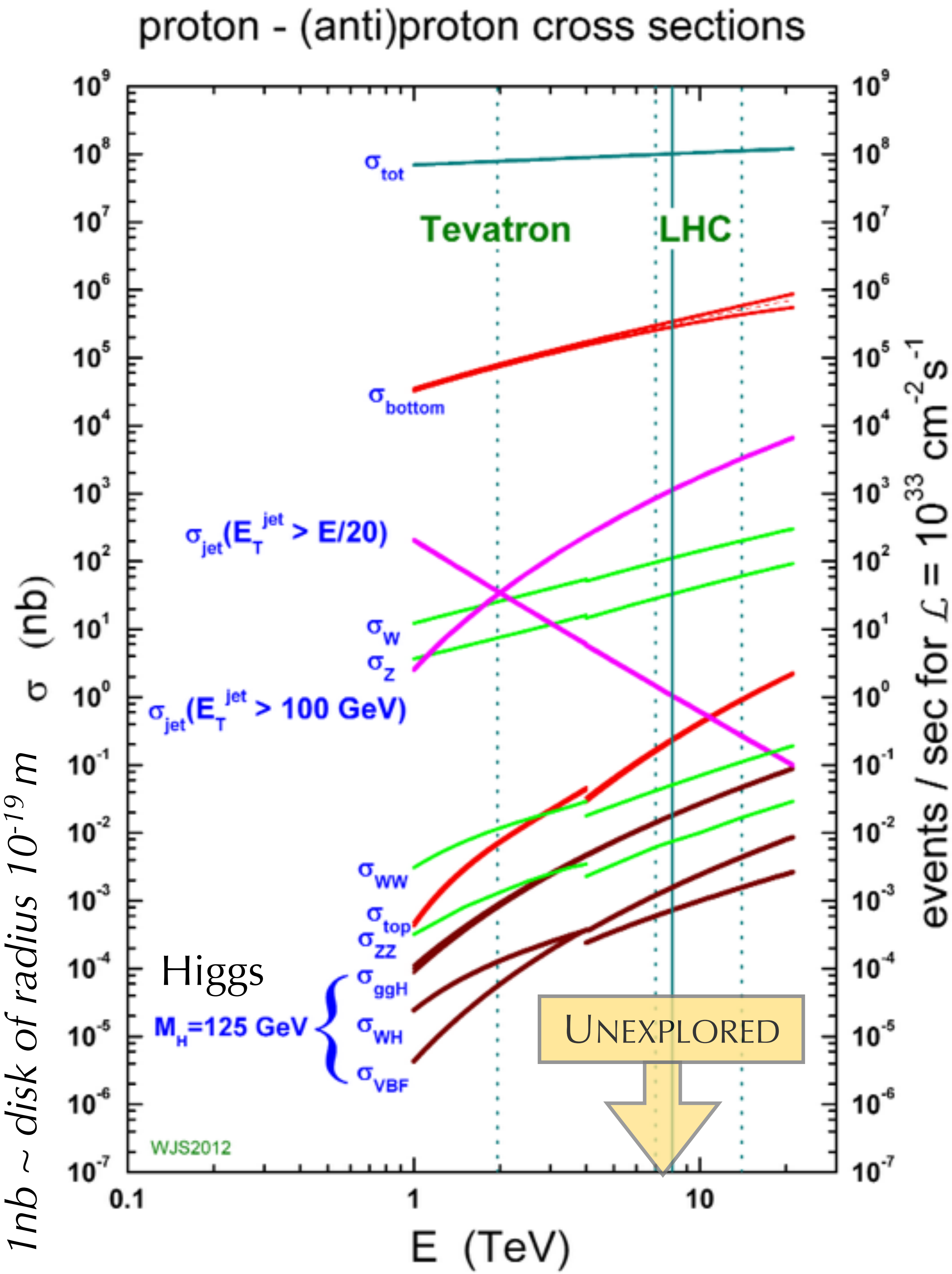
Triggers target the ***needles in the haystack***

Trigger on signatures of decays of heavy particles, violent reactions

“Photons” “Leptons”

“Missing Energy” “Jets”

Effective (quantum) area; 1nb ~ disk of radius 10^{-19} m



Precision

Precision & **Discovery** go hand in hand

quantum structure

E.g., after the Higgs disovery, now comes ***precision study***

Recognise the unknown: understand the known

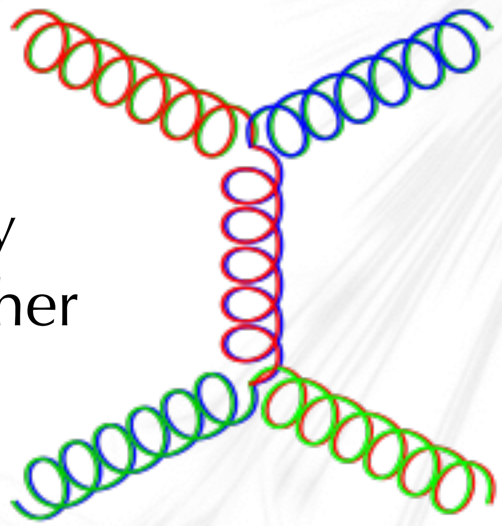
Calibrate your methods, test your strategies, …

& occasionally discover that you didn't understand "the known" …

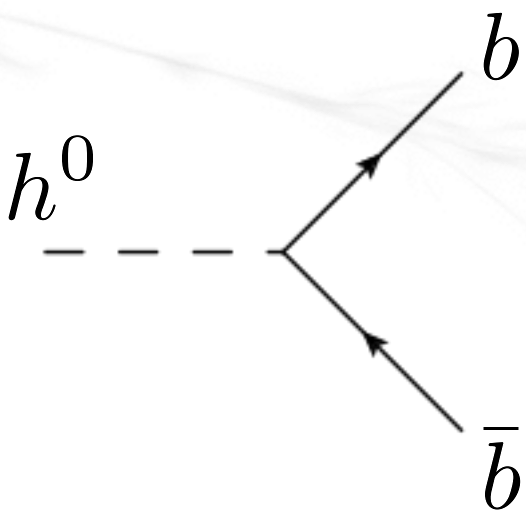
My team specialises in the modelling of "jets"

Sprays of nuclear matter, produced by energetic quarks and gluons

Such as when they scatter off each other



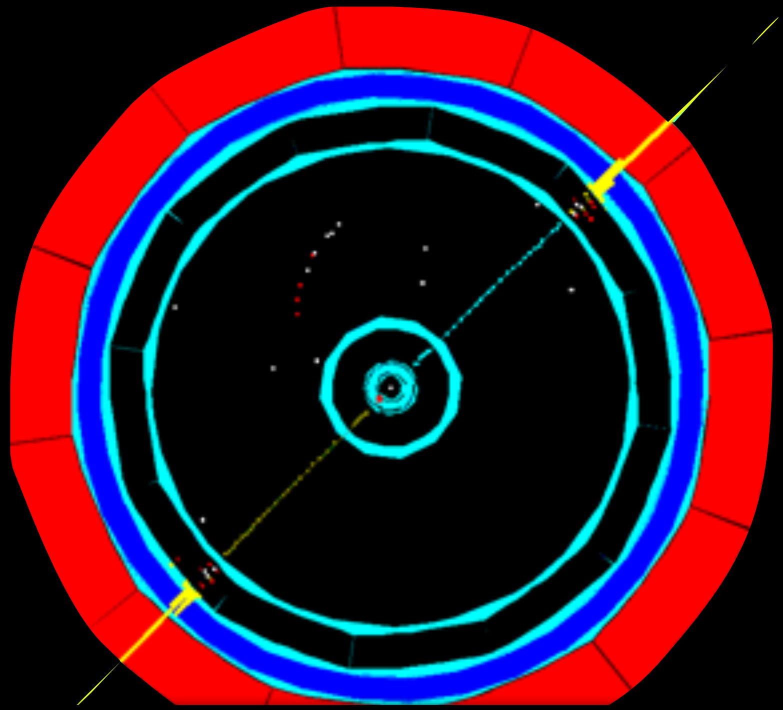
Or when a heavy particle decays to quarks / gluons

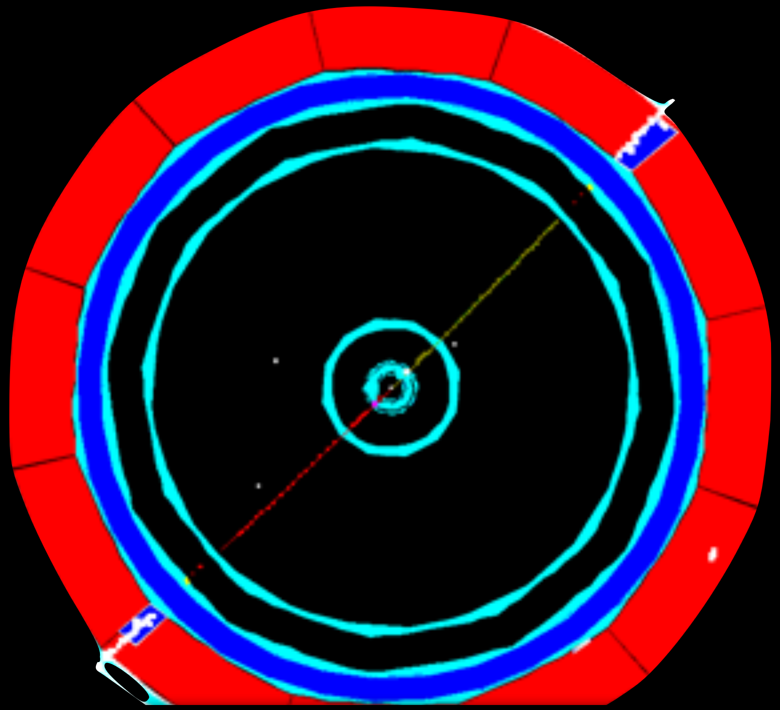


Example: Decays of the Z boson

Leptons

electron-
positron
pair creation



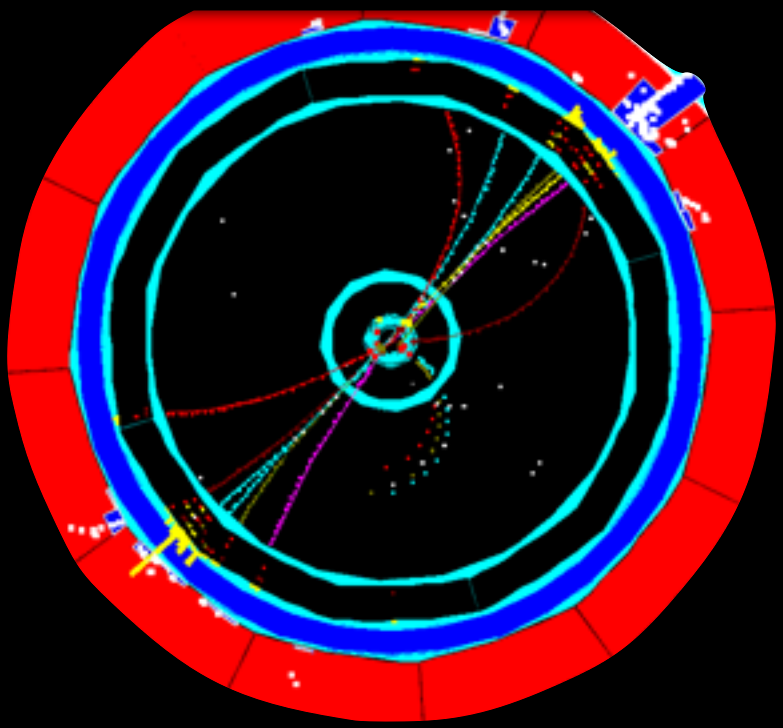


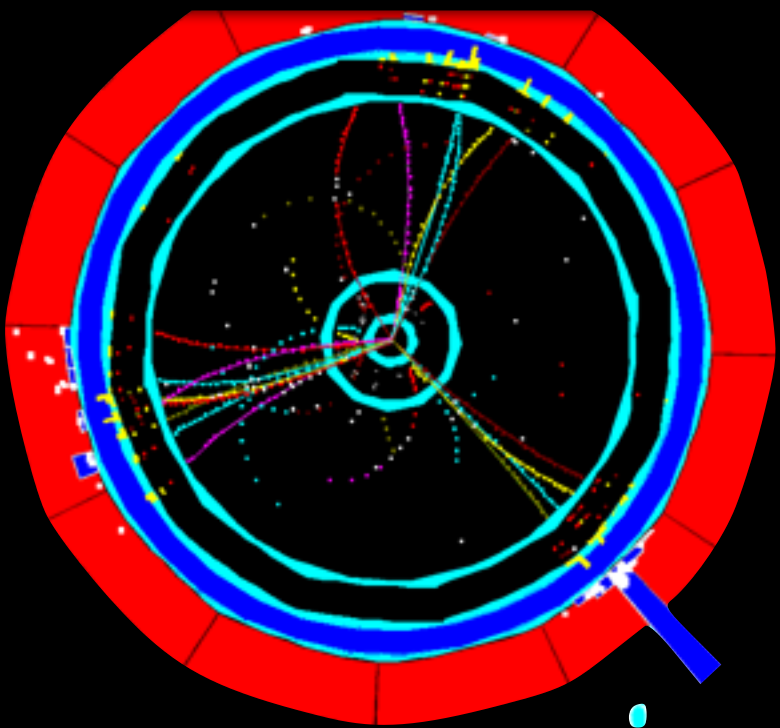
muon-
antimuon
pair creation

(from the ALEPH experiment at the Large Electron Positron Collider)

Jets

quark-
antiquark
pair creation
➜ 2 Jets





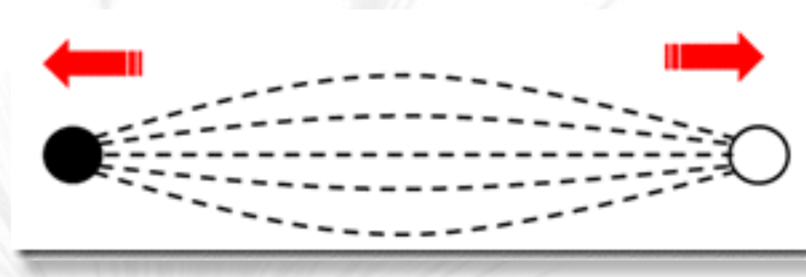
quark-
antiquark
+ gluon
➜ 3 Jets

Confinement

When highly energetic quarks fly apart, a very strong potential builds up between them

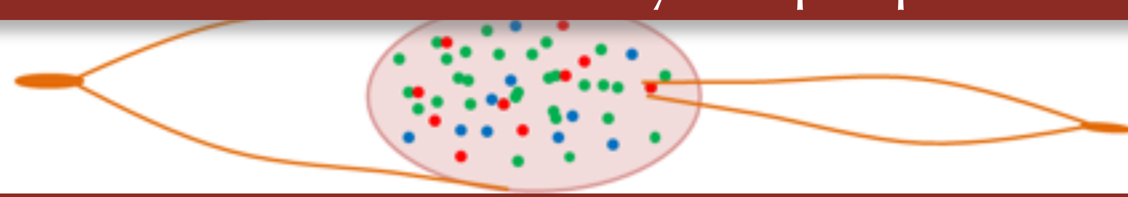
Increase in potential energy
~ 1 GeV / femtometer

(~ energy density of pure nuclear matter)

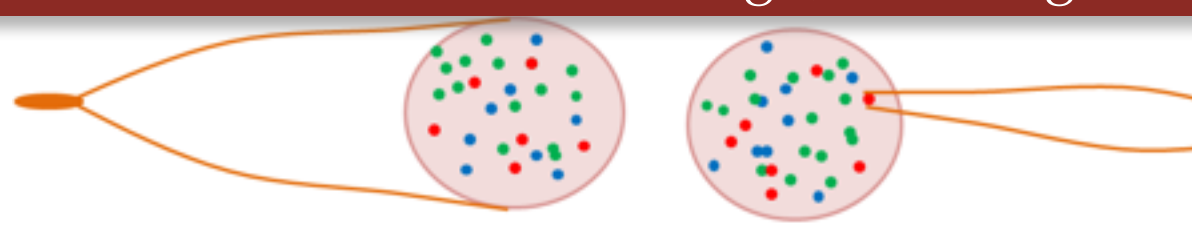


16-TON TRUCK

This is the force that normally keeps quarks locked inside hadrons



But when the kick is hard enough, $E=mc^2$ gets a second chance to act



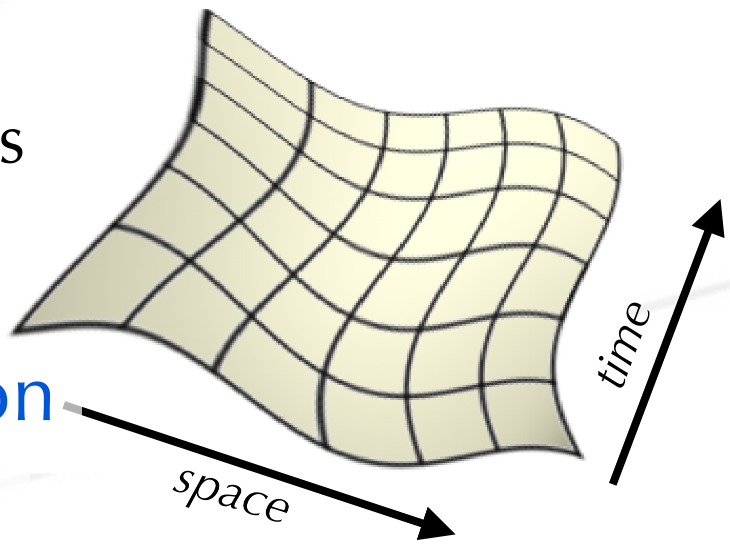
As the quarks separate, this happens multiple times → **Jets**

Vortices Through the Vacuum

The force is approximately **constant** with distance

Suggestive of **strings** (aka vortex lines)

Similar to those in superfluids and superconductors



Inspired the **"string model"** of jet fragmentation

Breakup process modelled by **quantum tunnelling**

Used for 30 years

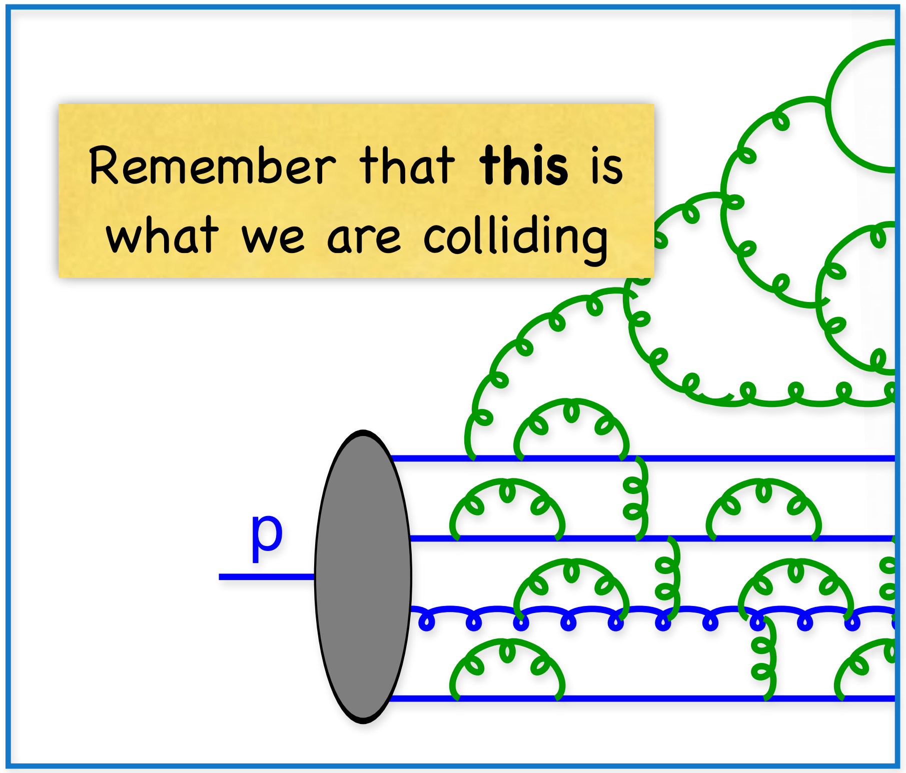
Generally good agreement with collider experiments

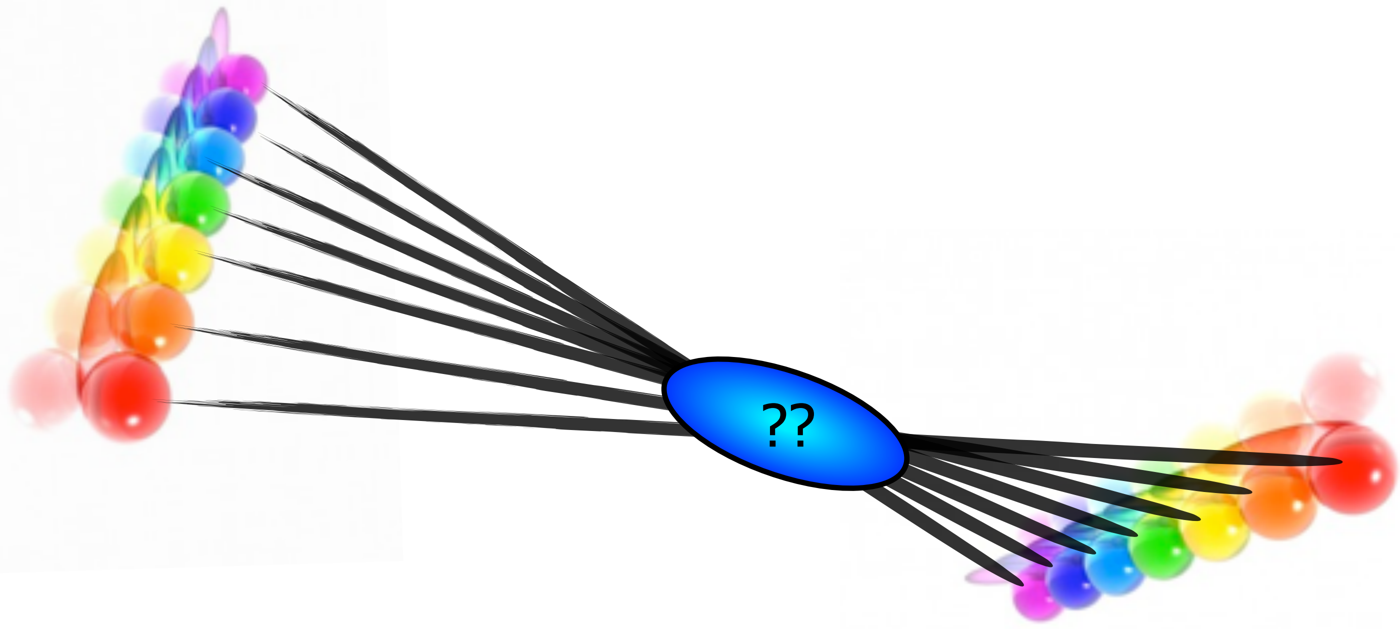
Until we started looking closely at the LHC Run-1 data …

More high-mass hadrons appear to be produced (than predicted)

And they appear to be moving faster (than predicted)

What's Going On?





This is one of the main problems that are currently causing me to scratch my head

Heat? Hydrodynamics?

String-String Forces?

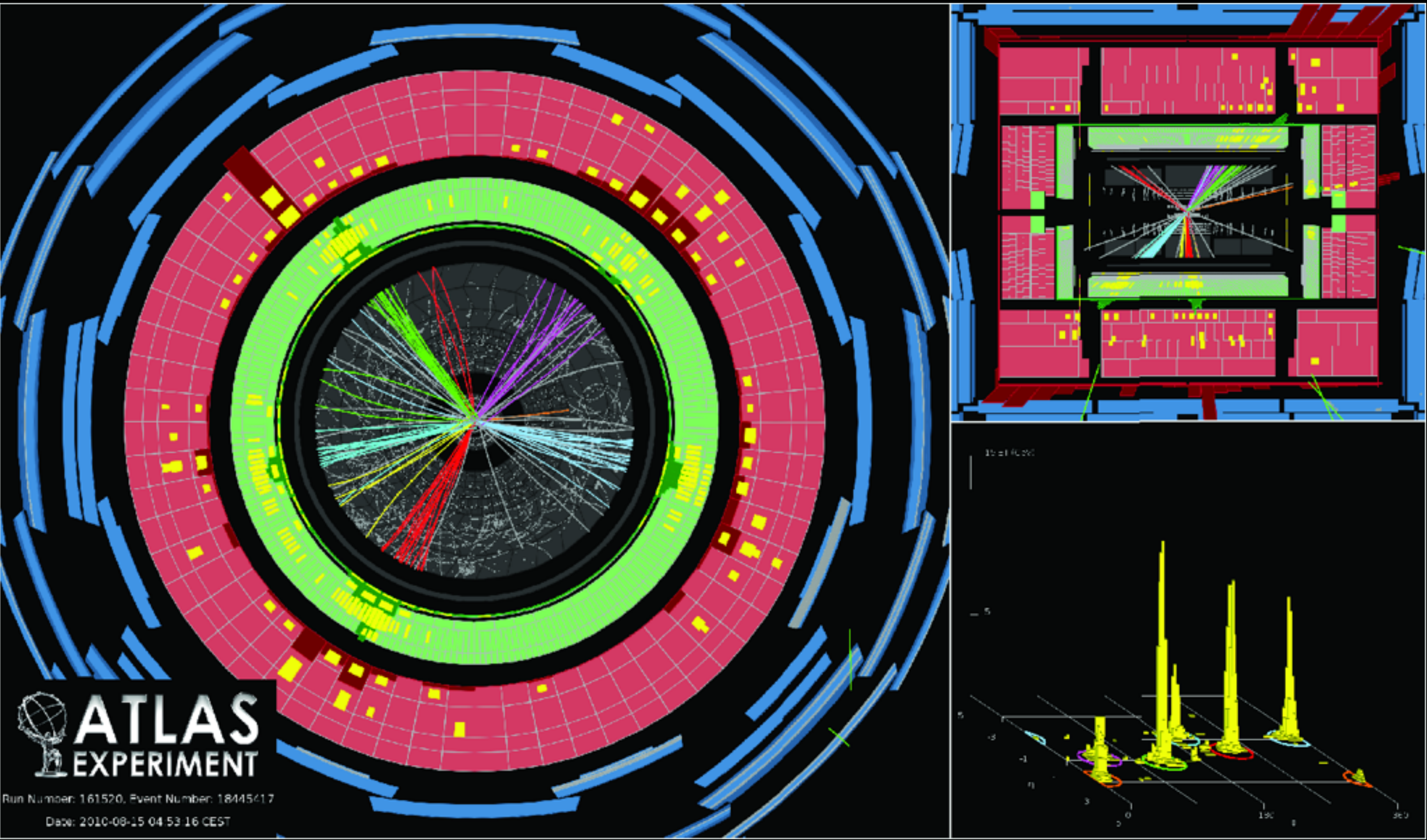
String Reconnections?

Fat Strings?

Black Strings?

Hadron-Gas Rescattering?

Next for us: understand jets



What We Hope to Learn

Understand the haystack

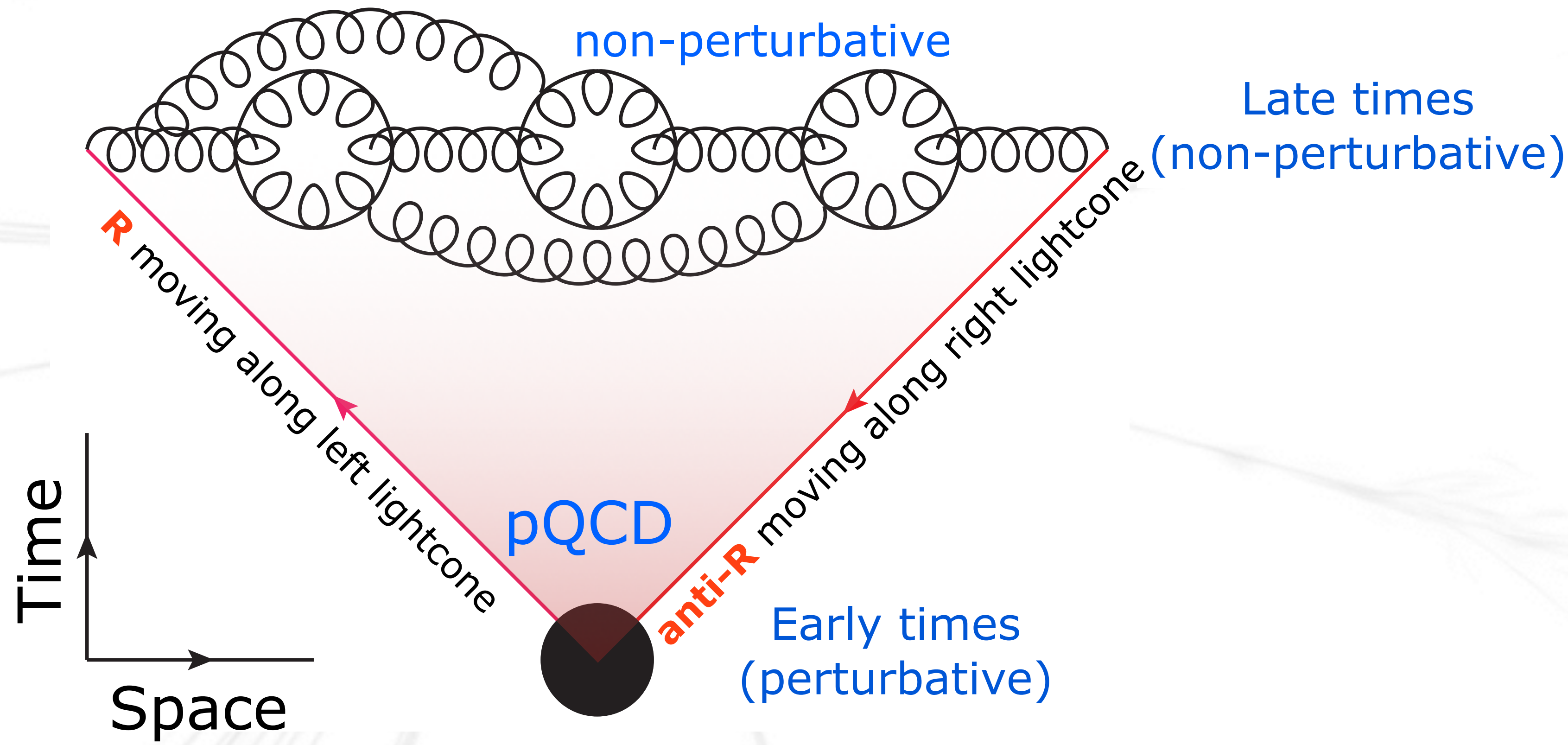
Go on to understand everything else the LHC can show us …

Extras

Colour Neutralization

A physical hadronization model

Should involve at least TWO partons, with opposite color charges (e.g., **R** and **anti-R**)



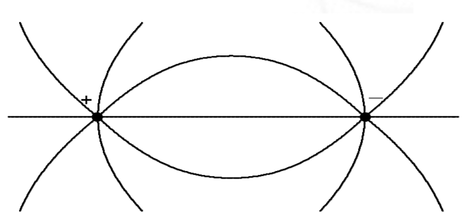
Strong "confining" field emerges between the two charges when their separation > ~ 1fm

Confinement

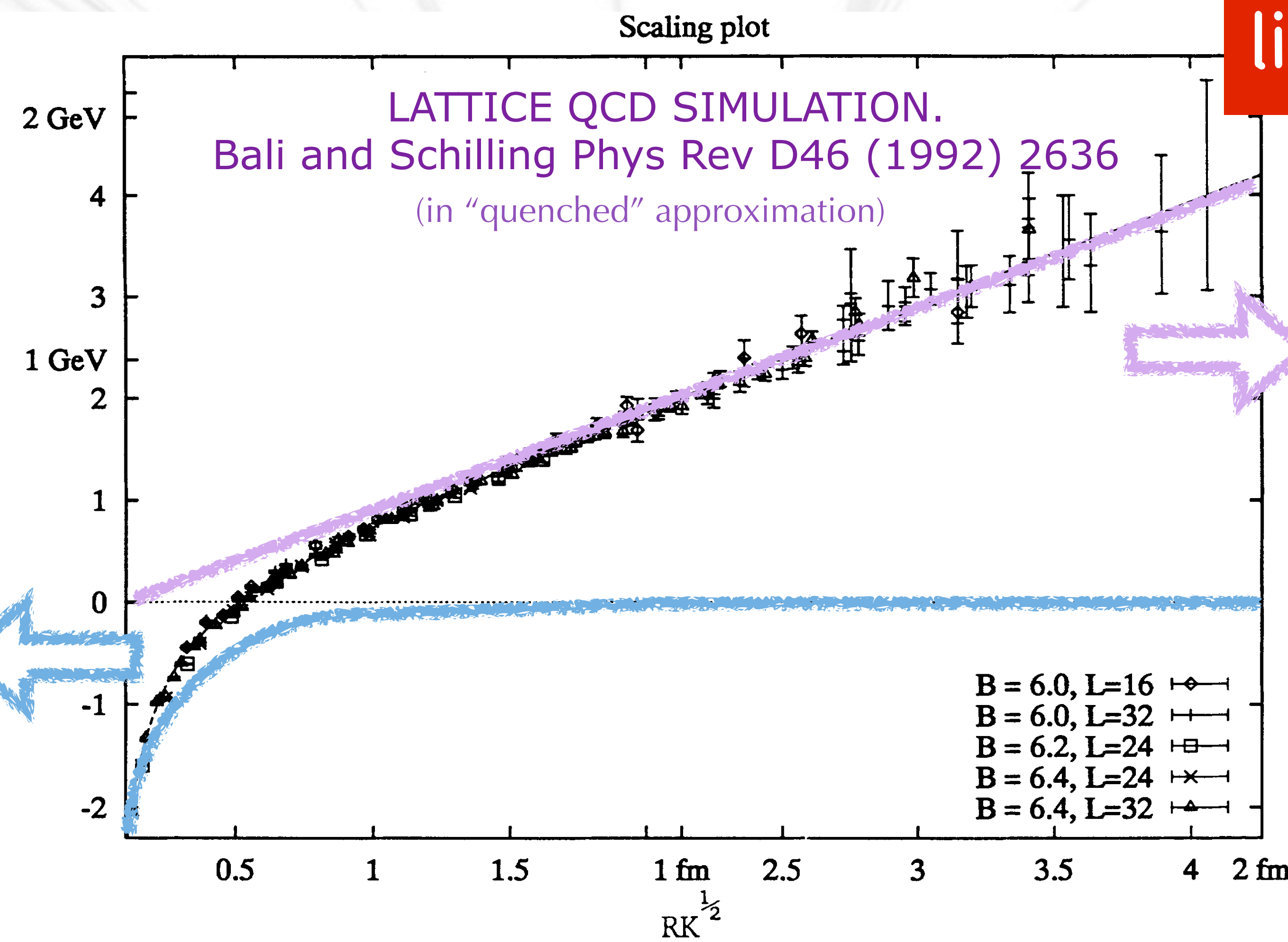
Quark-Antiquark Potential

As function of separation distance

Short Distances ~ "Coulomb"

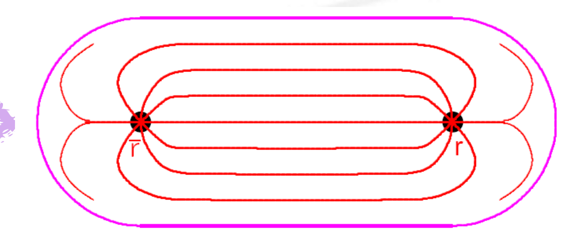


"Free" Partons



What physical system has a linear potential?

Long Distances ~ Linear Potential



"Confined" Partons
(a.k.a. Hadrons)

~ Force required to lift a 16-ton truck

String Breaks

In real QCD, strings can (and do) break!

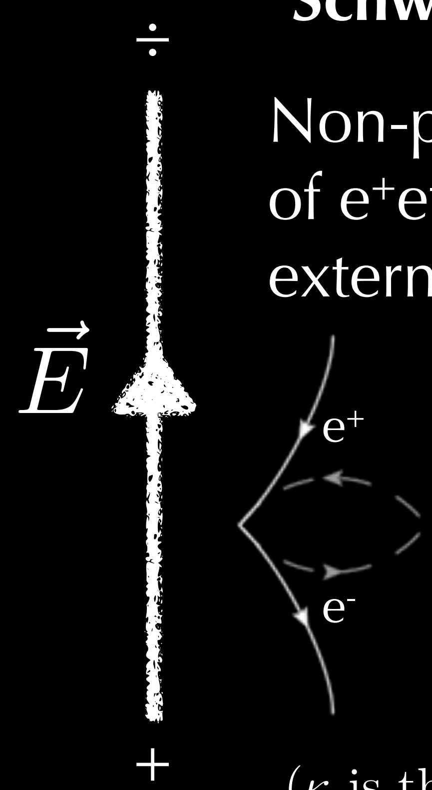
(In superconductors, would require magnetic monopoles)

In QCD, the roles of electric and magnetic are reversed

Quarks (and antiquarks) are "chromoelectric monopoles"

Physical analogy for string breaks: quantum tunnelling

Schwinger Effect



Non-perturbative creation of e^+e^- pairs in a strong external Electric field

Probability from Tunneling Factor

$$\mathcal{P} \propto \exp\left(\frac{-m^2 - p_\perp^2}{\kappa/\pi}\right)$$

(κ is the string tension equivalent)