Title: Large Extra Dimensions - ISSYP Keynote Session

Date: Aug 23, 2007 09:00 AM

URL: http://pirsa.org/07080061

Abstract: It is an open question why gravity is so much weaker than the other three interactions we know. One possible answer which has been suggested is that this mismatch is only apparently so, and a feature we observe on large distances.
The strength of gravity on small distances could grow faster than an extrapolation of Newton\'s law would imply, such that it becomes comparable to the other interactions at distances that will be testable in the soon future. The concrete scenario for this is that our world could have additional compactified extra dimensions. If that was the case, quantum gravitational effects could become observable at the Large Hadron Collider. The most prominent features in these models are the production of mini black holes, and graviton emission.

Large Extra Dimensions

Sabine Hossenfelder

Perimeter Institute

Large Extra Dimensions

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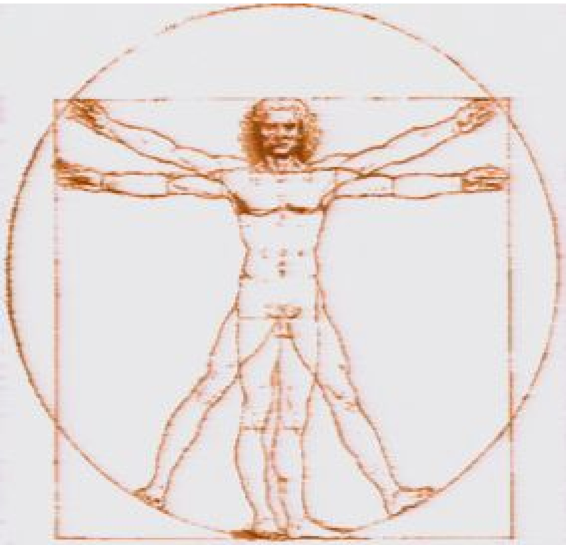
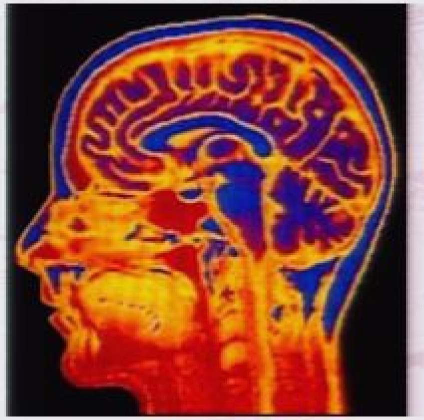
Perimeter Institute

micro



macro

messy



Research departs more and more from our every day experience

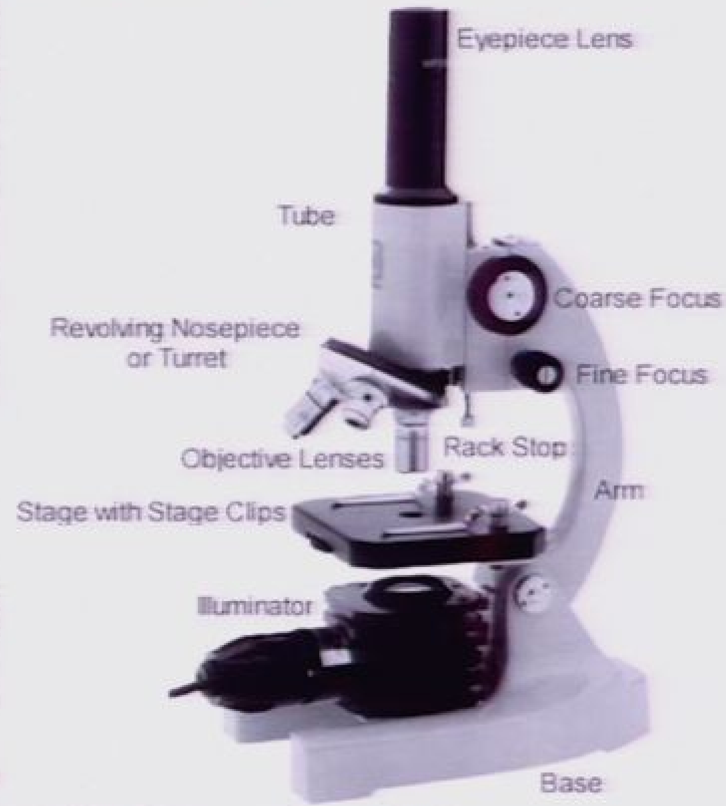
New experiments require more and more preparation/technology

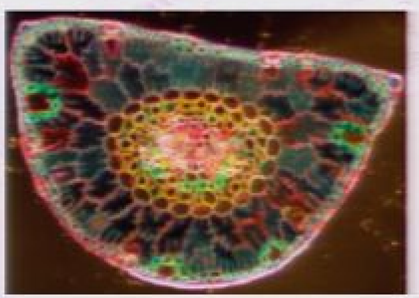
Light Microscope

- Uses light (photons)
- Directed with mirrors and lenses
- Resolution limited by wavelength of light

$$\Delta x > \lambda \propto \frac{1}{\omega}$$

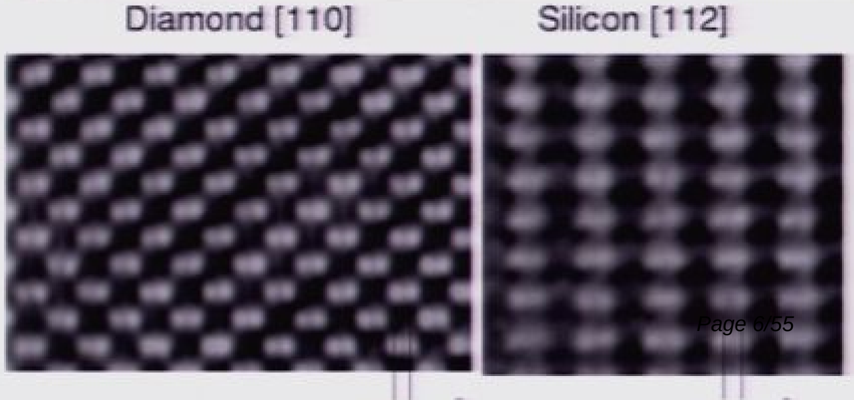
- Typically: size of cells or crystals





Electron Microscope

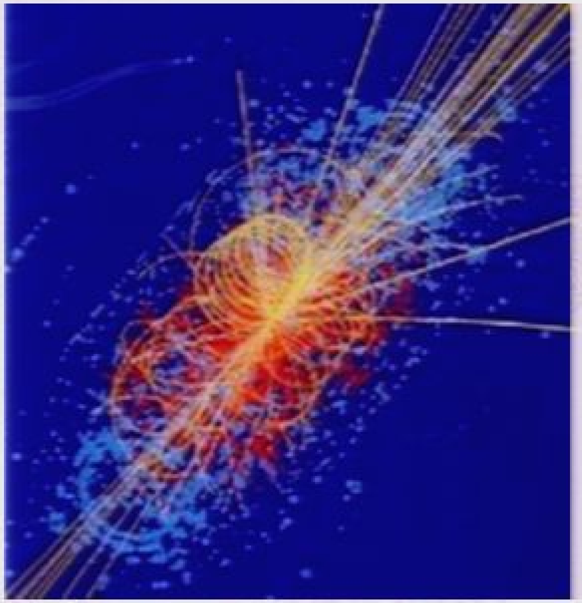
- Uses beams of electrons
- Directed with electric and magnetic fields
- The faster, the better the resolution $\lambda = \frac{h}{p}$
- Typically: about the size of an atom



Particle accelerator

- Fixed Target or Collider
- Examine Debris of Collision
- Linear or Circular
- Present resolution:

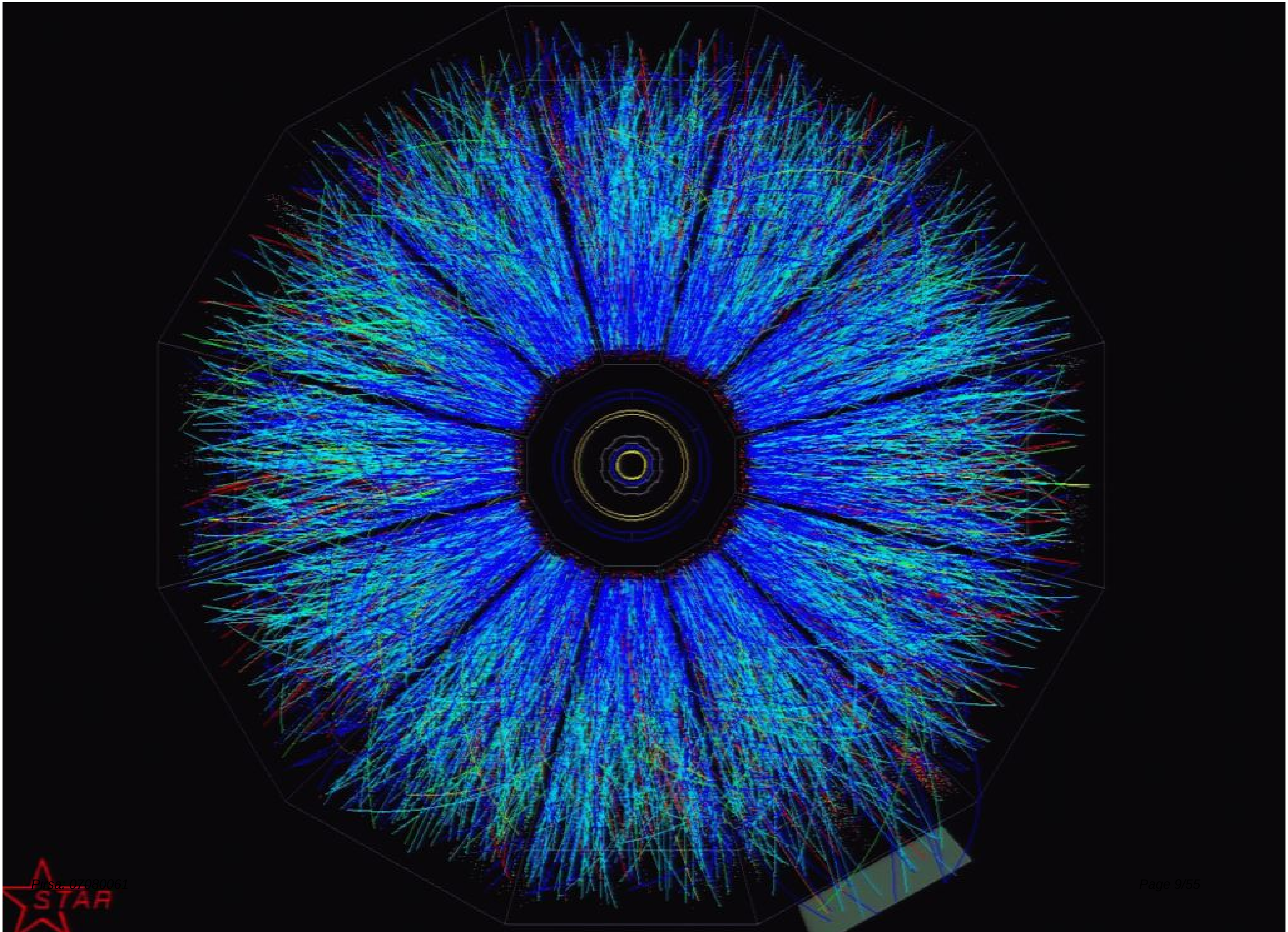
  proton sub-structure (quarks)



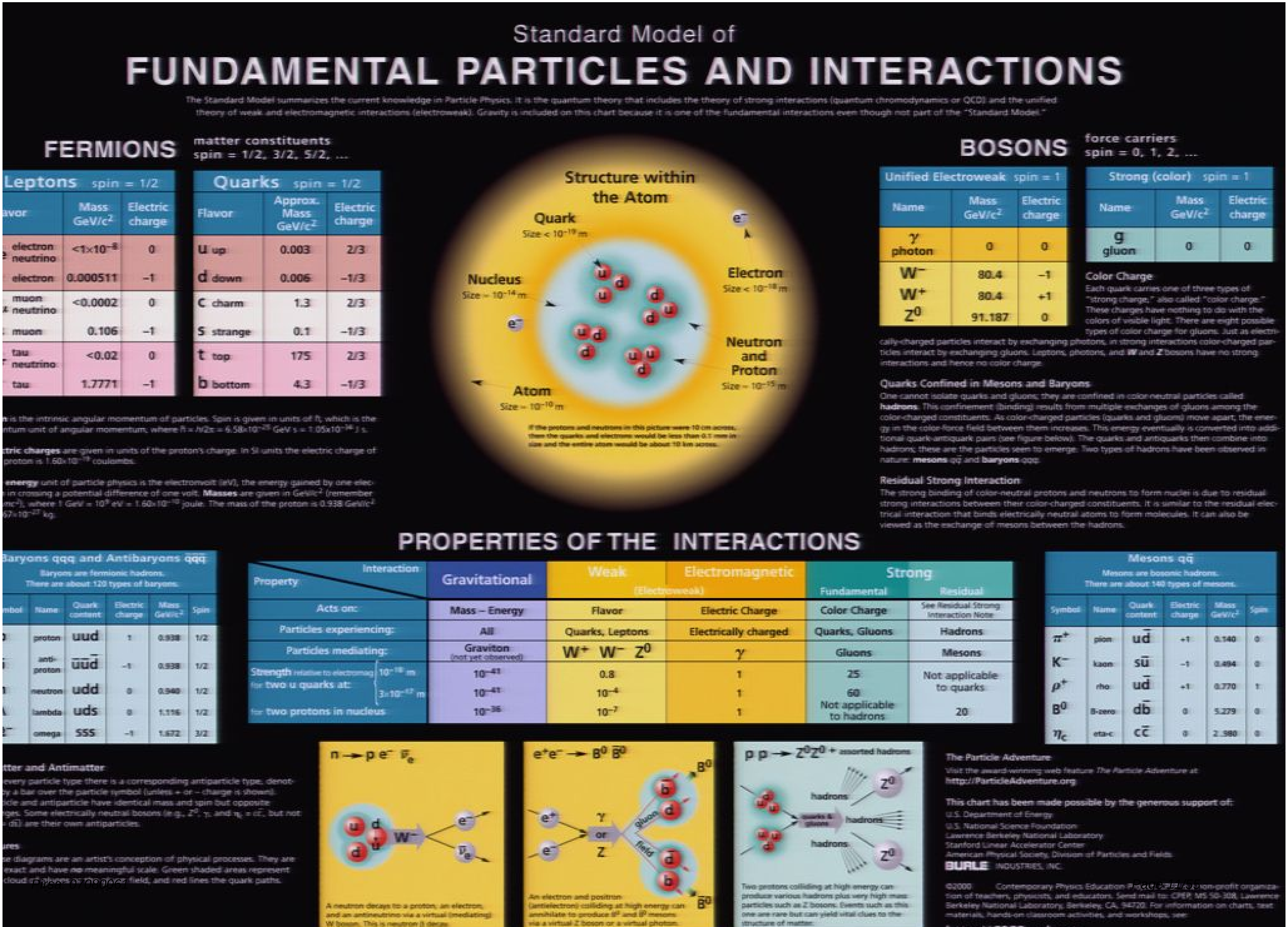
- Circular: Synchroton radiation loss

$$\text{Energy loss} \propto \left(\frac{E}{mc^2}\right)^4 \frac{1}{R^2}$$


Damping Rings
Linear Accelerator
Shops
Central Laboratory Complex
Main Control Center
End Station B
End Station A
SSRL Complex
PEP Detector Halls
PEP Detector Halls
Positron Arc
Electron Arc
Collider Experimental Hall



The current Frontier of our Knowledge:
The Standard Model of Particle Physics


Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS
FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...
Leptons spin = 1/2
Mass GeV/c²
Electric charge
electron neutrino
<1×10⁻⁸
0
electron
0.000511
−1
muon neutrino
<0.0002
0
muon
0.106
−1
tau neutrino
<0.02
0
tau
1.7771
−1
Quarks spin = 1/2
Flavor
Approx. Mass GeV/c²
Electric charge
u up
0.003
2/3
d down
0.006
−1/3
c charm
1.3
2/3
s strange
0.1
−1/3
t top
175
2/3
b bottom
4.3
−1/3
Structure within the Atom
Quark
Size < 10⁻¹⁹ m
Electron
Size < 10⁻¹⁸ m
Nucleus
Size ≈ 10⁻¹⁴ m
Neutron and Proton
Size ≈ 10⁻¹⁵ m
Atom
Size ≈ 10⁻¹⁰ m
BOSONS
force carriers
spin = 0, 1, 2, ...
Unified Electroweak spin = 1
Name
Mass GeV/c²
Electric charge
γ photon
0
0
W⁻
80.4
−1
W⁺
80.4
+1
Z⁰
91.187
0
Strong (color) spin = 1
g gluon
0
0
Color Charge
Quarks Confined in Mesons and Baryons
Residual Strong Interaction
PROPERTIES OF THE INTERACTIONS
Property
Interaction
Gravitational
Weak (Electroweak)
Electromagnetic
Strong
Fundamental
Residual
Acts on:
Mass – Energy
Flavor
Electric Charge
Color Charge
See Residual Strong Interaction Note
Particles experiencing:
All
Quarks, Leptons
Electrically charged
Quarks, Gluons
Hadrons
Particles mediating:
Graviton (not yet observed)
W⁺ W⁻ Z⁰
γ
Gluons
Mesons
Strength relative to electromag for two u quarks at:
10⁻¹⁸ m
10⁻⁴¹
0.8
1
25
Not applicable to quarks
3×10⁻¹⁷ m
10⁻⁴¹
10⁻⁴
1
60
for two protons in nucleus
10⁻³⁶
10⁻⁷
1
Not applicable to hadrons
20
Baryons qqq and Antibaryons q̄q̄q̄
Baryons are fermionic hadrons.
There are about 120 types of baryons.
proton
uud
1
0.938
1/2
anti-proton
ūūd̄
−1
0.938
1/2
neutron
udd
0
0.940
1/2
lambda
uds
0
1.116
1/2
omega
sss
−1
1.672
3/2
Mesons qq̄
Mesons are bosonic hadrons.
There are about 140 types of mesons.
Symbol
Name
Quark content
Electric charge
Mass GeV/c²
Spin
π⁺
pion
ud̄
+1
0.140
0
K⁻
kaon
sū
−1
0.494
0
ρ⁺
rho
ud̄
+1
0.770
1
B⁰
B-zero
db̄
0
5.279
0
ηc
eta-c
cc̄
0
2.980
0
Matter and Antimatter
n → p e⁻ ν̄e
e⁺e⁻ → B⁰ B̄⁰
p p → Z⁰Z⁰ + assorted hadrons
The Particle Adventure
http://ParticleAdventure.org
This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
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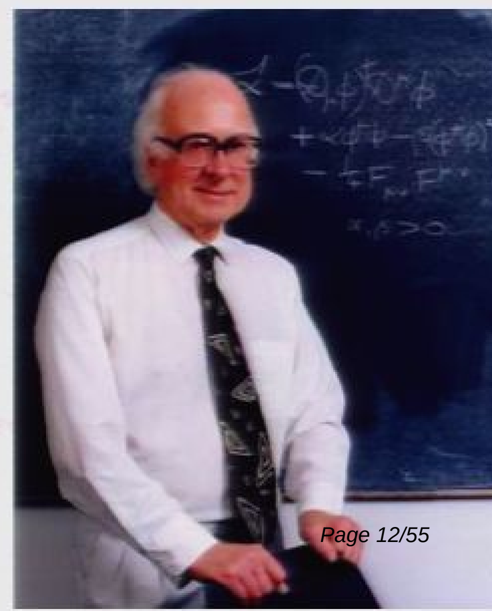
http://CPEPweb.org

The Higgs

- Gives particle masses (breaks electroweak symmetry through a non-zero vacuum expectation value)
- The standard model needs the Higgs for consistency
- It is theoretically predicted to become observable at energies around 150 GeV (TeVatron might just have missed it)

Only confirmed
sighting of a Higgs so far:



Peter Ware Higgs
(Born May 29, 1929)

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
electron neutrino	<1×10⁻⁸	0
electron	0.000511	−1
muon neutrino	<0.0002	0
muon	0.106	−1
tau neutrino	<0.02	0
tau	1.7771	−1

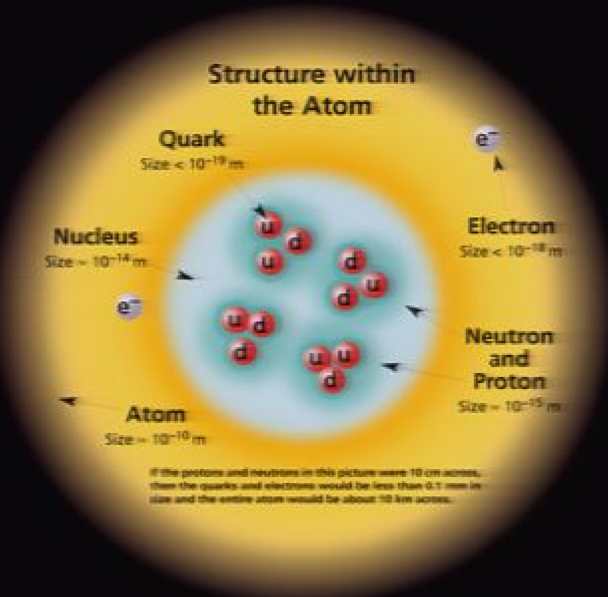
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

...n is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the ...ntum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

...tric charges are given in units of the proton's charge. In SI units the electric charge of ... proton is 1.60×10^{-19} coulombs.

... energy unit of particle physics is the electronvolt (eV), the energy gained by one elec... in crossing a potential difference of one volt. Masses are given in GeV/c² (remember ...mc²), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c² ...67×10⁻²⁷ kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W⁻	80.4	−1
W⁺	80.4	+1
Z⁰	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and *W* and *Z* bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W⁺ W⁻ Z⁰	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10⁻¹⁸ m	10⁻⁴¹	0.8	1	25	Not applicable to quarks
3×10⁻¹⁷ m	10⁻⁴¹	10⁻⁴	1	60	
for two protons in nucleus	10⁻³⁶	10⁻⁷	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω⁻	omega	sss	−1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons. There are about 140 types of mesons.

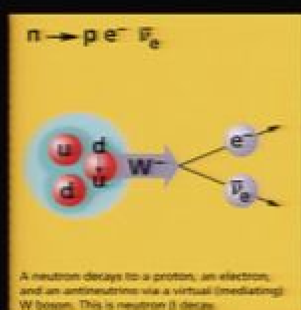
Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π⁺	pion	$u\bar{d}$	+1	0.140	0
K⁻	kaon	$s\bar{u}$	−1	0.494	0
ρ⁺	rho	$u\bar{d}$	+1	0.770	1
B⁰	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

...tter and Antimatter

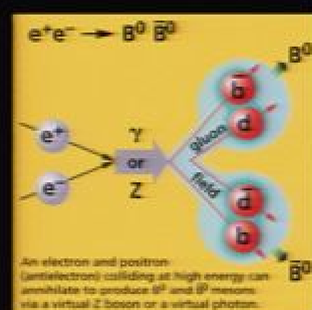
...every particle type there is a corresponding antiparticle type, denot... by a bar over the particle symbol (unless + or − charge is shown). ...icle and antiparticle have identical mass and spin but opposite ...ges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not ...$= d\bar{s}$) are their own antiparticles.

...ures

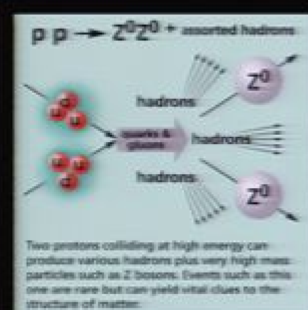
...se diagrams are an artist's conception of physical processes. They are ...exact and have no meaningful scale. Green shaded areas represent ... cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B⁰ and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at: http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

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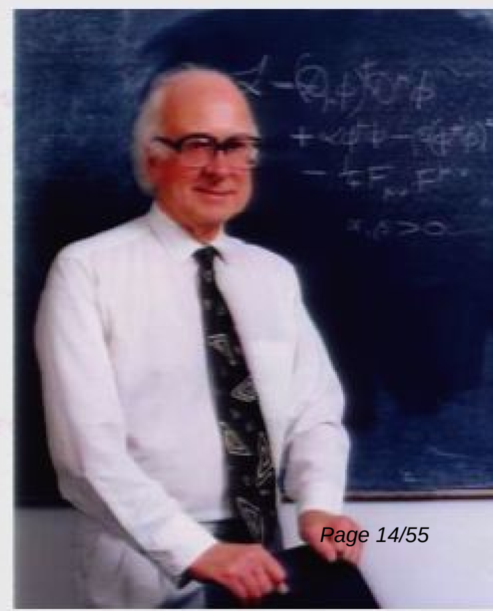

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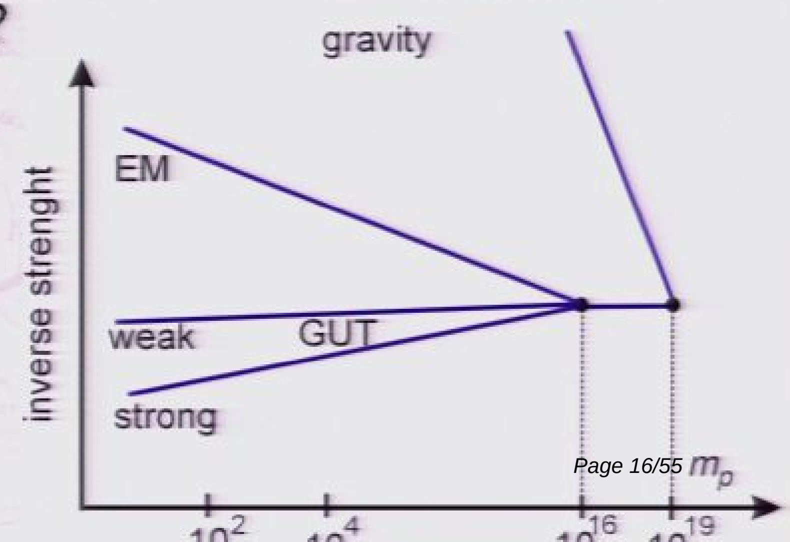
Supersymmetry

- Every boson is paired with a fermion (gluon-gluino, electron – selectron, graviton- gravitino…)
- Charges are not modified
- Doubles the number of particles in the SM
- Supersymmetric partners are considerably heavier – otherwise we had already seen them (the symmetry is 'broken')
- An essential feature of string theory
- Expected to become observable at the LHC (around energies of ~ TeV)

Looking closer

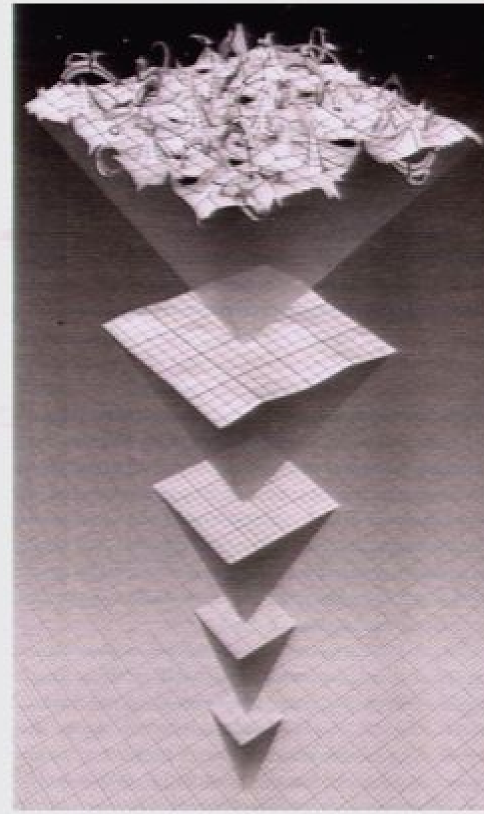
- Where is gravity?
- Gravity is much weaker than the other interactions:
  ⇨ *the 'Hierarchy problem'*
- Extrapolating the strength of forces, one expects gravity to show quantum effects at the so-called Planck-scale: 10^{-33} cm
- Can we trust this extrapolation?



The electromagnetic force between two electrons is 10^{43} times larger than the gravitational one!

Looking *even* Closer

- What if quantum effects of gravity aren't as far off as we thought they are?
- Surprisingly: we wouldn't have yet noticed
- Concrete scenario: extra dimensions

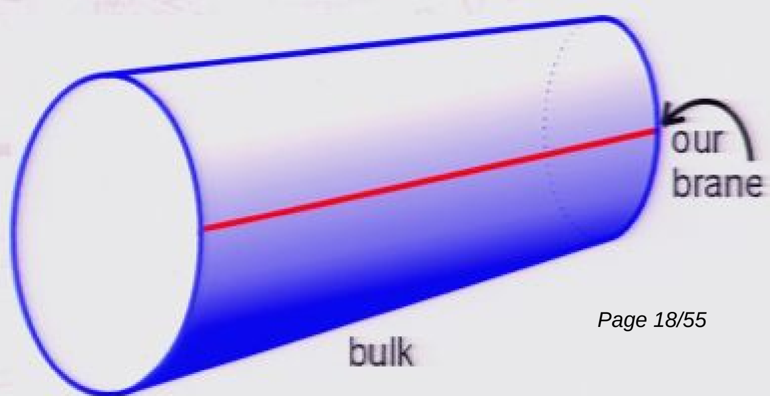


Oskar Klein
(Sep 15, 1894 - Feb 5, 1977)

Theodor Franz Eduard Kaluza
(Nov 9, 1885 – Jan 19, 1954)

Extra Dimensions

- Why do we live in a 3 dimensional space?
  - Nobody knows
- Could there be more dimensions that we have not noticed so far…?
  - … because they are curled up to small circles?
- Extra dimensions are required for consistency in string theory.
- How could we find out?



The Planck Scale

- Weakness of gravity could be a result of compactified extra dimensions:
- Unlike other interactions, gravitational force lines dilute into all dimensions
- Therefore gravity thins out faster
- At distances larger than the extra dimensions, it behaves as usual, but the total strength is lowered

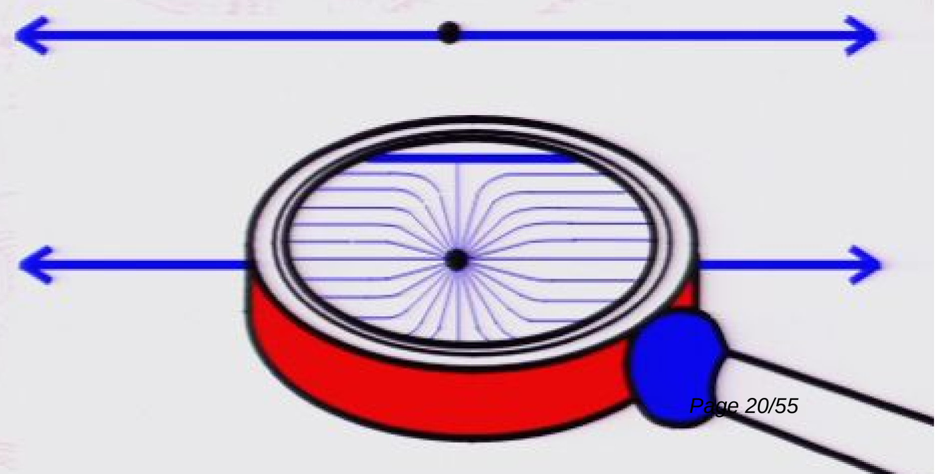
Quantum Gravity could be just around the corner...

Higher Dimensional Gravity

- Gravitational potential in 3 dimensions, coupling usual gravitational constant $G = 1/m_p^2$
- Gravitational potential in 3+d dimensions, with new higher dimensional coupling
- Matching at ~ R: relation between 'true' higher dimensional coupling and apparent coupling

$$V = \frac{1}{m_p^2}\frac{1}{r}$$

$$V = \frac{1}{M_f^{d+2}}\frac{1}{r^{d+1}} \rightarrow \frac{1}{M_f^{d+2}}\frac{1}{R^d}\frac{1}{r}$$



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$$V = \frac{1}{m_p^2}\frac{1}{r} \qquad m_p^2 = R^d M_f^{d+2}$$

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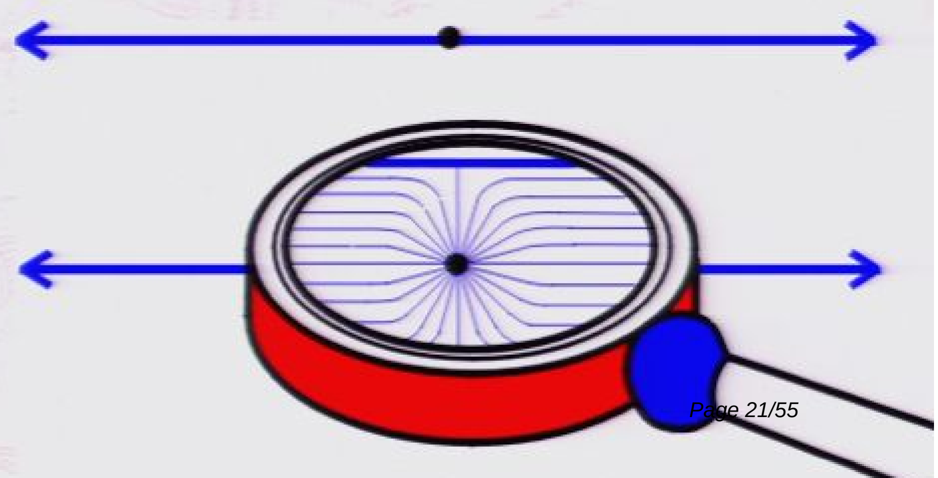

How 'Large' is Large?

If the 'true' higher dimensional scale for gravity is around the ElectroWeak scale then:

- $d=1$: $R=10^{12}$ m (excluded)
- $d=2$: $R=10^{-1}$ mm (sub-mm tests of Newton's law)
- $d=3$: $R=10^{6}$ fm
- $d=4$: $R=10^{3}$ fm
- ...

Large means: much larger than the Planck scale

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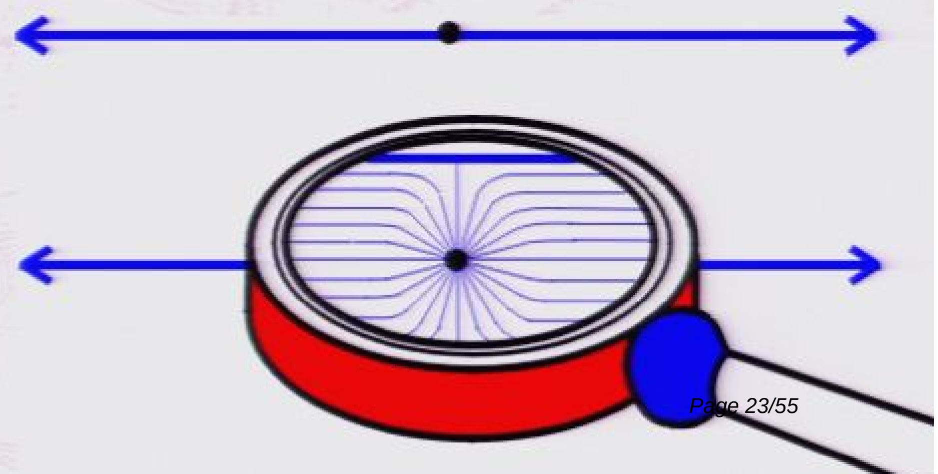

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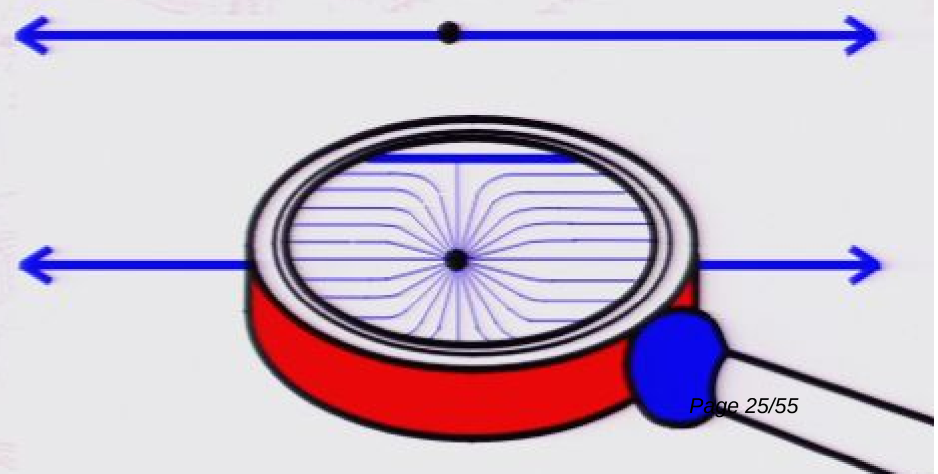

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- $d=4$: $R=10^{3}$ fm
- ...

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The Large Hadron Collider

- The World's Largest Microscope
- At CERN in Geneva (where the Web was born)
- Is expected to confirm the Higgs
- Hoped for:
  - Supersymmetry?
  - Quark sub-structure?
  - Dark Matter candidates?
  - Extra Dimensions?
- Expect the unexpected...

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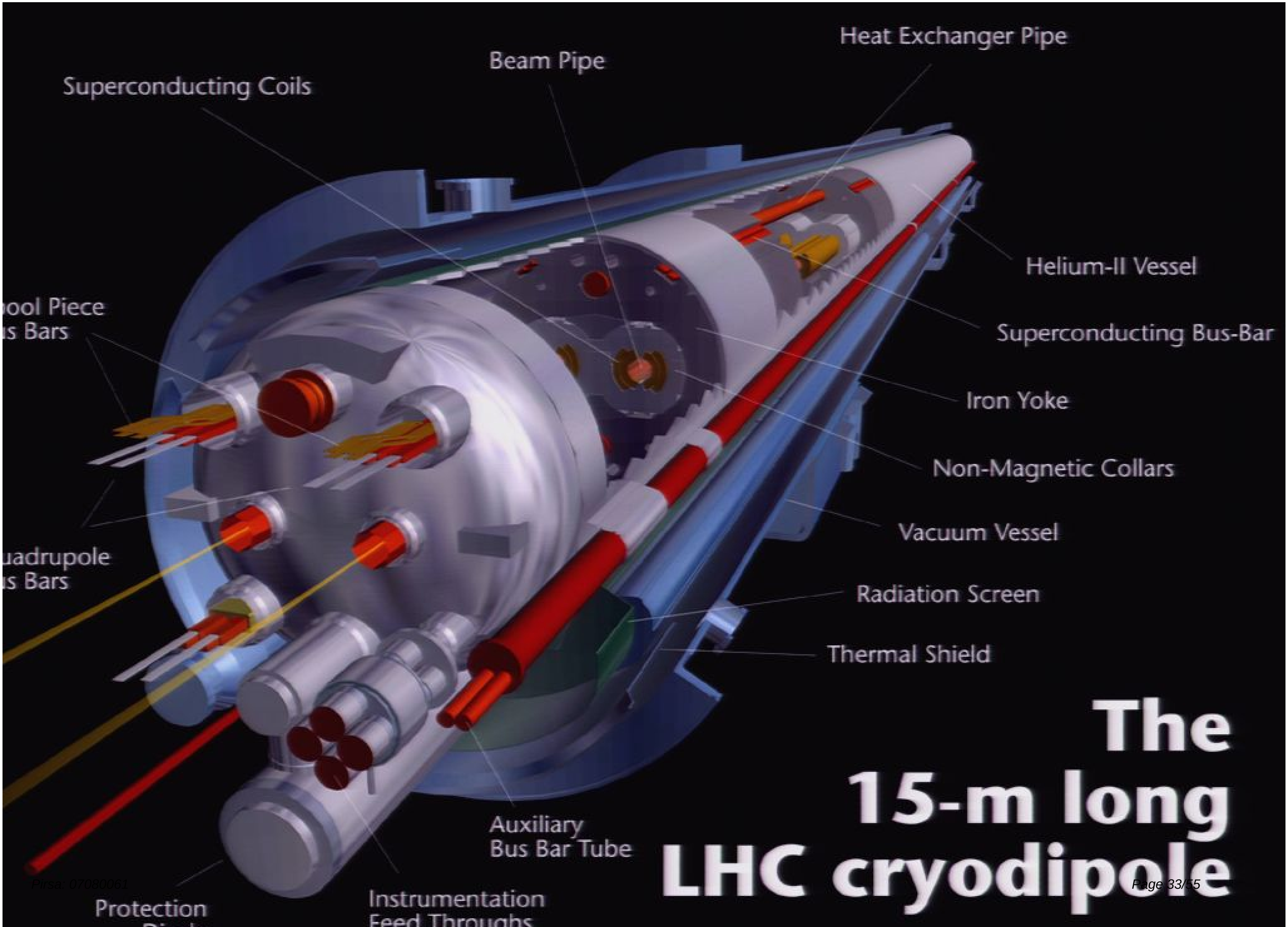
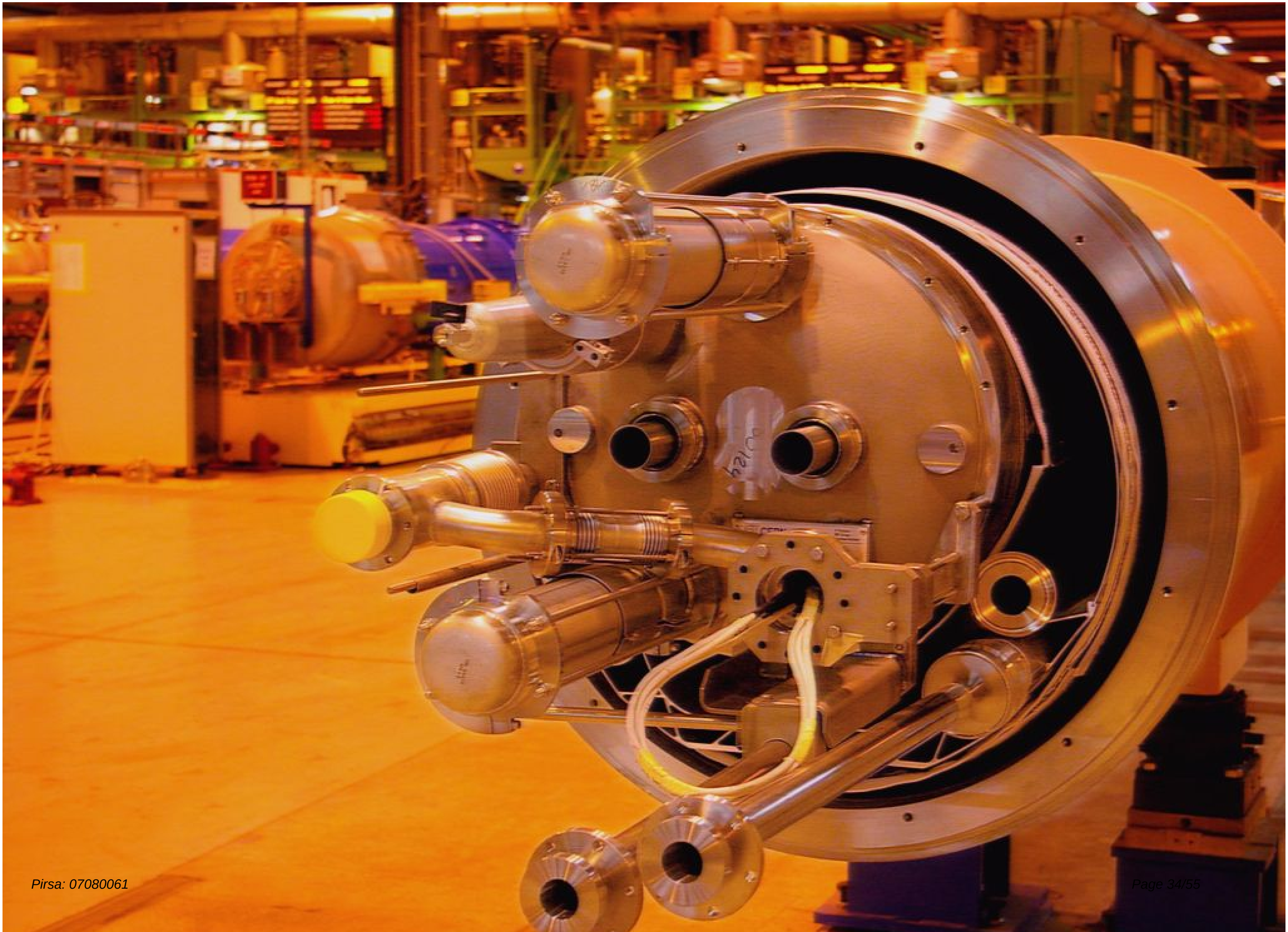
  - Dark Matter candidates?
  - Extra Dimensions?
- Expect the unexpected…

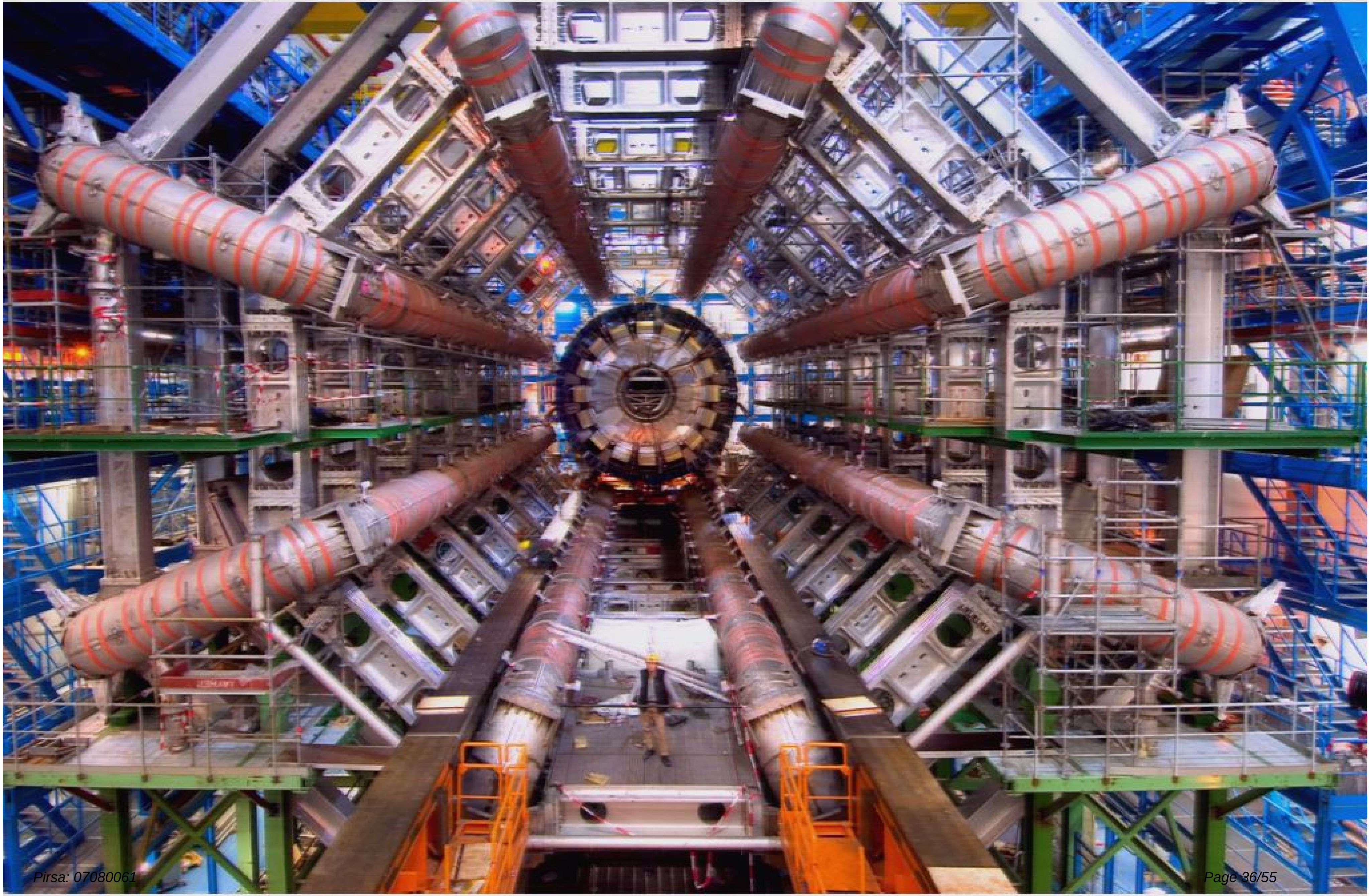
First Run: May 2008

LHC: some numbers

- Circumference: 26.6 km
- Tunnel is 50-150 m underground (re-used from LEP)
- Collides two proton beams a 7 TeV energy
- Will resolve distances as small as 10^{-18} m
- Dipole magnets are cooled to 1.9 K
- Vacuum in beam pipe comparable to outer space
- 1 proton makes 11,245 circuits every second
- Beam energy is influenced by the moon and the lake
- Cost: approx 3 Billion EUR.

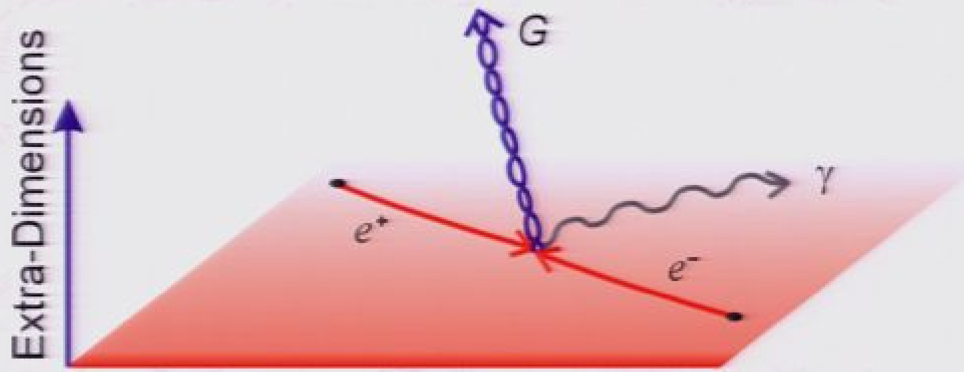

Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
ool Piece
s Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
uadrupole
s Bars
Radiation Screen
Thermal Shield
Auxiliary
Bus Bar Tube
Protection
Instrumentation
Feed Throughs
The
15-m long
LHC cryodipole





Quantum Gravity at the LHC

- Production of gravitons: energy loss because gravitons escape in the extra dimensions



- Virtual graviton contributions modify calculations of the standard model
- Black Hole production becomes possible!!

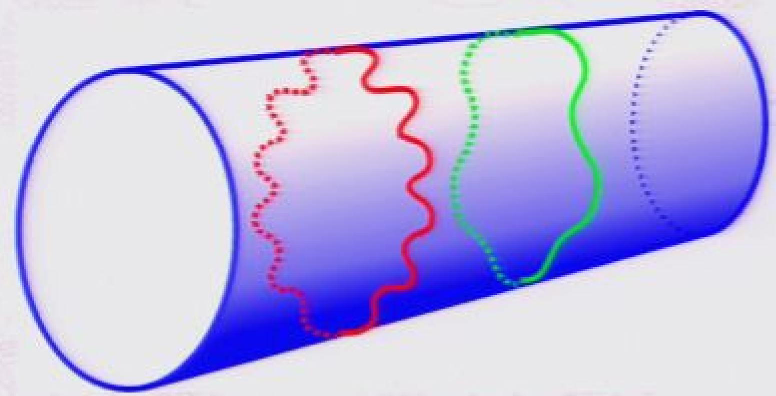
Caution: We still don't know how to consistently quantize gravity

Gravitons

- In the presence of extra dimensions, gravity is stronger at small distances (compared to no extra dimensions)
- Results in noticeable graviton emmission close by the fundamental scale
- Gravitons can propagate into all directions – momentum into extra dimensions is (geometrically) quantized
- This makes the gravitons appear as towers of massive particles on the submanifold

Gravitons

$$p_y \propto \frac{n}{R} \quad \rightarrow \quad \text{apparent mass}$$



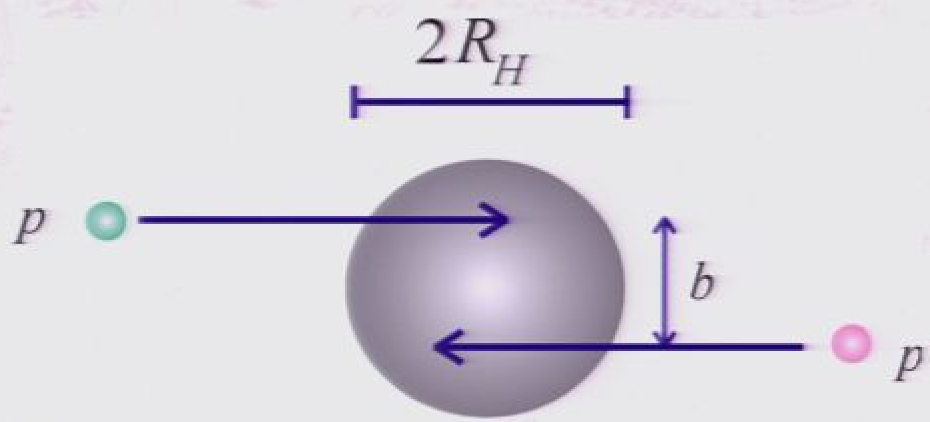
But these gravitons are not captured in the detector

So, this leads to a missing energy signal, denoted $\not{E}$

Inverse Problem

Black Holes at the LHC

- In the presence of extra dimensions, gravity is stronger at small distances (compared to no extra dimensions)
- This means: the horizon is at a larger radius
- Or: the compression of energy into a volume needed to cause a collapse can be reached at the LHC



Information Content of Black Holes

Thermodynamics

General Relativity

Quantum Field Theory

Stringtheory

Loop Gravity

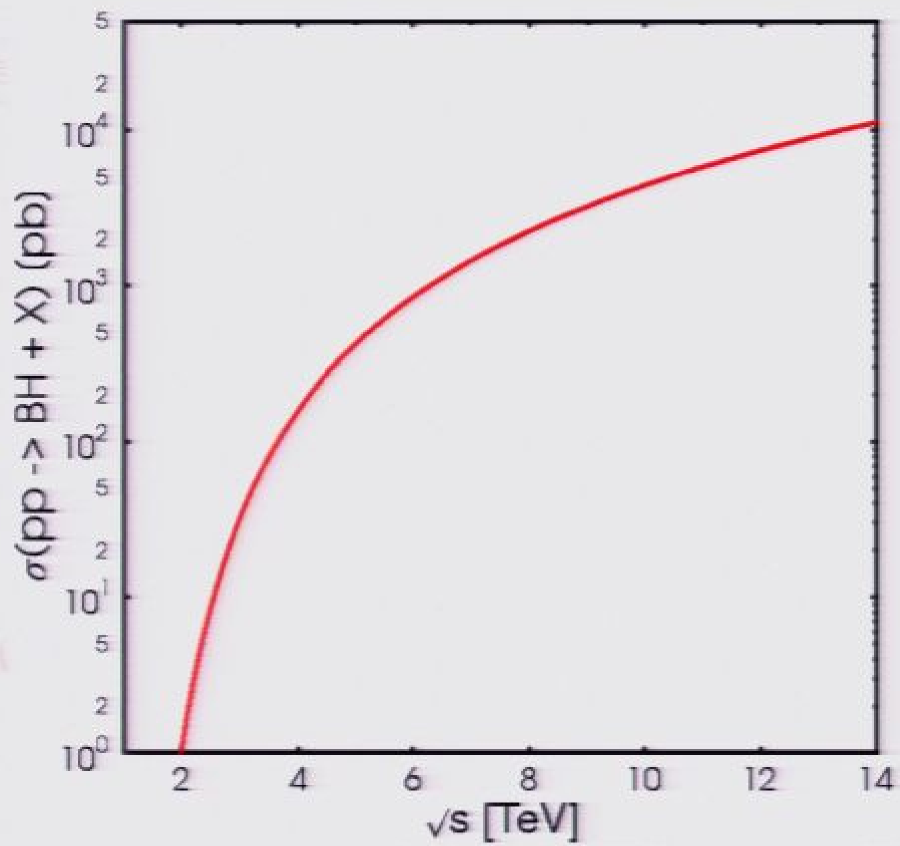
Particle Physics

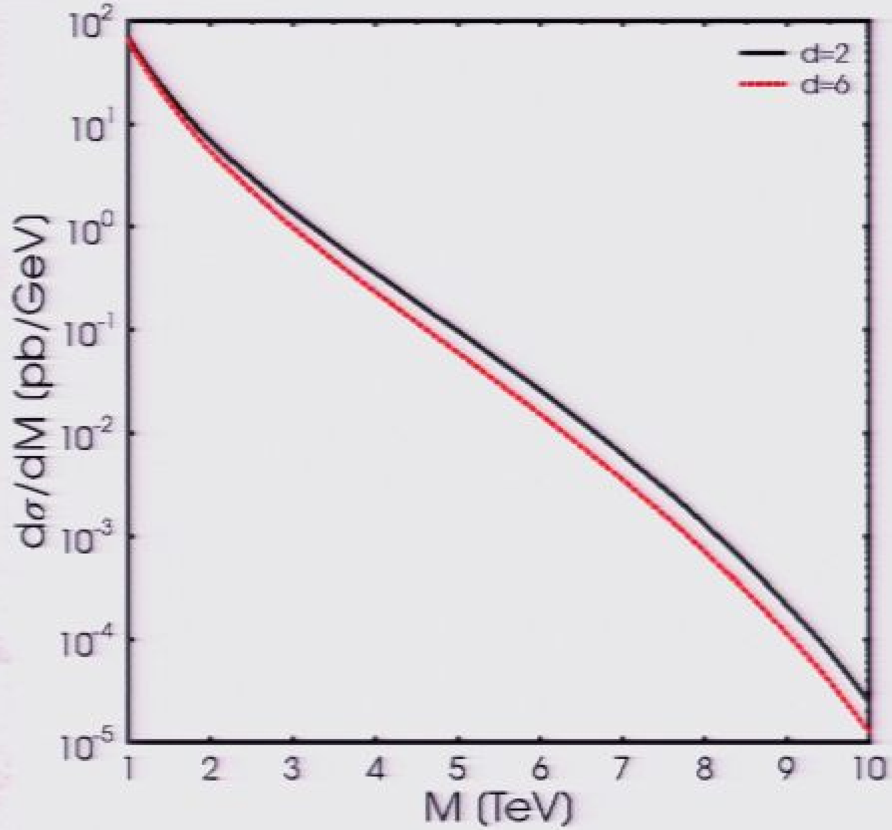
Black Hole Cross-Section

- Estimate cross-section with $\sigma = \pi R^2$
  Improve by using colliding wave-packages and examine for collapse condition
  LHC is a hadron collider ⇨ integrate over parton distribution functions
  Far less highest energetic collisions than for lepton collider

$$\frac{d\sigma}{dM} = \sum_{A_1 B_2} \int_0^1 dx_1 \frac{2\sqrt{\hat{s}}}{x_1 s} f_A(x_1, \hat{s}) f_B(y_2, \hat{s}) \sigma(\hat{s})$$

Black Hole Cross-Section





Expected production: 1 Black Hole per second

Are these Black Holes dangerous?

- Hawking (1975): black holes have temperature the 'Hawking radiation' with $T \sim m_p^2/M$
- The smaller the black hole, the larger its temperature
- Black holes at LHC are extremely hot
  - approx 200 GeV or 10^{16} K !!
- They evaporate within approx 10^{-22} seconds

⇨ They don't have time to grow

ORSCHUNG & TECHNIK

EILCHENPHYSIK

Angst vor dem großen Knall

Physiker wollen bei New York den Anfang des Universums erforschen und lösen Endzeitstimmung aus

VOR DEM ERSTEN STOSS Seit Juli flitzen Goldatome durch den unterirdischen Ringtunnel. Ab Herbst gehen sie auf Kollisionskurs

In der „Unendlichen Geschichte" von Michael Ende breitet sich das Nichts unaufhaltsam aus. Es reißt Tiere und Pflanzen fort, verschlingt Berge und Seen – und lässt von ganz Phantásien nicht mehr als ein Sandkorn übrig.

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CRASH-TESTS MIT ATOMEN SIMULIEREN URKNALL

Goldatome umrunden den Beschleunigerring fast 80 000-mal pro Sekunde. Wenn sie zusammenstoßen, schmelzen ihre Kerne zu einem Quark-Gluon-Plasma. Dieser ***eigenartige Materiebrei*** *existierte nur einen Sekundenbruchteil nach dem Urknall.*

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The London Times July 18, 1999

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Beim Aufprall pressen sich die Goldkerne zu einem winzigen Schwarzen Loch zusammen

Das Schwarze Loch saugt alles in seiner Umgebung auf und verschlingt den ganzen Erdball in Minuten

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Evaporation is faster than Mass Gain

The mass loss of the black hole from the evaporation

$$\frac{\mathrm{d}}{\mathrm{d}t}M_{-} \approx 10^{3}\,\mathrm{GeV/fm}$$

is much larger than any possible mass gain even in a very hot and dense medium (QGP, neutron star)

$$\frac{\mathrm{d}}{\mathrm{d}t}M_{+} = R_H^2 T^4 \approx 10^{-9}\,\mathrm{GeV/fm}$$

(even with a very high γ factor ~ 10^8)

⇨ The black hole decays and can not grow

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Black Hole Evaporation

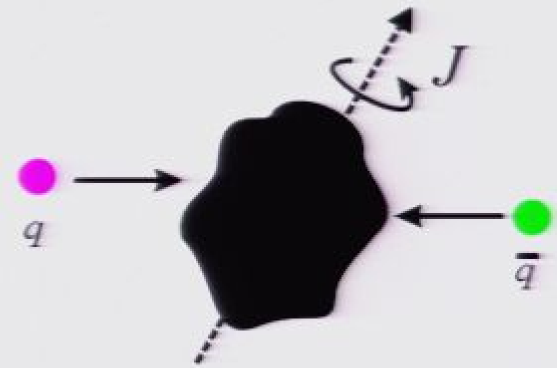
Three phases:

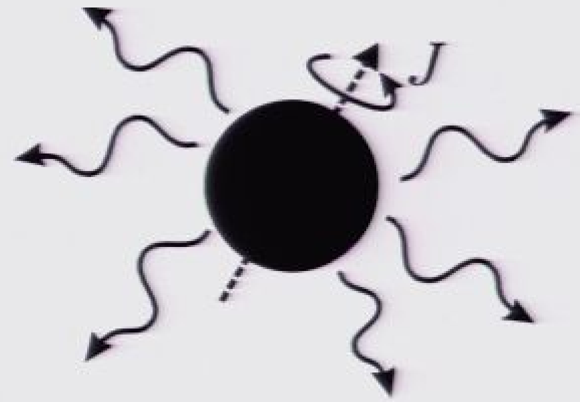
– **Balding phase:** multipole moments are radiated off some energy is lost into gravitational radiation.

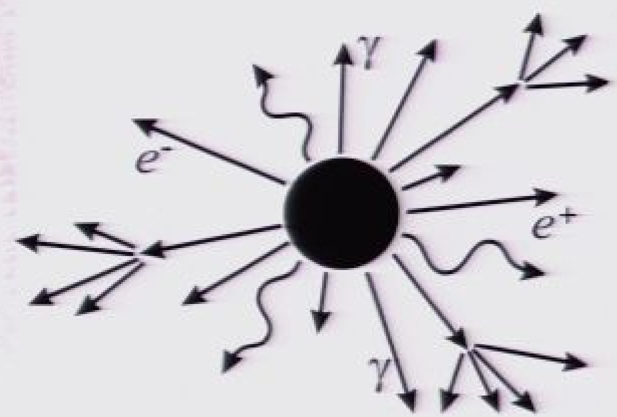
– **Hawking phase:** Spin down followed by thermal radiation into all particles of the SM and gravitons

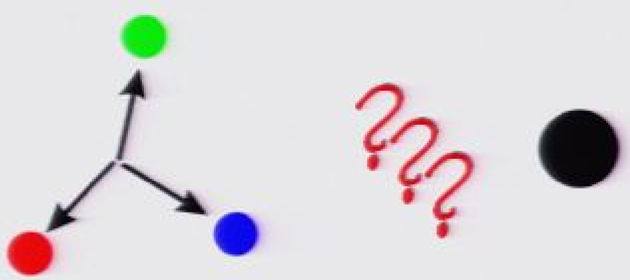
⇨ Depends on number and size of extra dimensions: possibility to examine space-time geometry

– **Planck phase:** final decay or stable remnant, nobody knows exactly

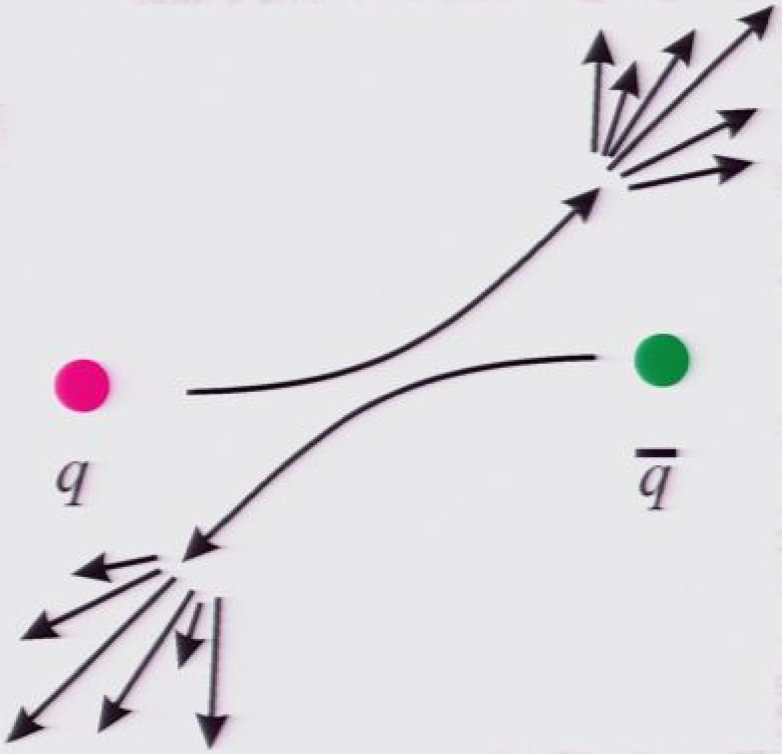


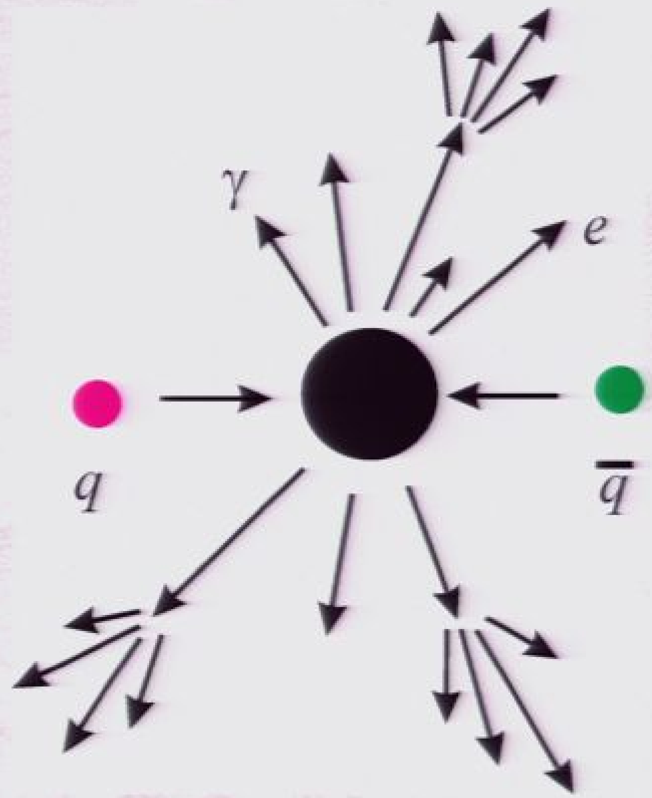






Black Hole Event at the LHC





QCD:

Two partons scatter inelastically
Outgoing particles hadronize
And create a 'jet'

QG:

Two partons collapse to a black hole
The black hole decays with a thermal spectrum

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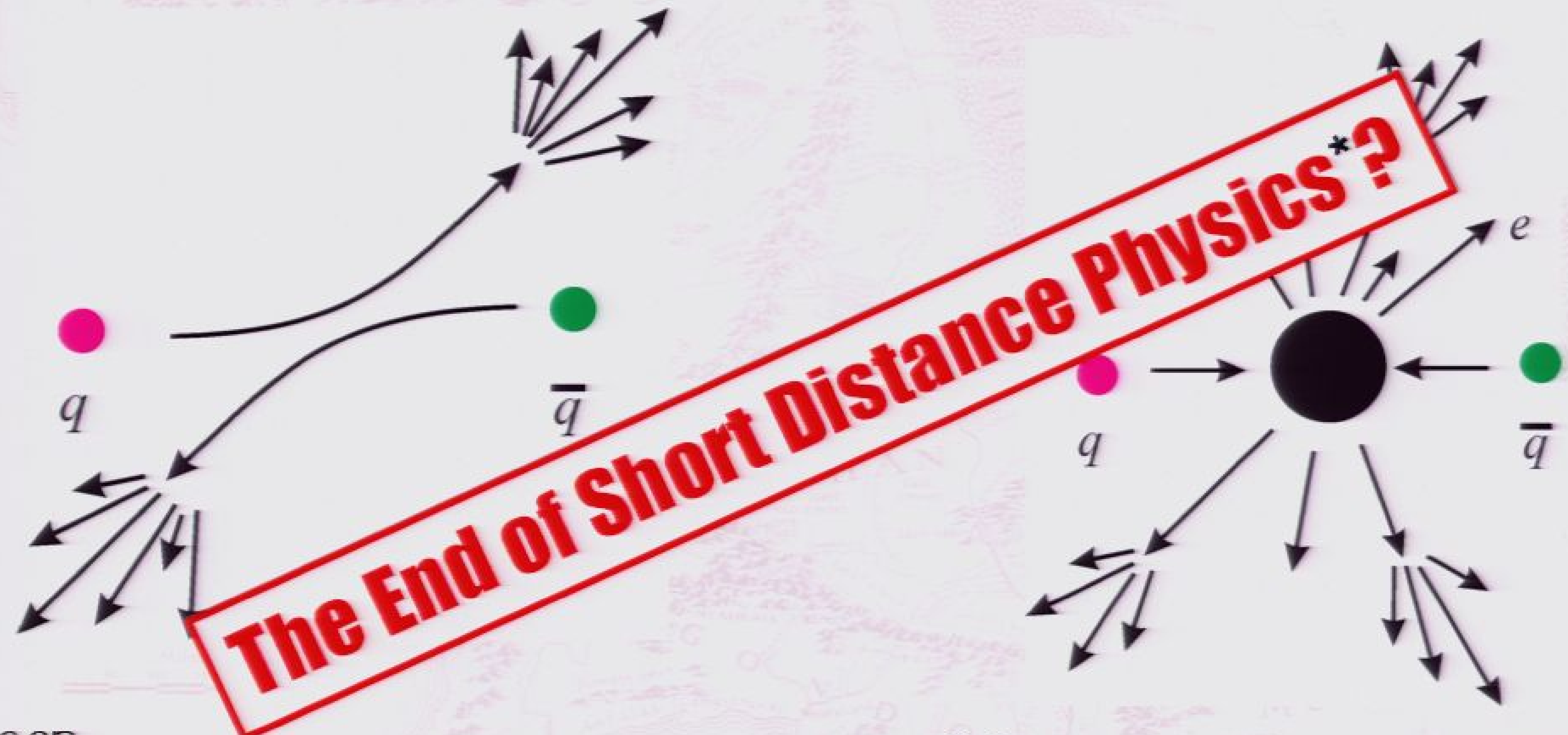

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* Thomas & Giddings, PRD 65: 056010 (2002)

Homework Assignment

- Why are the particle masses what they are?
- Why are there three generations?
- Why are there three families?
- Why are there three large dimensions?
- Why these interactions?

Summary

"Somewhere, something incredible is waiting to be known."

~ Carl Sagan