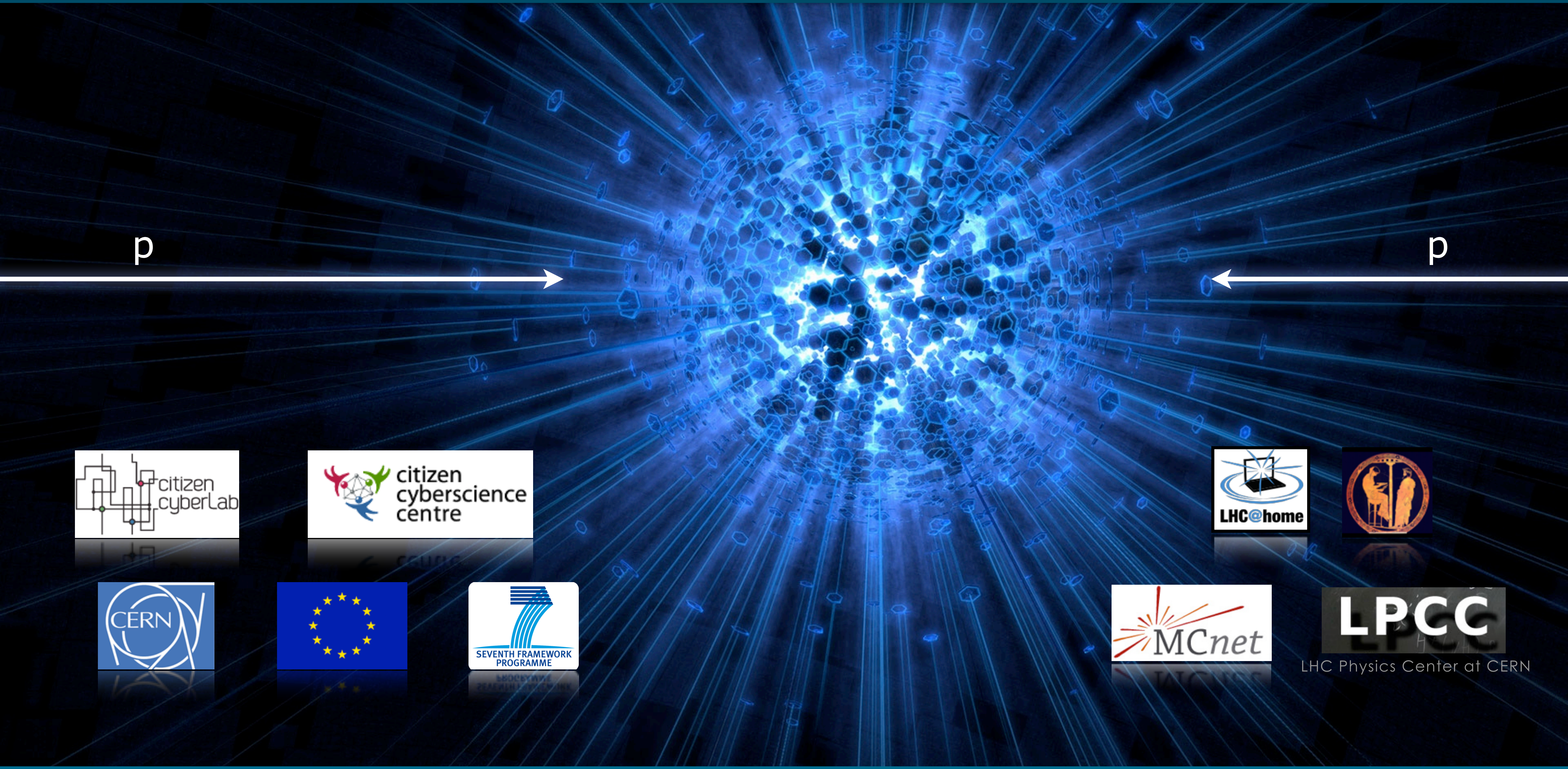
Virtual Atom Smashers

Peter Skands (CERN Theoretical Physics Dept)



High School Teachers Program 2013
CERN

Background

Who am I?

Theorist (PhD 2004 from Lund U, Sweden) working on improving solutions to Quantum Chromodynamics (QCD)

… to write good "Monte Carlo event generators"

- Used by experiments to give "theory predictions", to compare with data
- Used to design and optimize detectors and analysis strategies
- Used by theorists to explore new solutions, new ideas, new physics

Not a computer scientist. But the numerical calculations I (want to) do require a lot of power

→ distributed computing: farms / GRID / clouds
In particular the LHC@Home 2.0 project "Test4Theory"

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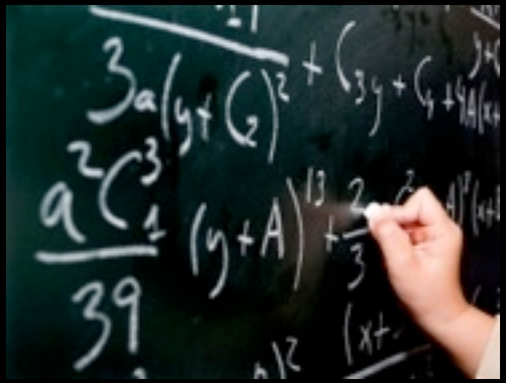
Why did Mick invite me?

To explore possibilities for high school students/teachers in these areas? Some half-baked ideas and examples.

Nutshell



Theory

Experiment

Adjust this to agree with this

Nutshell

Theory

Experiment

Adjust this to agree with this

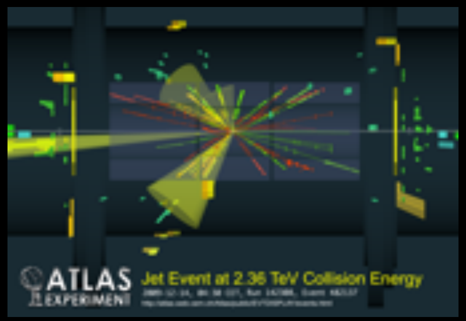
→ Science

In Practice

VINCIA

PYTHIA

...



"Virtual Colliders"
= Simulation Codes

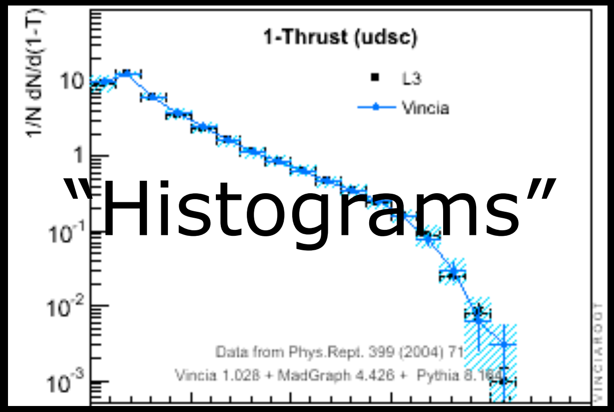
Real Universe
→ Experiments & Data

Particle Physics Models, Algorithms, …

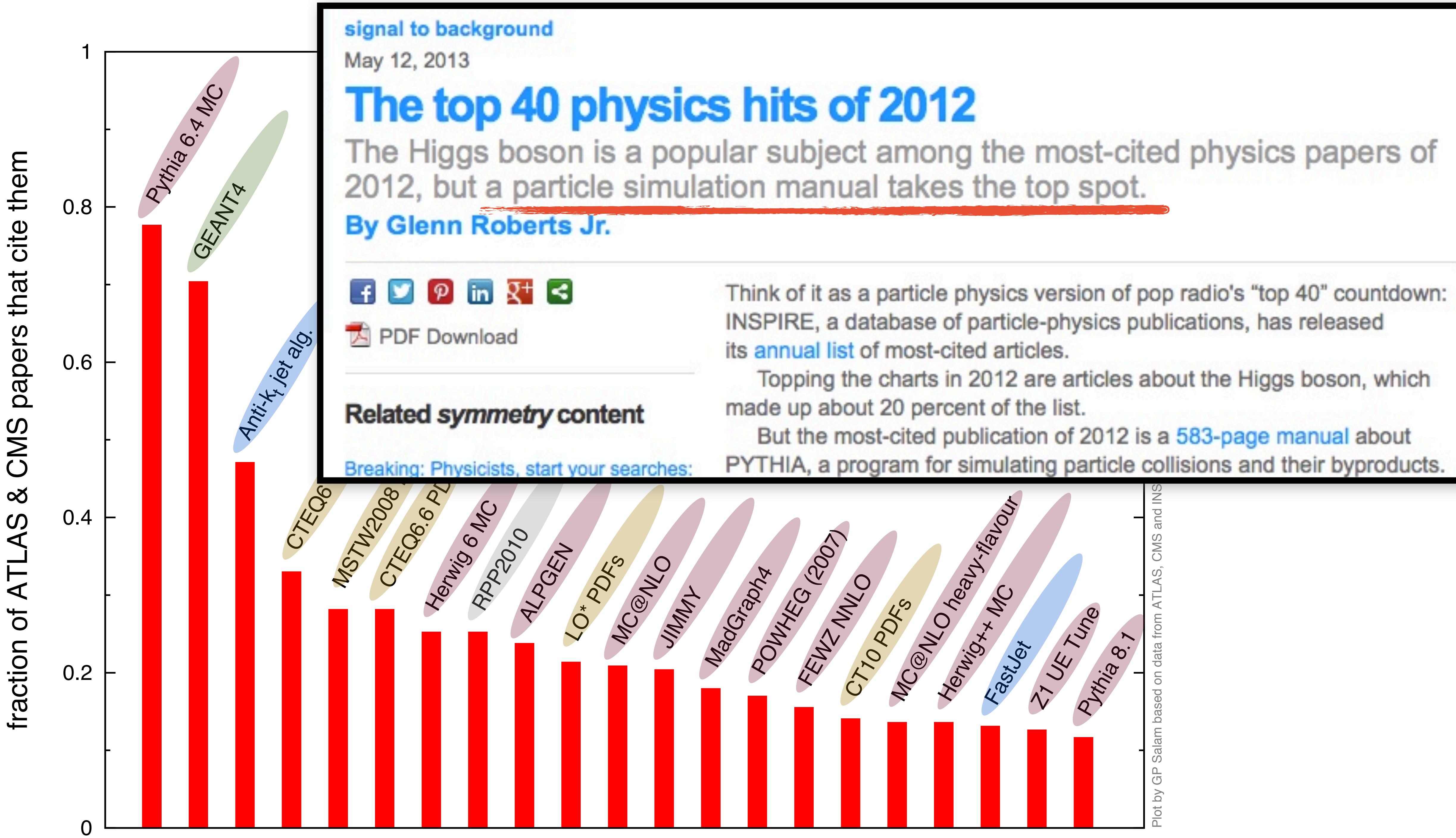
Particle Accelerators, Detectors, and Statistical Analyses

→ Simulated Particle Collisions

→ Published Measurements



Tools for HEP Experiments



signal to background

May 12, 2013

The top 40 physics hits of 2012

The Higgs boson is a popular subject among the most-cited physics papers of 2012, but a particle simulation manual takes the top spot.

By Glenn Roberts Jr.

PDF Download

Related *symmetry* content

Breaking: Physicists, start your searches:

Think of it as a particle physics version of pop radio's "top 40" countdown: INSPIRE, a database of particle-physics publications, has released its annual list of most-cited articles.

Topping the charts in 2012 are articles about the Higgs boson, which made up about 20 percent of the list.

But the most-cited publication of 2012 is a 583-page manual about PYTHIA, a program for simulating particle collisions and their byproducts.

PYTHIA

Sjöstrand, Mrenna & Skands, Computer Physics Communications 178 (2008) 852

The most widely used event generator in HEP

Select incoming beams, energy, process type, …

Generates collisions, particle decays, radiation, hadronization, …

→ Simulated Events

What can you do with that?

Can count particles, identify their types, study their spectra

Compare with measured experimental results

Study effects of changing the model parameters → physics

What does it require?

PYTHIA is written by ~ 7 people. It is ~ 6MB of standalone C++ code. Compiles easily on Macs and Linux (Windows not recommended).

A bit of C++ experience and an ordinary laptop or desktop.

Help: many examples and a written tutorial (so far oriented towards scientists and university students). If useful for teaching, interesting to develop material targeted at younger people?

Test4Theory

Theory ↔ Data Comparisons

Task: determine “best” parameters for theory models

→ Compare against thousands of measurements, taken under different conditions, by different experiments, at different colliders

+ do this for many simulators & versions, with different setups

LEP Tevatron

SLC LHC ISR

HERA SPS

RHIC

Quite technical
Quite tedious
→
Ask someone else

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LHC@home 2.0
TEST4THEORY

citizen cyberscience centre

CERN

J. Blomer,
P. Buncic,
I. Charalimpidis,
F. Grey,
A. Haratyunyan,
A. Karneyeu,
D. Lombrana-Gonzalez,
M. Marquina,
B.Segal,
P. Skands,

7000 Volunteers - 20000 Hosts
Over 900 billion simulated collision events

LHC@Home 2.0 - Test4Theory

Idea: ship volunteers a virtual atom smasher
(to help do high-energy theory simulations)

Runs when computer is idle. Sleeps when user is working.

Problem: Lots of different machines, architectures

(tedious, technical)

Use Virtualization (CernVM) → provides standardized computing environment on *any* machine (in our case: Scientific Linux)

Replica of our normal working environment.

Separation of IT and Science

Virtualization: never previously done for a volunteer cloud

Test4Theory

LHC@home 2.0 Test4Theory volunteers' machines seen during the past **24** hours (7011 machines overall)

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.

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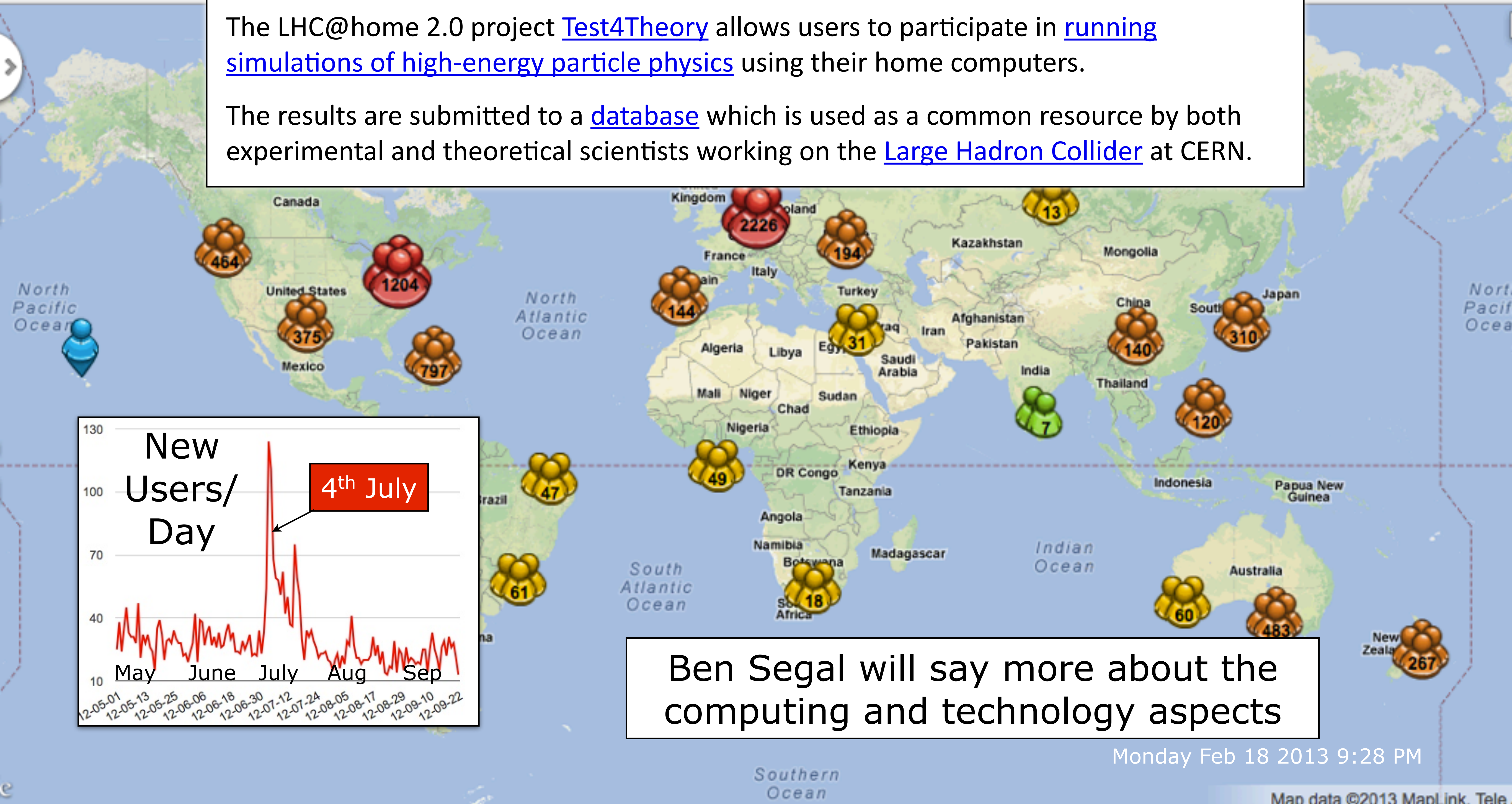


Ben Segal will say more about the computing and technology aspects

Monday Feb 18 2013 9:28 PM

More than the sum of its parts

Test4Theory combines:

Theoretical high-energy physics

In particular the strong nuclear force

Random-number based Monte Carlo techniques

& Markov-chain algorithms

Programming

Distributed computing

In particular virtualization & cloud computing

Citizen science

Experimental particle physics

Including statistical data analysis

Used to provide comprehensive tests of the theory models used at LHC.

Accurate theory → accurate measurements

LHC@home

Possible projects or study topics?

Maths

- Basic statistics (and data analysis, can also be related to social studies, polling, etc)
- Random numbers
- Markov chains

Physics

- The strong nuclear force (and explicit simulations of it)
- Setting up and running your own virtual atom smasher, and learning about the particles it produces

Computer Science

- Virtual Machines (e.g., Linux-CernVM), with the Test4Theory project as a concrete example
- Distributed computing, using the Test4Theory volunteer cloud as a real-world example that individuals can participate in

Example in Statistics:
Fostering Healthy Skepticism

A friend pointed me to a story on FB

A Scottish study had found that the IQ of the eldest child was higher than that of the younger siblings

Disturbing news (I am the younger one)

A professor somewhere was commenting on what this meant about how we treat each child differently, etc.

The difference was 1%, on average

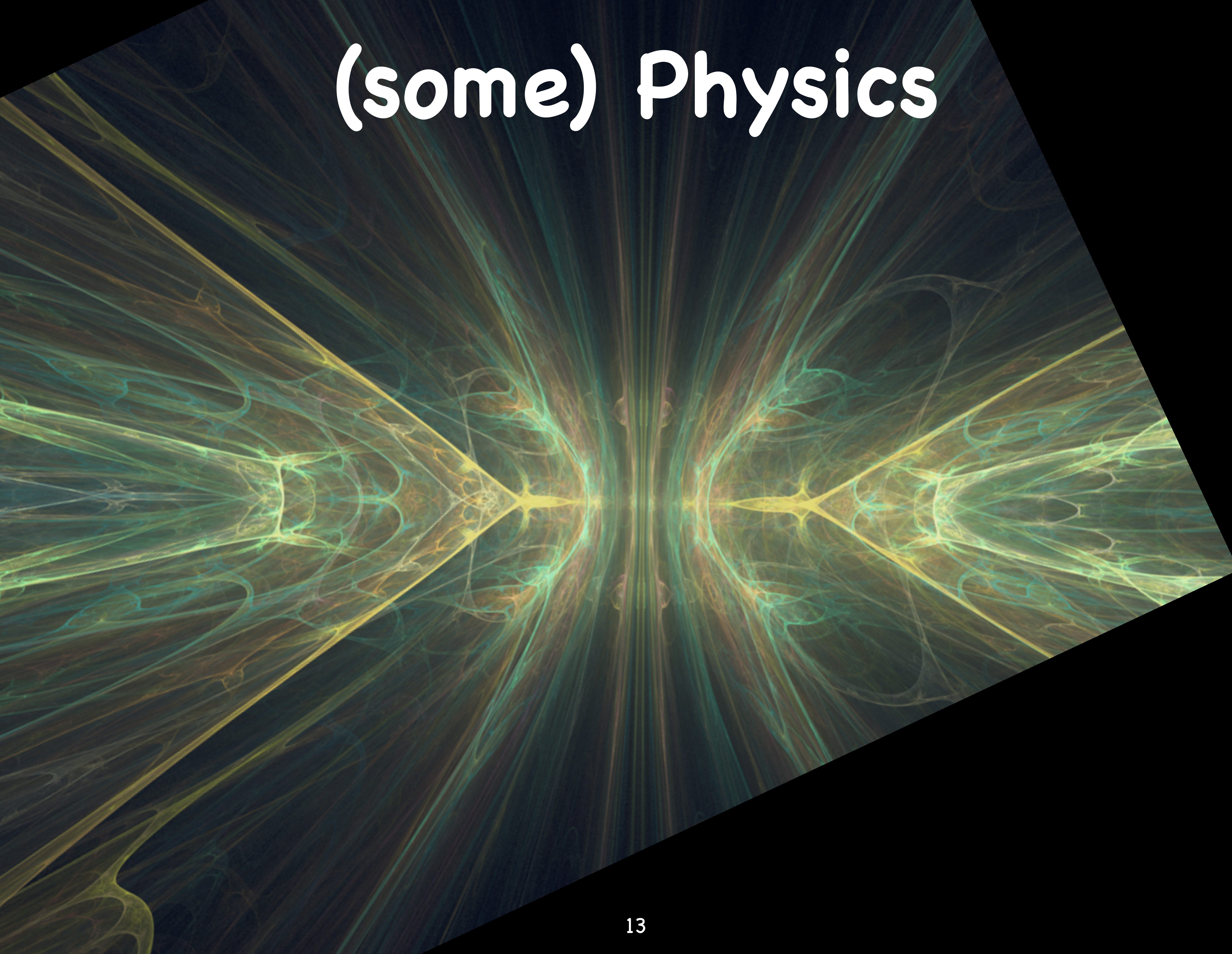
They had examined 10,000 cases

The statistical uncertainty for 10,000 counts is: **1%**

With very little statistics knowledge, students could be given cases like this to debunk, and see it work in practice

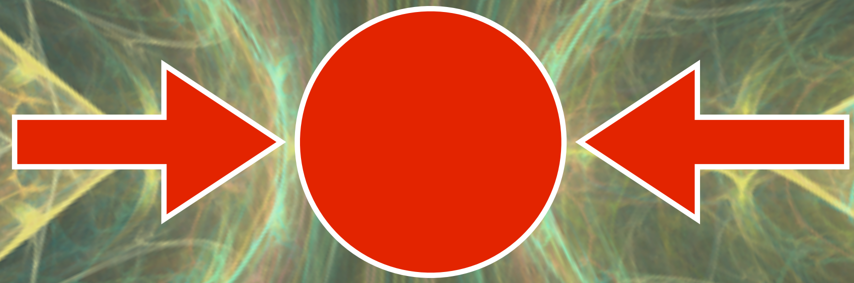
Other more CERN-related examples could draw from data analysis and particle physics. How do you know you've made a discovery? Significance.

(some) Physics



(some) Physics

Charges Stopped
or kicked



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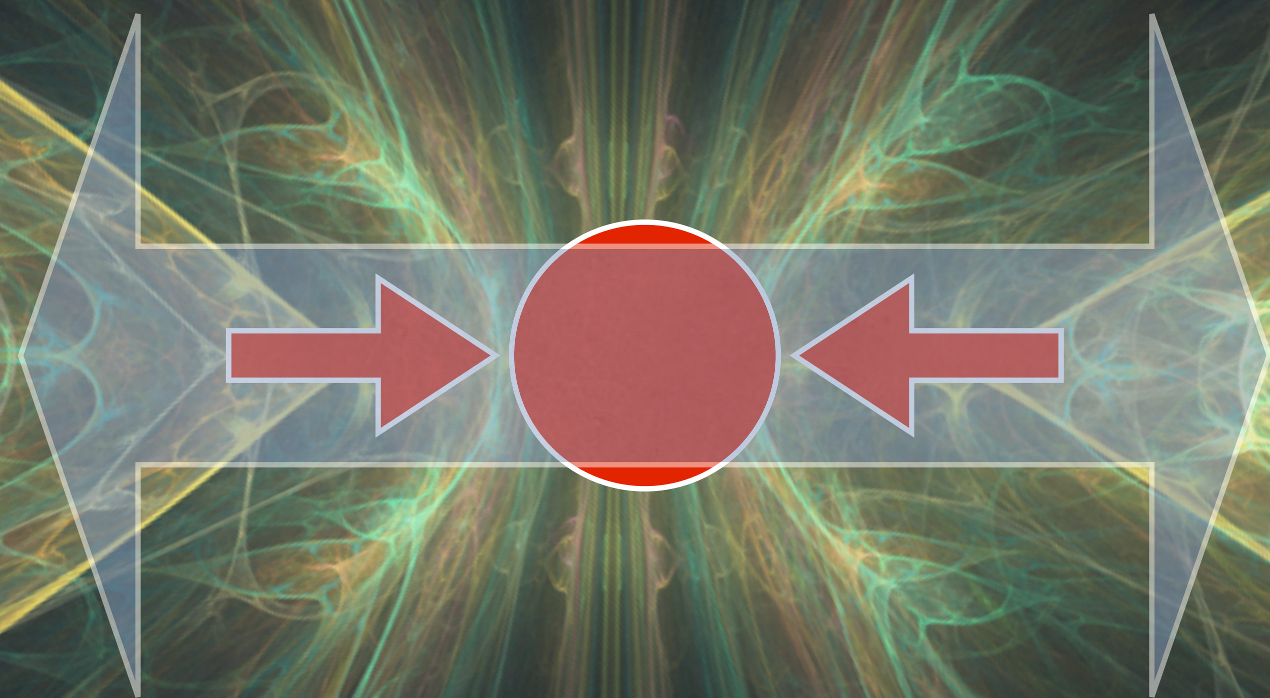

Associated field
(fluctuations) continues

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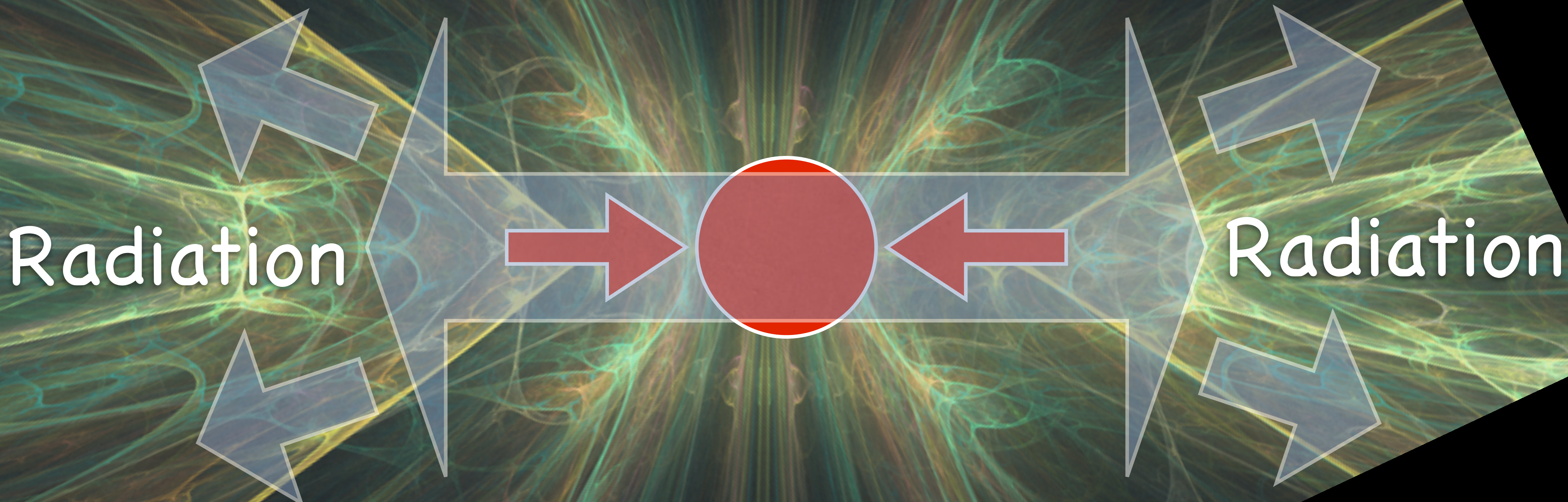

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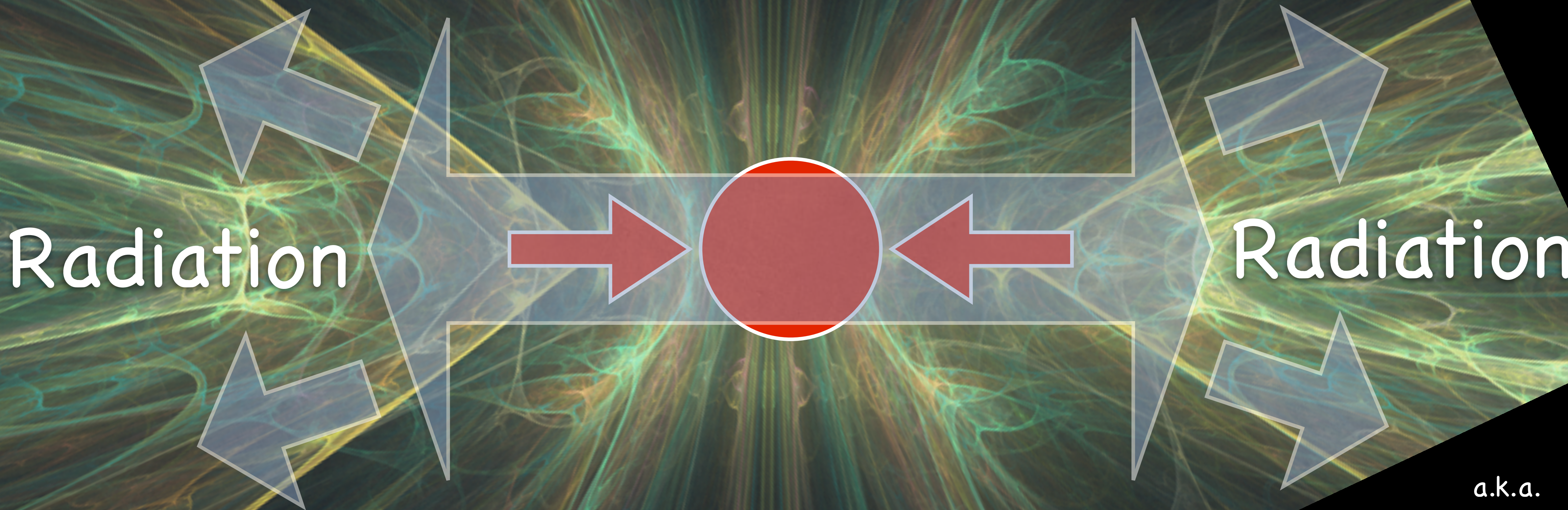


a.k.a.
Bremsstrahlung
Synchrotron Radiation

The harder they stop, the harder the fluctations that continue to become radiation

Jets = Fractals!

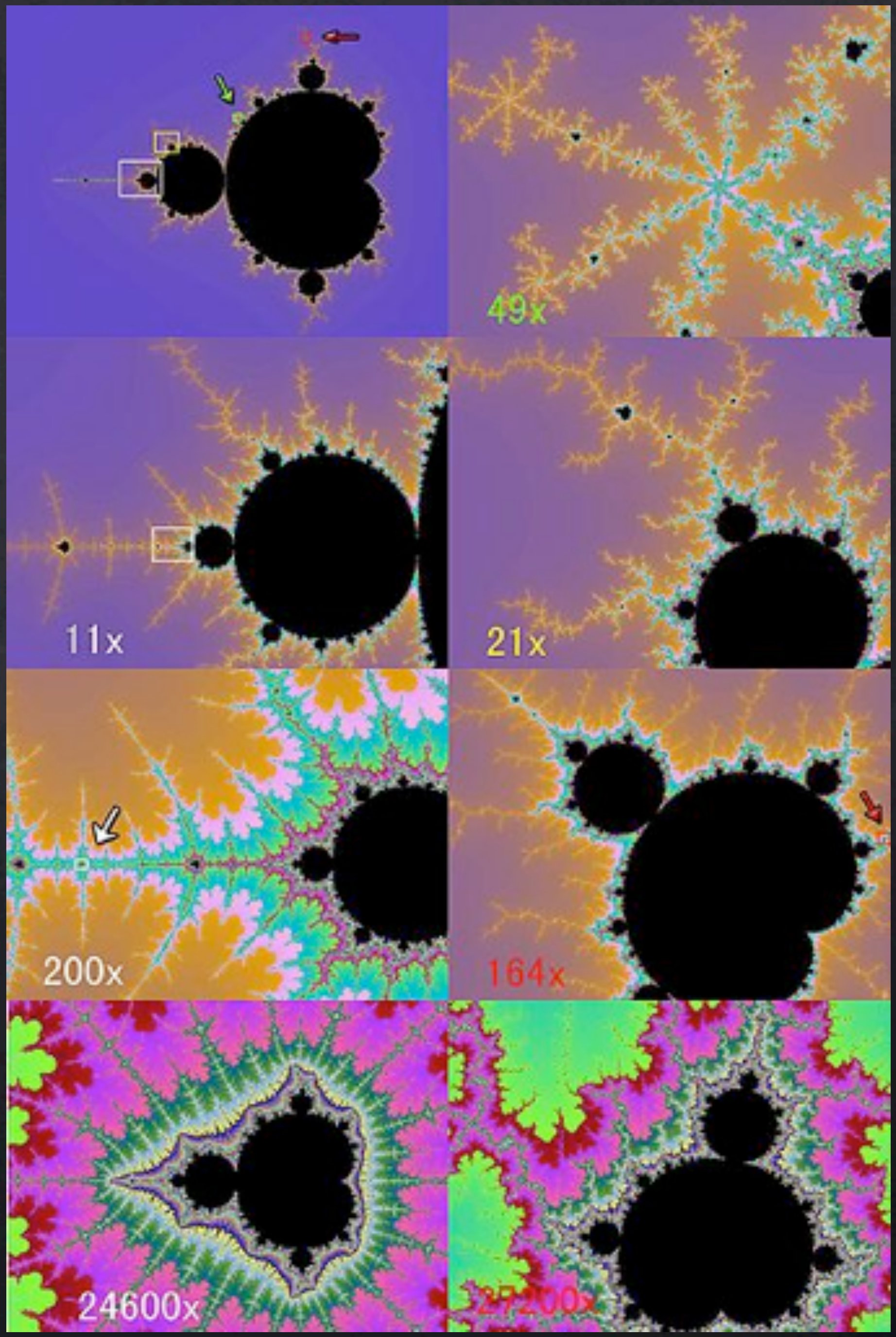
Bjorken scaling

To first approximation, gauge theories (like QCD) are SCALE INVARIANT

A quantum fluctuation inside a fluctuation inside a fluctuation ...

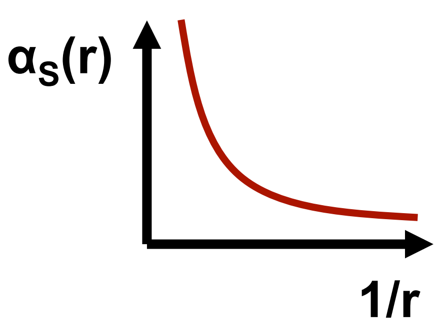
A gluon emits a gluon emits a gluon emits a gluon ...

If the coupling "constant" of the strong force was a constant, this would be absolutely true



Asymptotic Freedom

“What this year's Laureates discovered was something that, at first sight, seemed completely contradictory. The interpretation of their mathematical result was that the closer the quarks are to each other, the *weaker* is the 'colour charge'. When the quarks are really close to each other, the force is so weak that they behave almost as free particles. This phenomenon is called ‘asymptotic freedom’. The converse is true when the quarks move apart: the force becomes stronger when the distance increases.”



Nobelprize.org
The Official Web Site of the Nobel Prize

2004

The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

David J. Gross | H. David Politzer | Frank Wilczek

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.

Photos: Copyright © The Nobel Foundation

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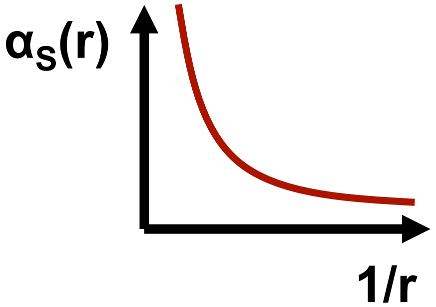


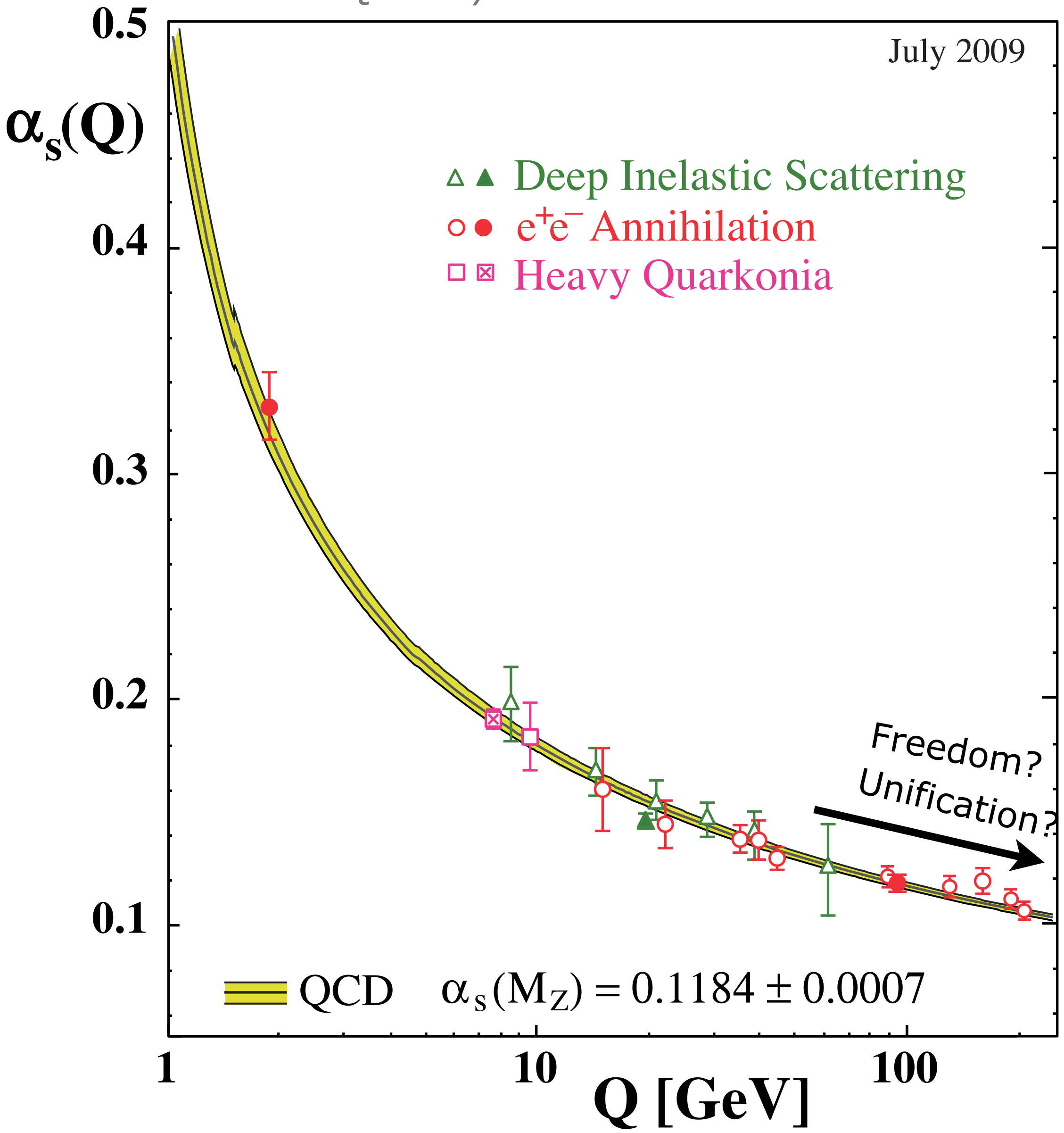
*1 The force still goes to ∞ as $r \to 0$ (Coulomb potential), just less slowly

*2 The potential grows linearly as $r \to \infty$, so the force actually becomes constant (even this is only true in "quenched" QCD. In real QCD, the force eventually vanishes for r>>1fm)

The Strong Coupling "Constant"

The Strong Coupling "Constant"
as function of energy scale, Q

From PDG Review on QCD. by Dissertori & Salam



At low scales

Coupling $\alpha_s(Q)$ actually runs rather fast with Q

Perturbative solution diverges at a scale Λ_{QCD} somewhere below

$\approx$ 1 GeV

So, to specify the strength of the strong force, we usually give the value of α_s at a unique reference scale that everyone agrees on: M_Z = 91.2 GeV/c

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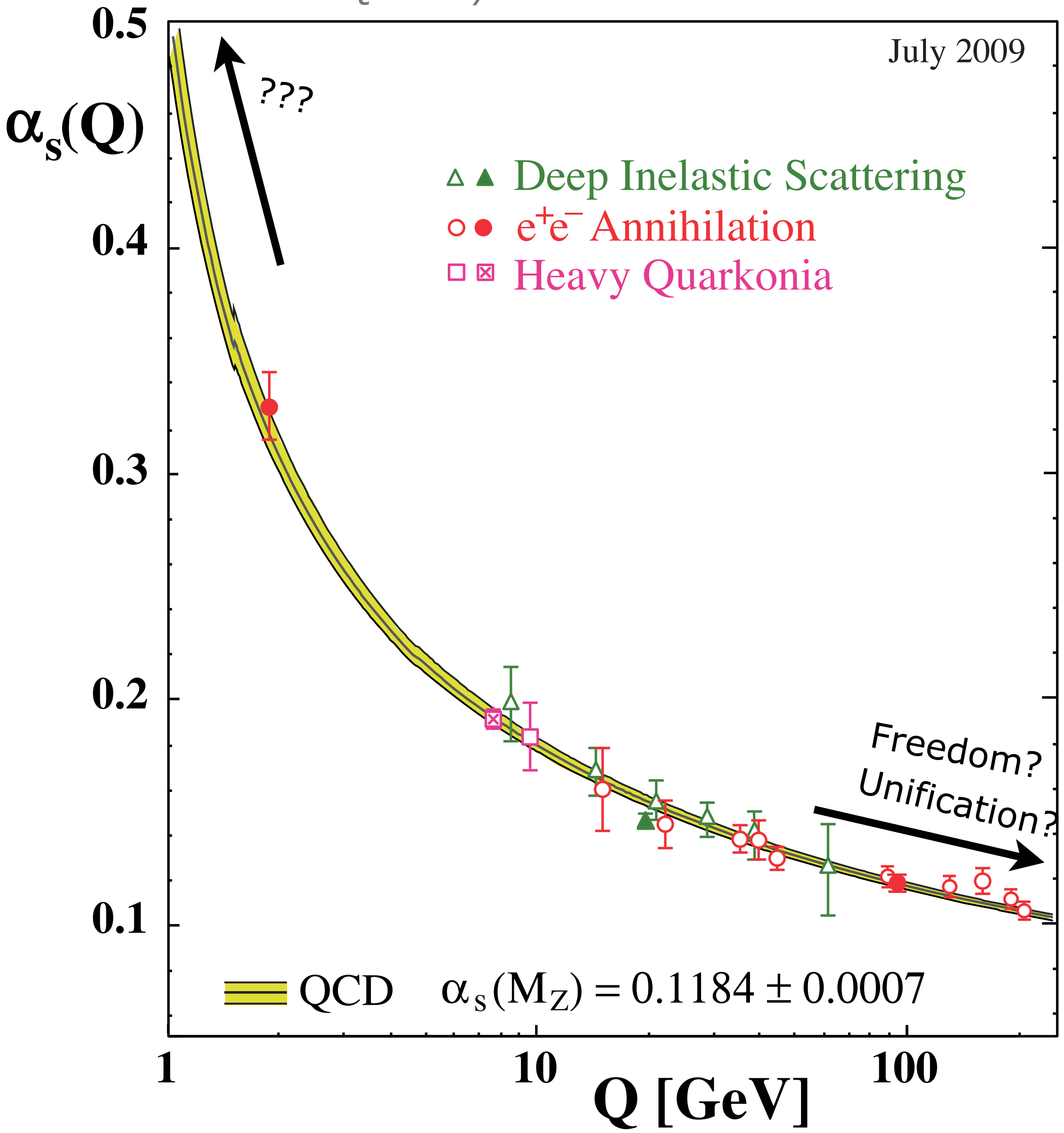

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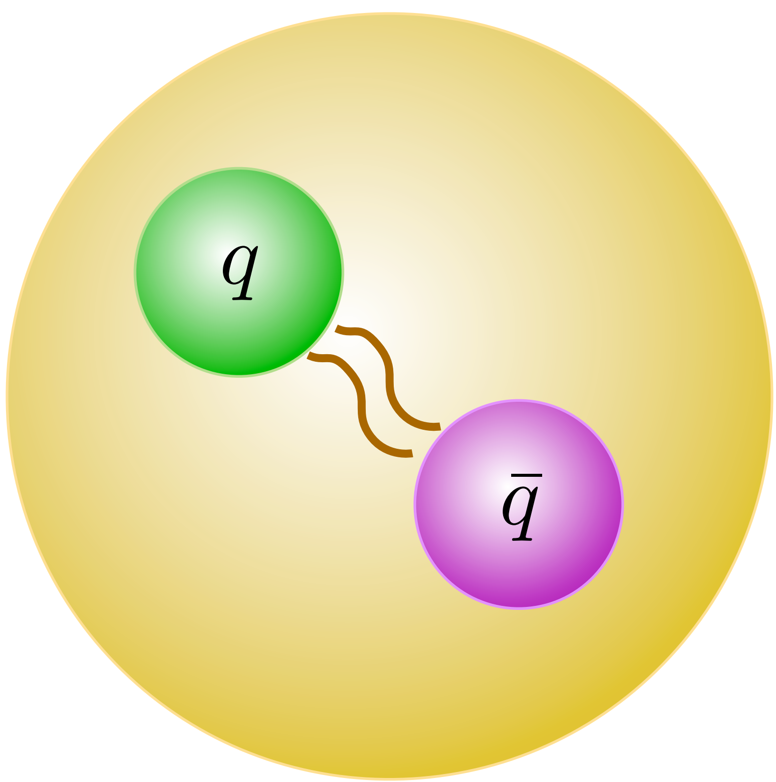
Confinement

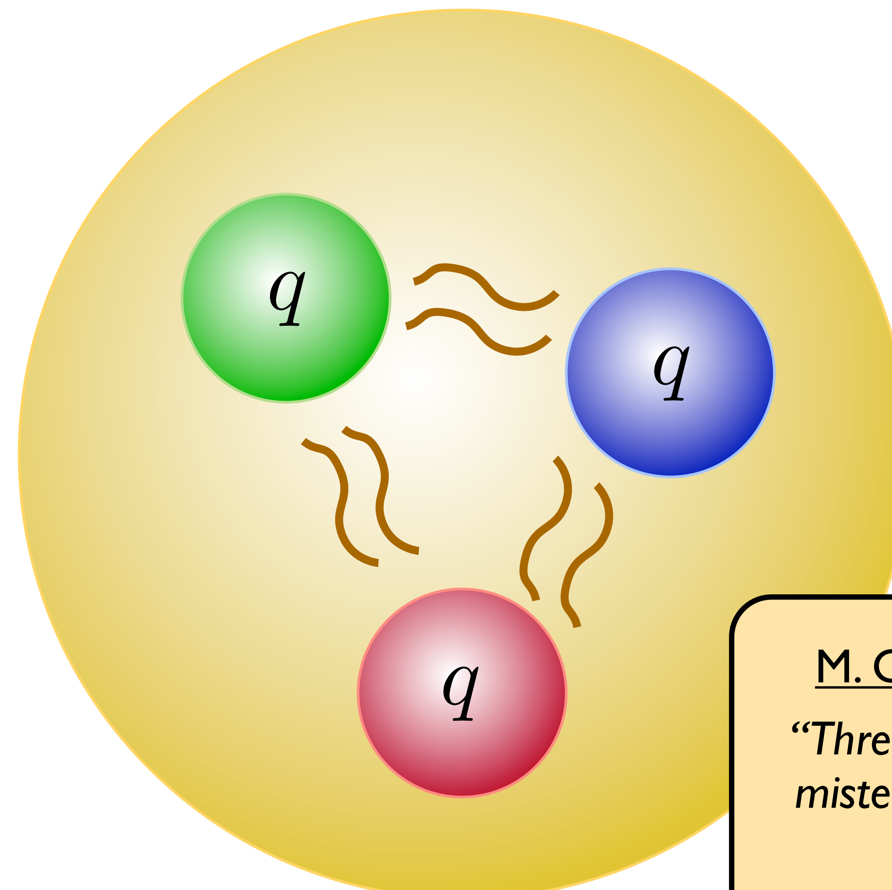
We don't see quarks and gluons …

Mesons

Quark-Antiquark Bound States

$\pi^0, \pi^\pm, K^0, K^\pm, \eta, \ldots$





M. Gell-Mann:

"Three quarks for mister Mark, …"

James Joyce, Finnegans Wake

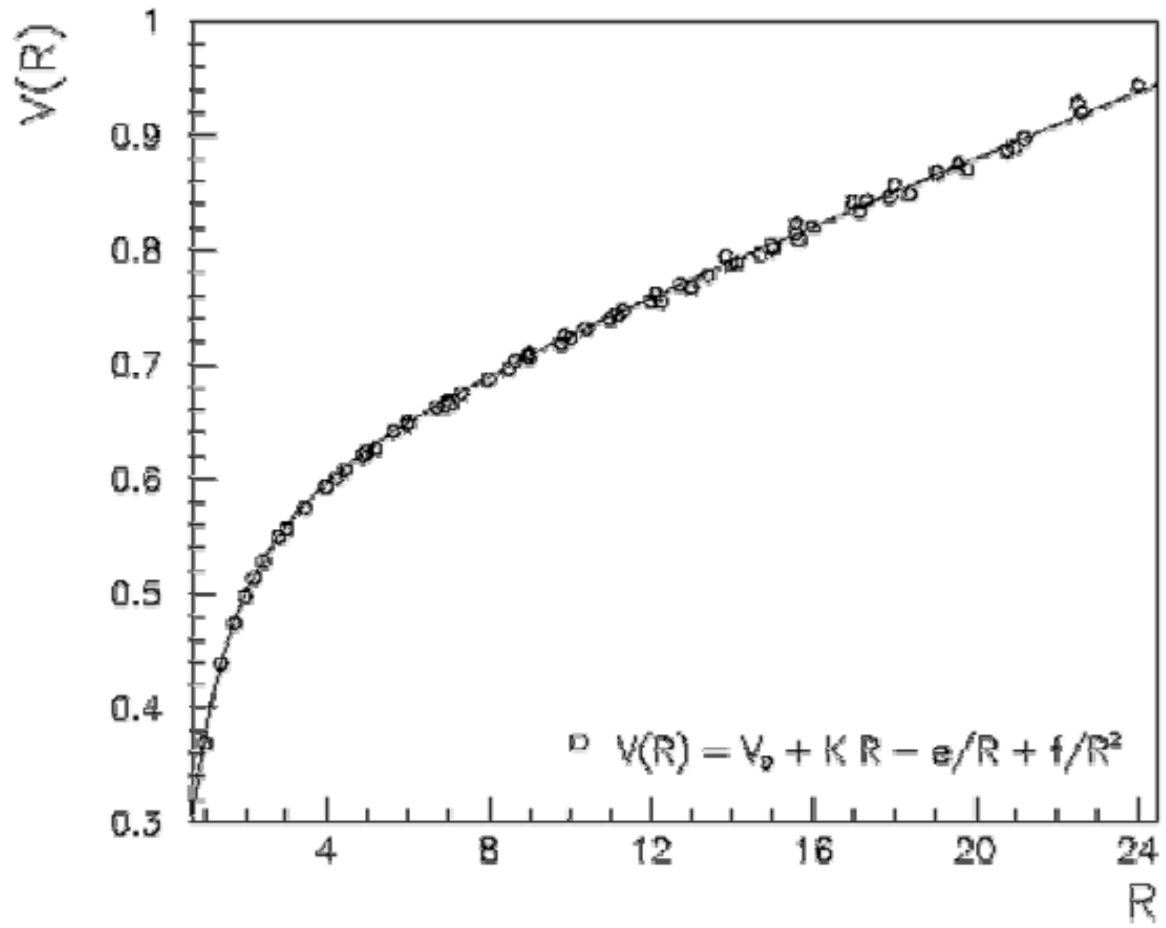
Baryons

Quark-Quark-Quark Bound States

$p^\pm, n^0, \Lambda^0, \ldots$

Linear Confinement

Potential between a quark and an antiquark as function of distance, R



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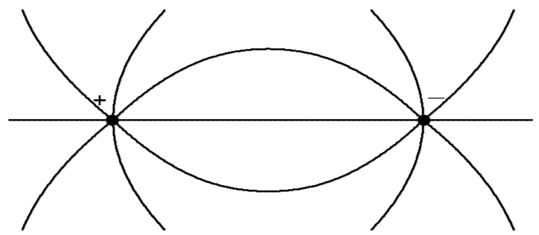
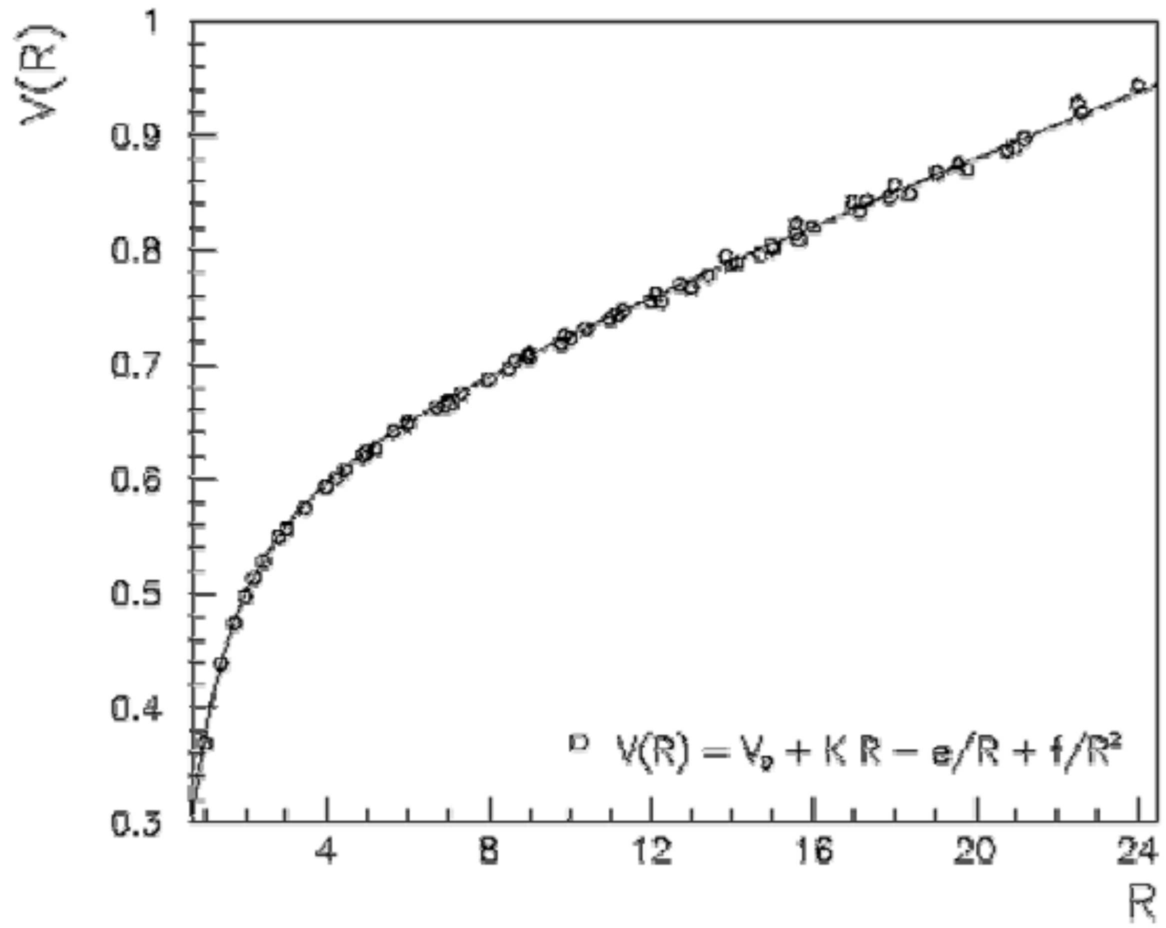
Short Distances ~ "Coulomb"



Partons



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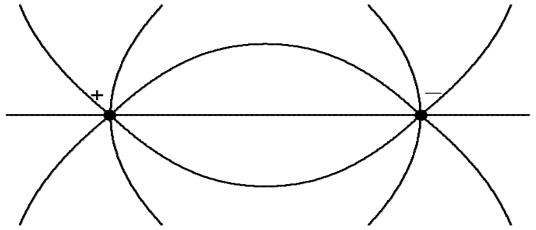

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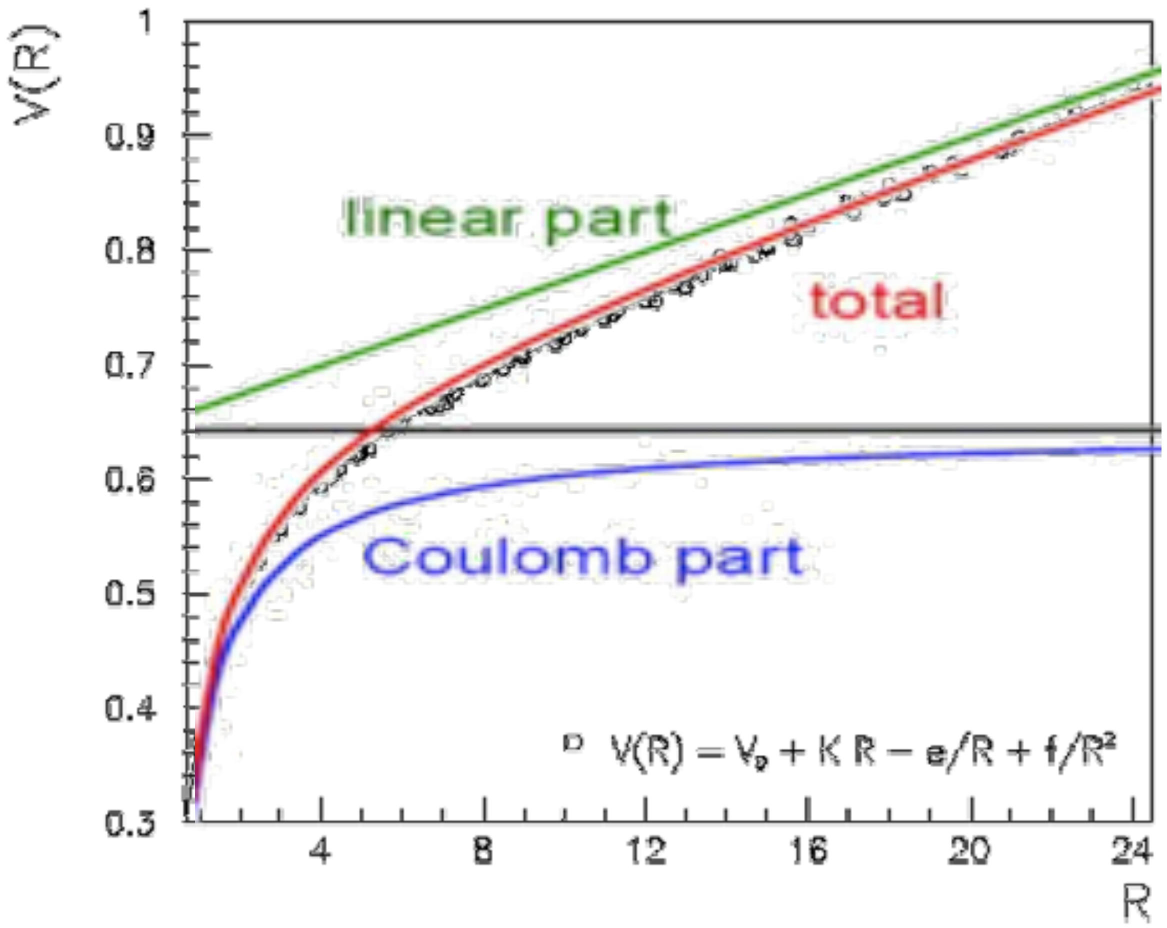

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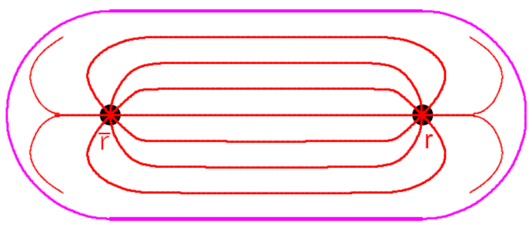
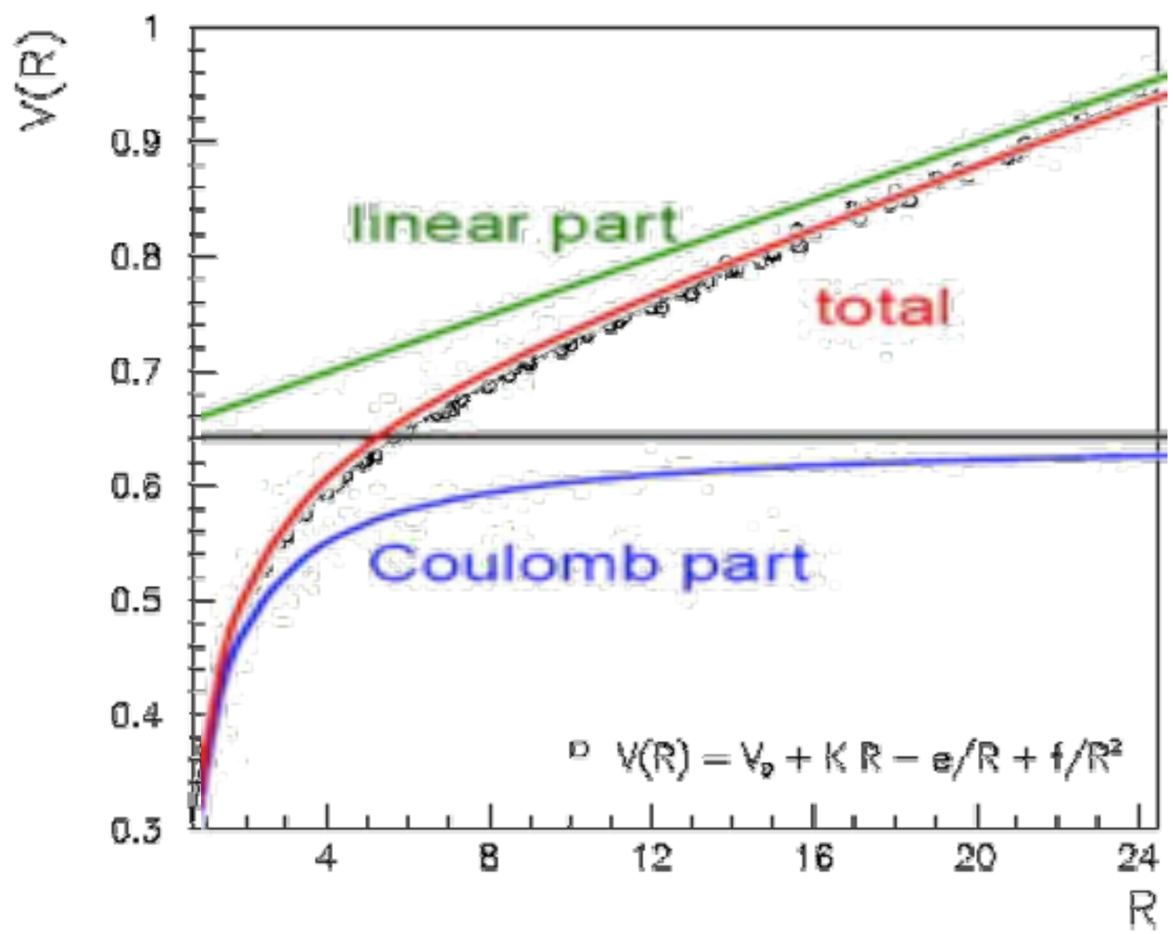
Long Distances ~ Linear Potential



Quarks (and gluons) confined inside hadrons



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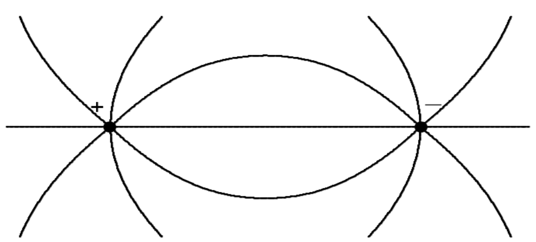

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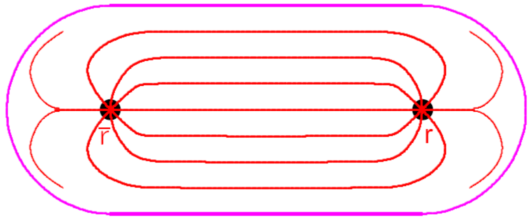

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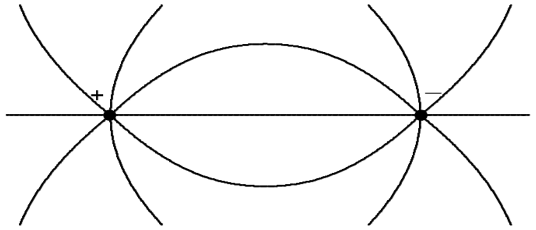

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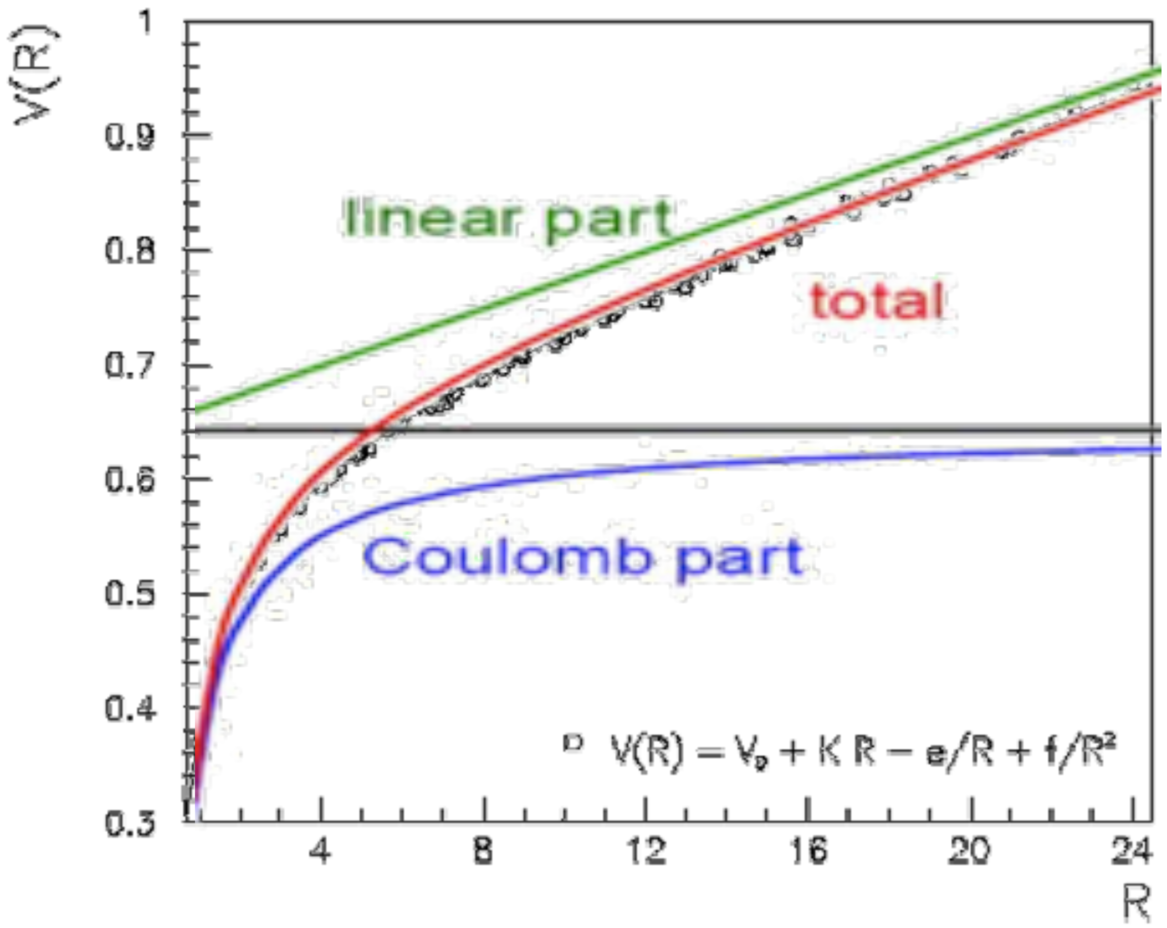


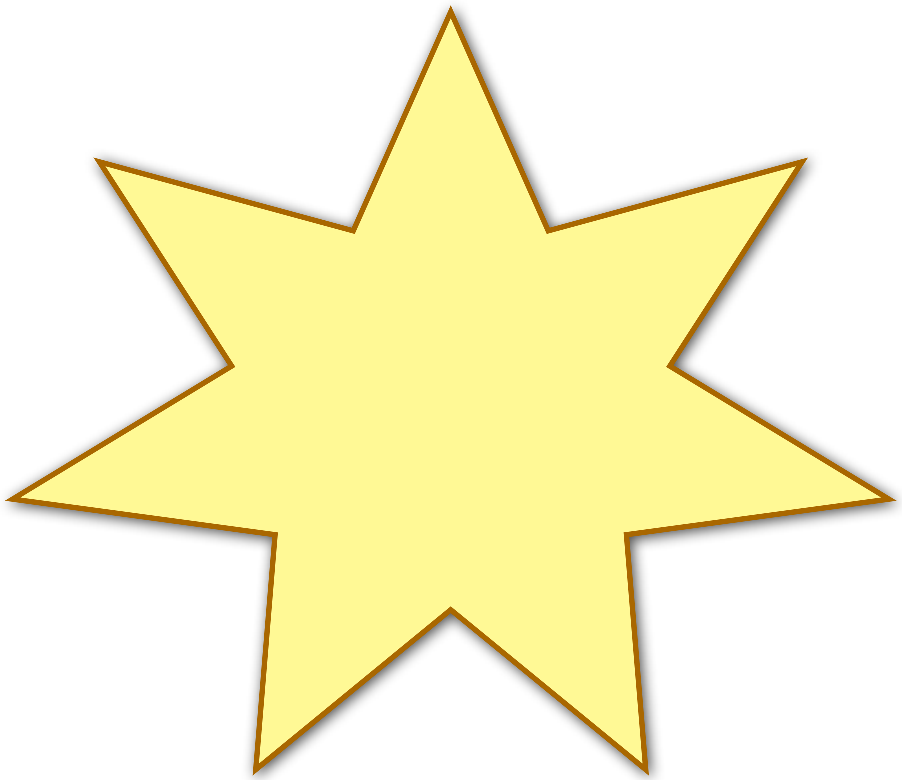
$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$$


Monte Carlo

Random Numbers

(apologies, I did not have much time to adapt these slides)

You want: to know the area of this shape:



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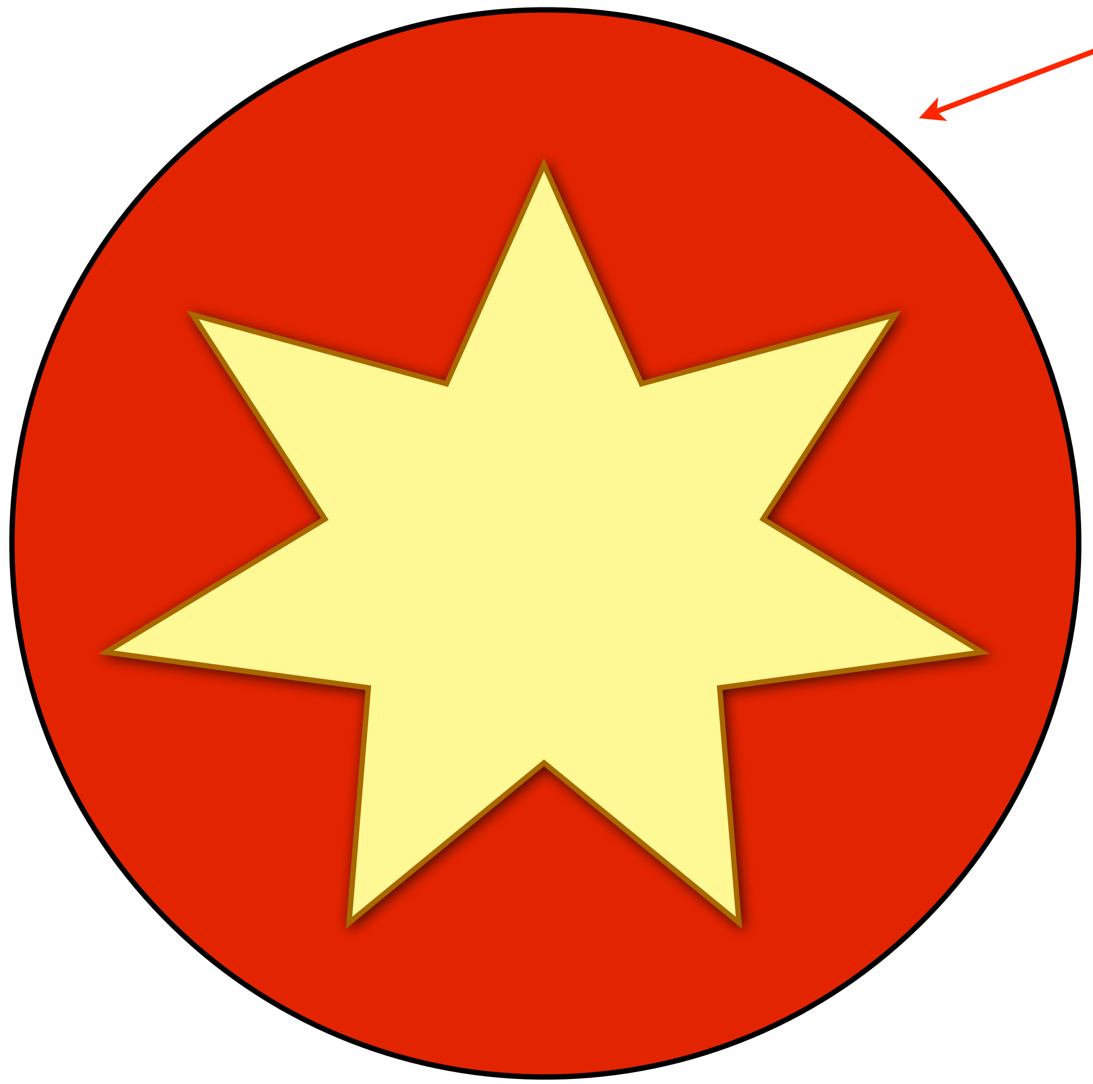

Assume you know the area of <u>this</u> shape:
πR^2
(an overestimate)

Random Numbers

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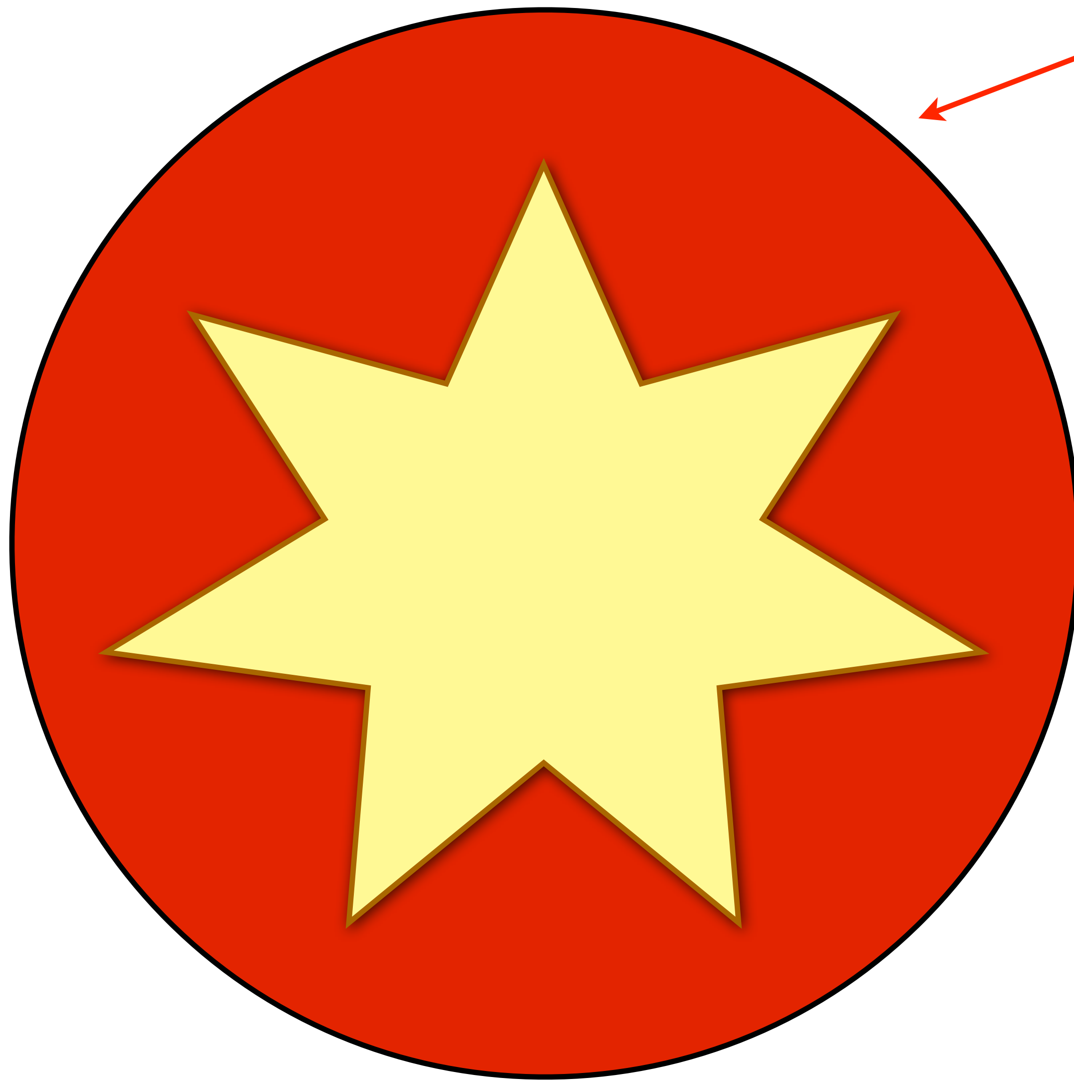
You want: to know the area of this shape:

Now get a few friends, some balls, and throw random shots inside the circle
(but be careful to make your shots truly random)



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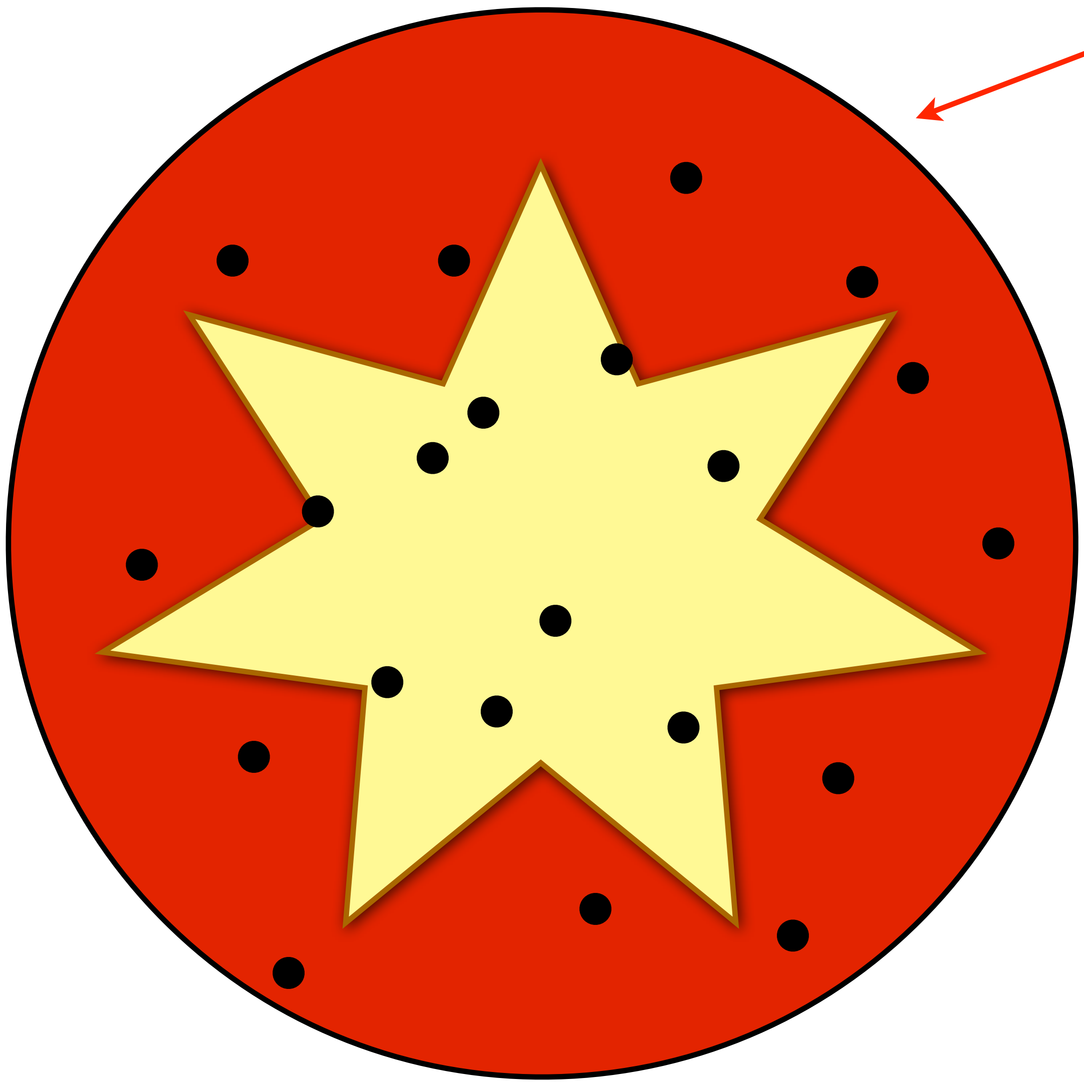

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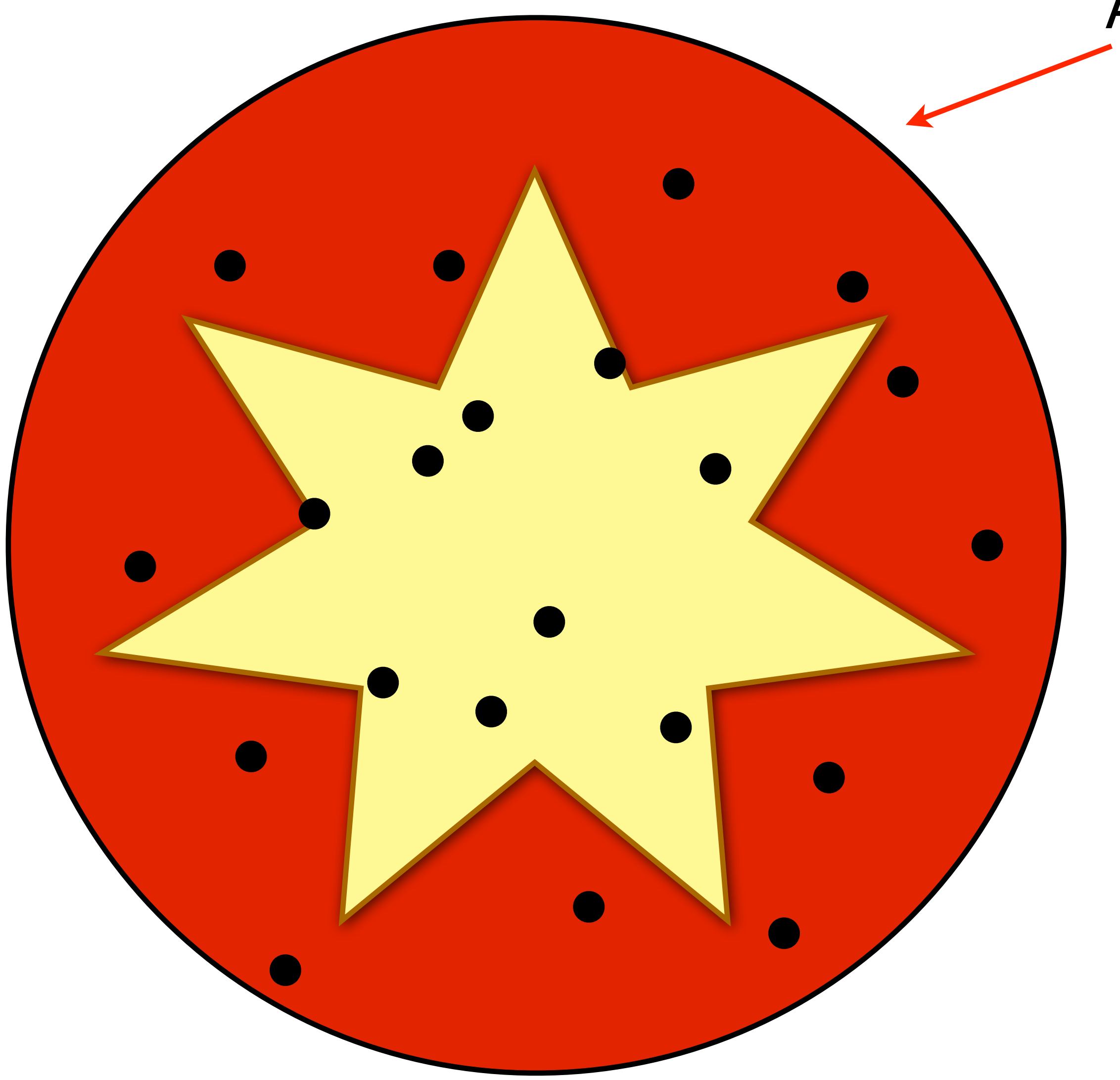

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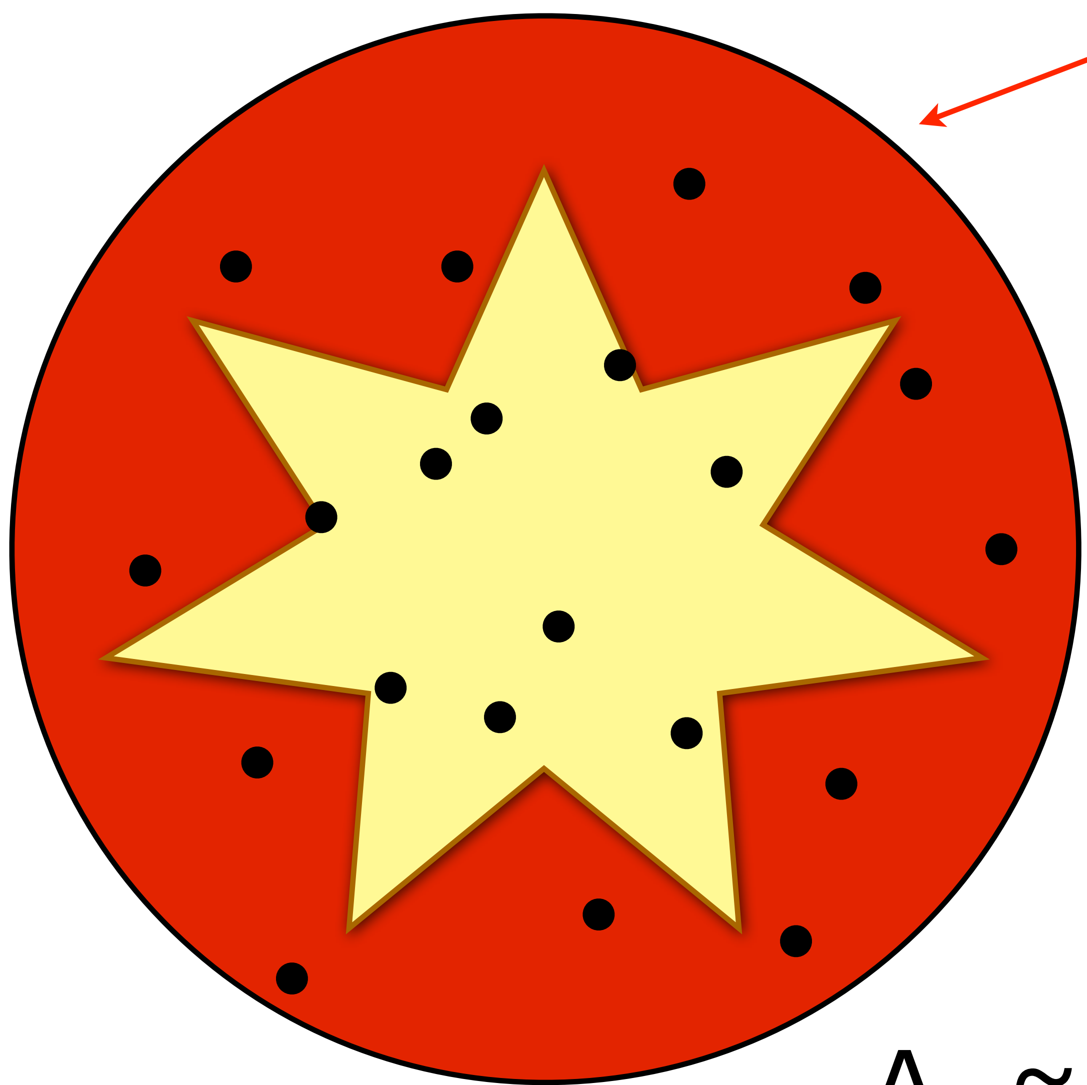

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$$A_{\star} \approx N_{hit}/N_{miss} \times \pi R^2$$

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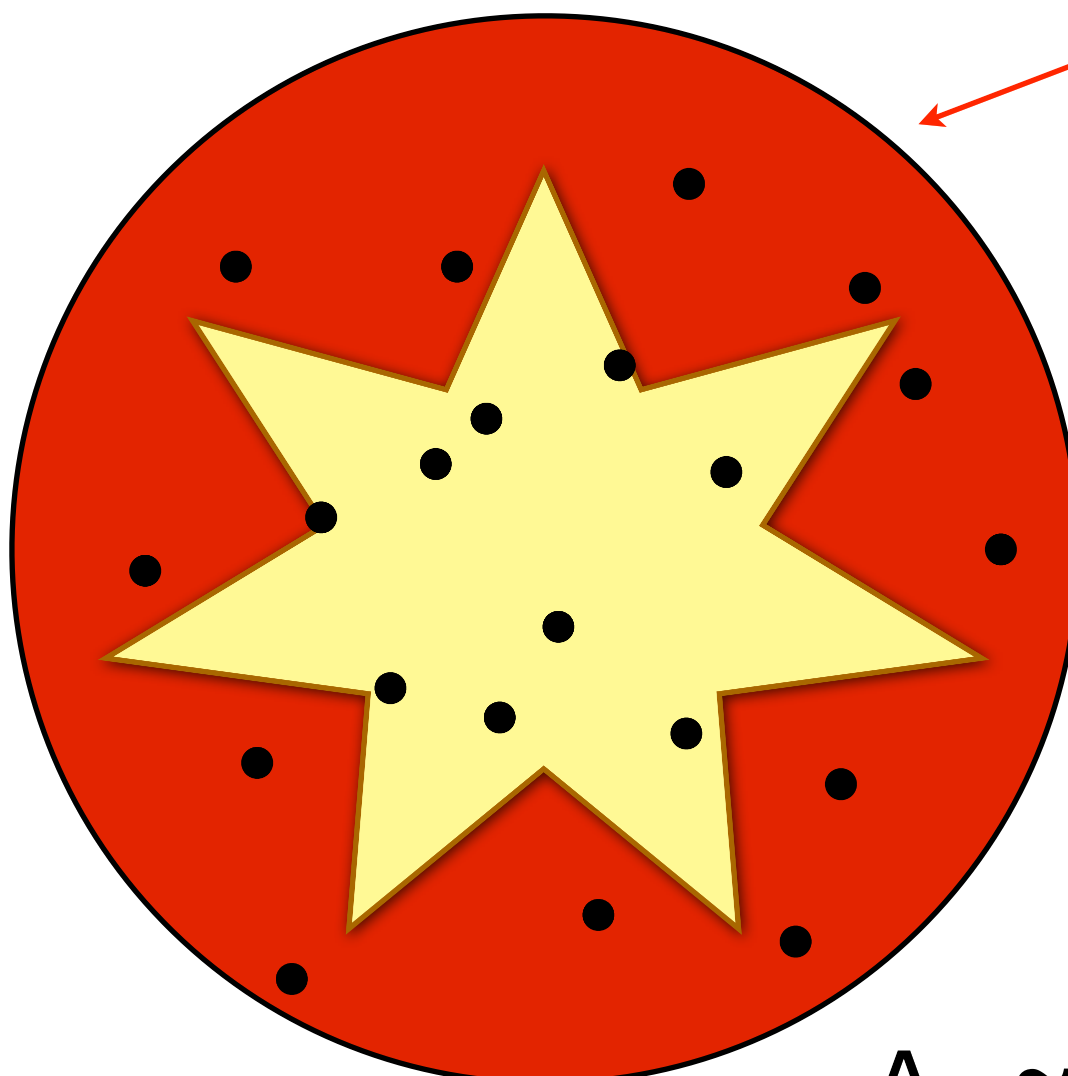

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πR^2
(an overestimate)

Earliest Example of MC calculation: Buffon's Needle (1777) to calculate π

G. Leclerc, Comte de Buffon (1707-1788)

$$A_{\star} \approx N_{hit}/N_{miss} \times \pi R^2$$

A Monte Carlo technique: is any technique making use of random numbers to solve a problem

A Monte Carlo technique: is any technique making use of random numbers to solve a problem

Convergence:

Calculus: {A} converges to B if an n exists for which $|A_{i>n} - B| < \varepsilon$, for any $\varepsilon > 0$

Monte Carlo: {A} converges to B if n exists for which the probability for $|A_{i>n} - B| < \varepsilon$, for any $\varepsilon > 0$, is > P, for any P[0<P<1]

A Monte Carlo technique: is any technique making use of random numbers to solve a problem

Convergence:

Calculus: {A} converges to B if an n exists for which $|A_{i>n} - B| < \varepsilon$, for any $\varepsilon > 0$

Monte Carlo: {A} converges to B if n exists for which the probability for $|A_{i>n} - B| < \varepsilon$, for any $\varepsilon > 0$, is > P, for any P[0<P<1]

"This risk, that convergence is only given with a certain probability, is inherent in Monte Carlo calculations and is the reason why this technique was named after the world's most famous gambling casino. Indeed, the name is doubly appropriate because the style of gambling in the Monte Carlo casino, not to be confused with the noisy and tasteless gambling houses of Las Vegas and Reno, is serious and sophisticated."

F. James, "Monte Carlo theory and practice", Rept. Prog. Phys. 43 (1980) 1145

Random Numbers

I will not tell you how to *write* a Random-number generator (interesting topic & history in its own right)

Instead, I *assume* that you can write a computer code and link to a random-number generator, from a library

E.g., ROOT includes one that you can use if you like.

PYTHIA also includes one

From the PYTHIA 8 HTML documentation, under "Random Numbers":

Random numbers R uniformly distributed in 0 < R < 1 are obtained with

```
Pythia8::Rndm::flat();
```

+ Other methods for exp, x*exp, 1D Gauss, 2D Gauss.

Example: Number of summer students who will get hit by a car during the next 3 weeks

Complicated Function:

- **Time-dependent**
  - Traffic density during day, week-days vs week-ends
    - (i.e., non-trivial time evolution of system)
- **No two students are the same**
  - Need to compute probability for each and sum
    - (simulates having several distinct types of “evolvers”)
- **Multiple outcomes:**
  - Hit → keep walking, or go to hospital?
  - Multiple hits = Product of single hits, or more complicated?

Monte Carlo Approach

Approximate Traffic

Simple overestimate:

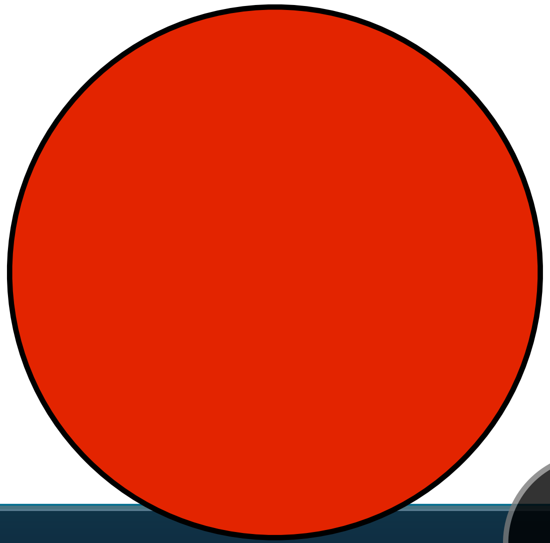
highest recorded density
of most careless drivers,
driving at highest recorded speed
etc.

Approximate Student

by most accident-prone student / famous person / movie star / …

(not making fun of handicapped people …)

This extreme guess will be the equivalent of our simple overestimate from before:



Hit Generator

Off we go…

Throw random accidents according to:

$$\sum_{i=1}^{n_{\mathrm{stud}}} \alpha_i(x,t)\ \rho_i(x,t)\ \rho_C(x,t)$$

Sum over students — Student-Car hit rate — Density of Student i — Density of Cars

(Also generate trial x_e, e.g., uniformly in your town)

(Also generate trial i; a random student gets hit)

Hit Generator

Off we go…

Throw random accidents according to:

$$R = \int_{t_0}^{t_e} \mathrm{d}t \int_x \mathrm{d}x \sum_{i=1}^{n_\mathrm{stud}} \alpha_i(x,t)\, \rho_i(x,t)\, \rho_C(x,t)$$

Sum over students

Student-Car hit rate

Density of Student i

Density of Cars

t_e : time of accident

(Also generate trial x_e, e.g., uniformly in your town)

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Sum over students

$\alpha_i(x,t)$: Student-Car hit rate

$\rho_i(x,t)$: Density of Student i

$\rho_c(x,t)$: Density of Cars

t_e : time of accident

Too Difficult

(Also generate trial x_e, e.g., uniformly in your town)

(Also generate trial i; a random student gets hit)

Hit Generator

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Throw random accidents according to:

$$R = \int_{t_0}^{t_e} \mathrm{d}t \int_x \mathrm{d}x \sum_{i=1}^{n_{\mathrm{stud}}} \alpha_i(x,t)\, \rho_i(x,t)\, \rho_c(x,t)$$

- $\sum_{i=1}^{n_{\mathrm{stud}}}$: Sum over students
- $\alpha_i(x,t)$: Student-Car hit rate
- $\rho_i(x,t)$: Density of Student i
- $\rho_c(x,t)$: Density of Cars

t_e : time of accident

Too Difficult → Simple Overestimate

(Also generate trial x_e, e.g., uniformly in your town)

(Also generate trial i; a random student gets hit)

Hit Generator

Off we go…

Throw random accidents according to:

$$R = \int_{t_0}^{t_e} \mathrm{d}t \int_x \mathrm{d}x \sum_{i=1}^{n_{\mathrm{stud}}} \alpha_i(x,t)\, \rho_i(x,t)\, \rho_c(x,t)$$

Sum over students

Student-Car hit rate

Density of Student i

Density of Cars

Too Difficult

t_e : time of accident

$$R = (t_e - t_0)\Delta x \quad \alpha_{\max}\, n_{\mathrm{stud}}\, \rho_{c\max}$$

Hit rate for most accident-prone student

Rush-hour density of cars

Simple Overestimate

(Also generate trial x_e, e.g., uniformly in your town)

(Also generate trial i; a random student gets hit)

Hit Generator

Accept trial hit (i,x,t) with probability

$$\text{Prob(accept)} = \frac{\alpha_i(x,t)\ \rho_i(x,t)\ \rho_c(x,t)}{\alpha_{\max}\ n_{\text{stud}}\ \rho_{\text{cmax}}}$$

Using the following:

ρ_c : actual density of cars at location x at time t

ρ_i : actual density of student i at location x at time t

α_i : The actual “hit rate” (OK, not really known, but can make one up)

Hit Generator

Accept trial hit (i,x,t) with probability

Prob(accept) = $\dfrac{\alpha_i(x,t)\ \rho_i(x,t)\ \rho_c(x,t)}{\alpha_{\mathrm{max}}\ n_{\mathrm{stud}}\ \rho_{\mathrm{cmax}}}$

Using the following:

ρ_c : actual density of cars at location x at time t

ρ_i : actual density of student i at location x at time t

α_i : The actual "hit rate" (OK, not really known, but can make one up)

→ True number = number of accepted hits
(note: we didn't really treat multiple hits … → Markov Chain)

VINCIA

The “Jeppsson” Project

April 2010

The Jeppsson Project

April 2009: FB message from friend of friend: can a 15-yr old be a one-week intern at CERN?

We were developing a run-time display for our simulation anyway.

April 2010: simple text editor to edit input cards. Run-time display to compare output histograms to data.

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```
! * Strong-force Coupling
Vincia:alphaSValue        = 0.138

! * Hadronic Energy Scale
Vincia:cutoffScale        = 0.45

! * String parameters
StringZ:aLund             = 0.38
StringZ:bLund             = 0.62
StringPT:sigma            = 0.26
```

```
! * Quark flavor parameters
StringFlav:probStoUD      = 0.21
StringFlav:mesonUDvector  = 0.35
StringFlav:mesonSvector   = 0.55
StringFlav:probQQtoQ      = 0.08
StringFlav:probSQtoQQ     = 1.00
StringFlav:probQQ1toQQ0   = 0.03
StringFlav:decupletSup    = 1.00
StringFlav:etaSup         = 0.60
StringFlav:etaPrimeSup    = 0.10
```

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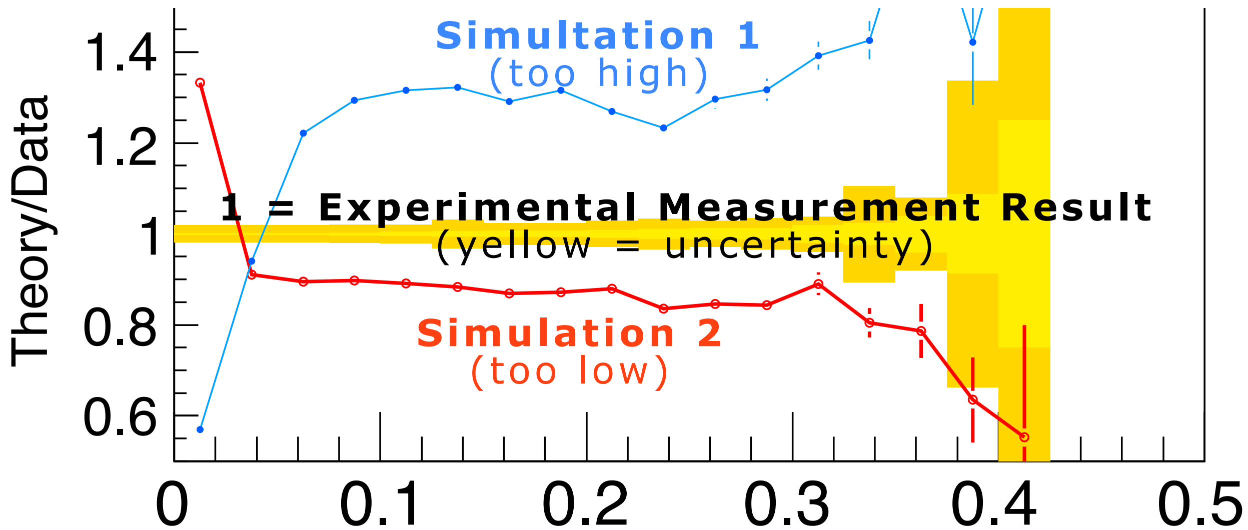
Example: the effect of changing Vincia:alphaSvalue



"Thrust": Measures how "spherical" events are → 1-T (udsc)

```
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! * Hadronic Energy Scale
Vincia:cutoffScale         = 0.45

! * String parameters
StringZ:aLund              = 0.38
StringZ:bLund              = 0.62
StringPT:sigma             = 0.26
```

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StringFlav:mesonSvector  = 0.55
StringFlav:probQQtoQ       = 0.08
StringFlav:probSQtoQQ      = 1.00
StringFlav:probQQ1toQQ0  = 0.03
StringFlav:decupletSup    = 1.00
StringFlav:etaSup          = 0.60
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→ Citizen Cyberlab Pilot Project

The Citizen Cyberlab ICT Project

Standalone 3-yr Project funded by EU (2012-2015)

CERN Task: create citizen science pilot project in particle physics

The EU funds a 2-year "CERN fellowship", started in May: Ioannis Charalimpidis

We will

Develop an application that lets citizen scientists **learn about, interact with, and optimize high-energy physics simulations**, by **comparing them to real data**

→ feedback to scientists

How?

Combine the framework and lessons from Test4Theory / LHC@home 2.0 with those from the Jeppsson project → **Atom Smasher Application**

Provide content, explanations, visualizations (**mod**ifiable and open)

Organize one or more **citizen-science events** at CERN (e.g., hack fests, event for CERN open day in September), host **summer students** (IT or Physics masters student), ...

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We now have ~ 6 months to develop the first rough prototype

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Possible study / project topics?

Maths

- Basic statistics (and data analysis, can also be related to social studies, polling, etc)
- Random numbers
- Markov chains

Physics

- The strong nuclear force (and explicit simulations of it)
- Setting up and running your own virtual atom smasher, and learning about the particles it produces

Computer Science

- Virtual Machines (e.g., Linux-CernVM), with the Test4Theory project as a concrete example
- Distributed computing, using the Test4Theory volunteer cloud as a real-world example inviting participation