The hidden dimensions of the Universe

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CERN

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Particle physics: structure of matter & fundamental forces

Experimental tools: Particle colliders at very high energies $\Rightarrow$

physical laws of nature at very short distances

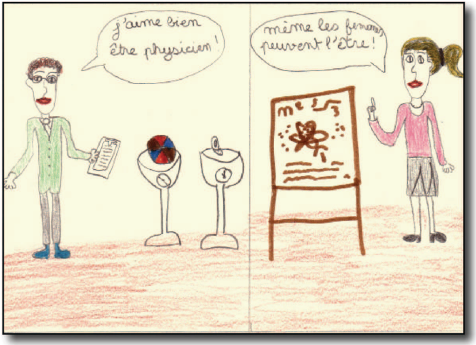
- LEP2 (CERN): electron - positron collisions at 200 GeV $\rightarrow 10^{-15}$ cm
- TEVATRON (USA): protons - antiprotons at 2 TeV $\rightarrow 10^{-16}$ cm
- LHC (CERN): proton - proton collisions at 14 TeV * $\rightarrow 10^{-17}$ cm

Th description: simple mathematical theories with predictive power

encoding the symmetries of physical phenomena

* for the moment 8 TeV

Dessine-moi un physicien

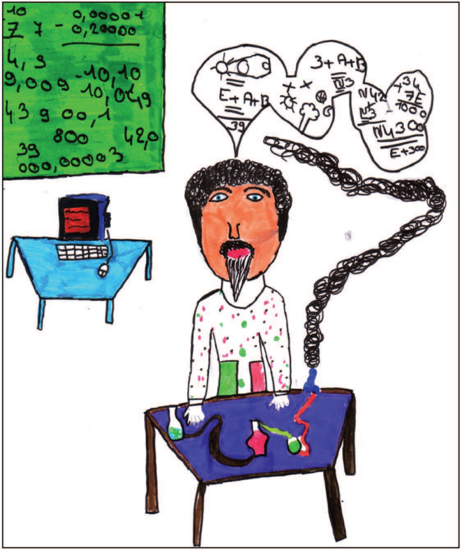


Le travail d'un physicien c'est de trouver les secrets de la Nature.

Chloé

www.cern.ch/dessine-moi-un-physicien

Un physicien est un monsieur qui boit du café toute la journée. *Endrit*

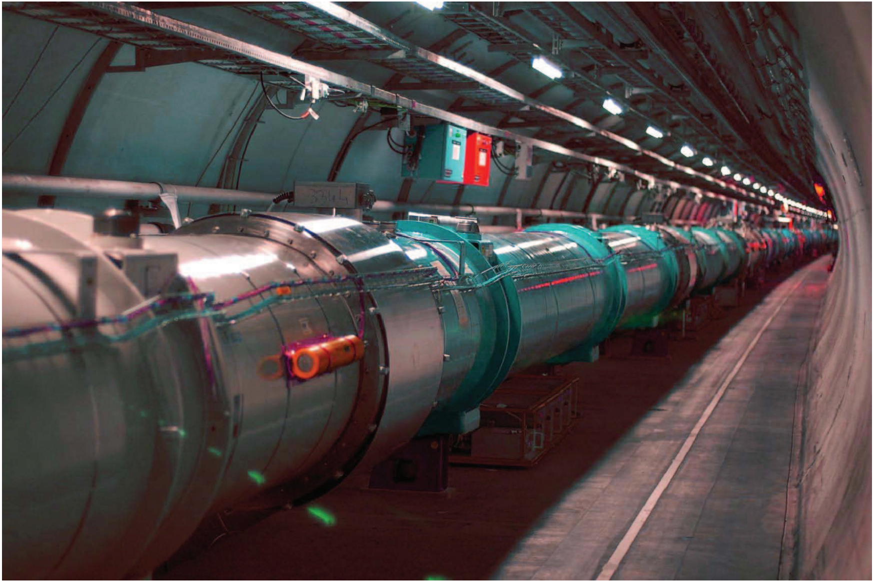


Un physicien fait des milliers de calculs et cherche ce qu'il y a après l'espace. *Lise*

the Large Hadron Collider (LHC)

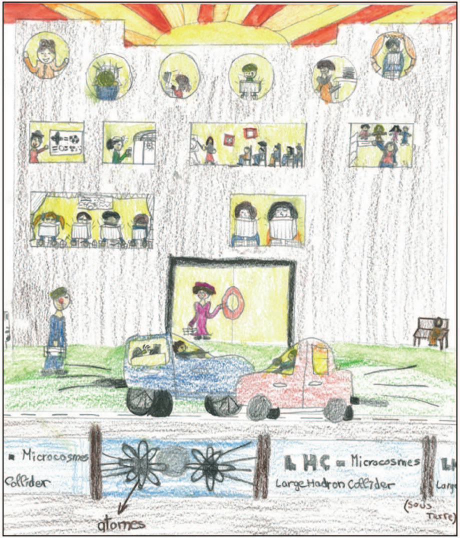
- Largest scientific instrument ever built, 27km of circumference
- >10 000 people involved in its design and construction

at CERN *Accelerating Science and Innovation*

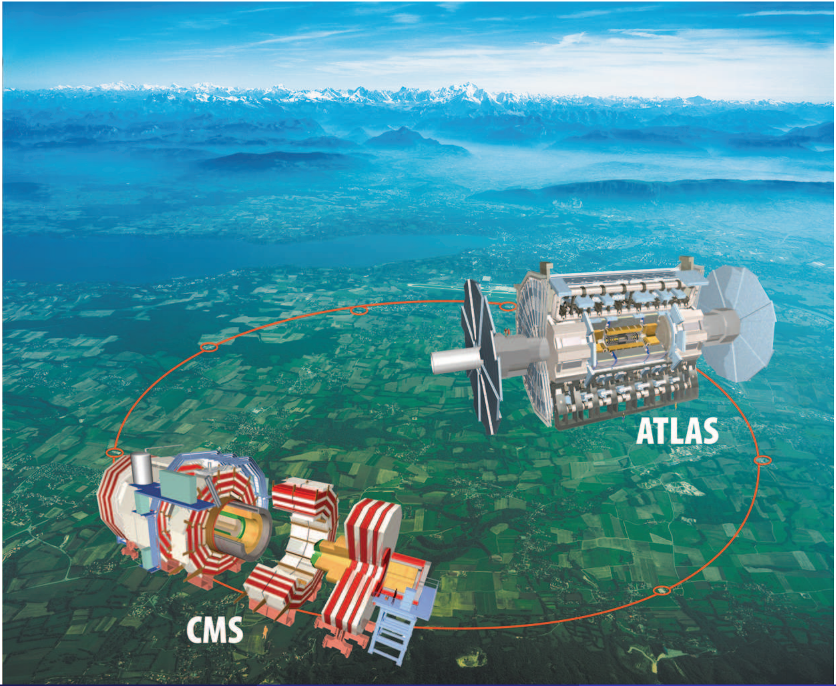


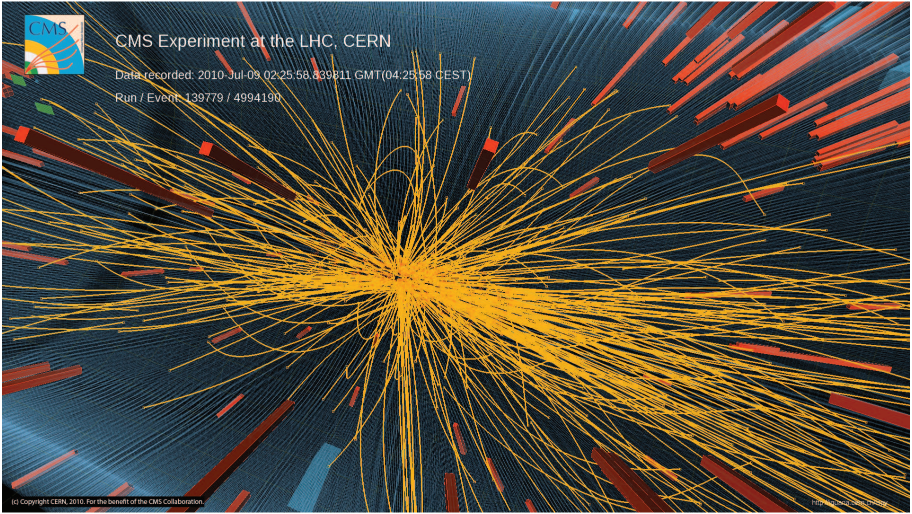
superconducting magnets at 1.9^o K $\Rightarrow$ accelerate protons at 0.99999999c

orbit LHC ring 11000 times/sec $\Rightarrow$ several thousand billion protons



Un physicien veut explorer les secrets de la Nature. Sous terre, il y a le LHC, un grand tunnel où les atomes font des collisions. *Isabel*


ATLAS
CMS

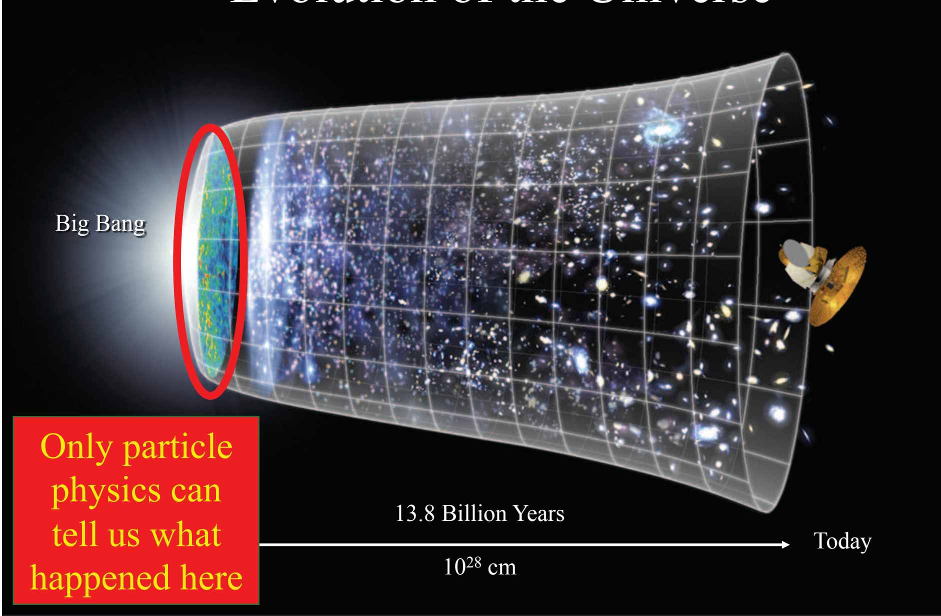


A billion p-p collisions per second

each collision has over a thousand particles produced

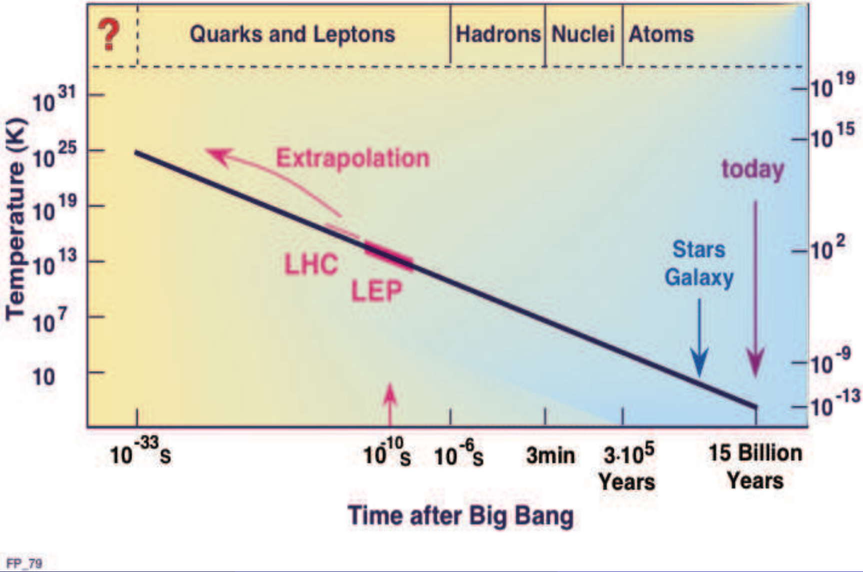

The LHC is the world's most powerful microscope …
… and also a telescope

Evolution of the Universe



Only particle physics can tell us what happened here

Evolution of the Universe



Standard Model of electroweak + strong forces

- Quantum Field Theory   Quantum Mechanics + Special Relativity
- Principle: gauge invariance $U(1) \times SU(2) \times SU(3)$

Very accurate description of physics at present energies   17 parameters

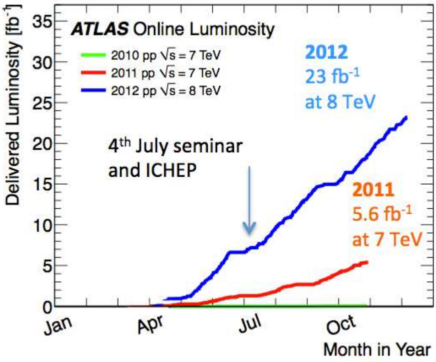
1. mediators of gauge interactions (vectors): photon, $W^\pm$, Z + **8 gluons**
2. matter (fermions): (leptons + quarks) $\times$ 3

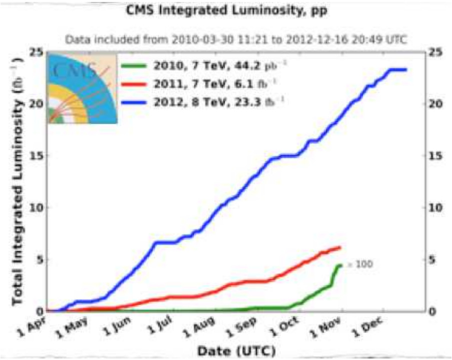
   electron, positron, neutrino   (up, down) **3 colors**
3. Higgs sector: new scalar(s) particle(s):
   - break the EW symmetry $U(1) \times SU(2) \rightarrow U(1)_\gamma$ at $M_W \sim 100$ GeV
   - generate mass for all elementary particles   Brout-Englert Higgs 1964

   Its discovery was one of the main goals of LHC

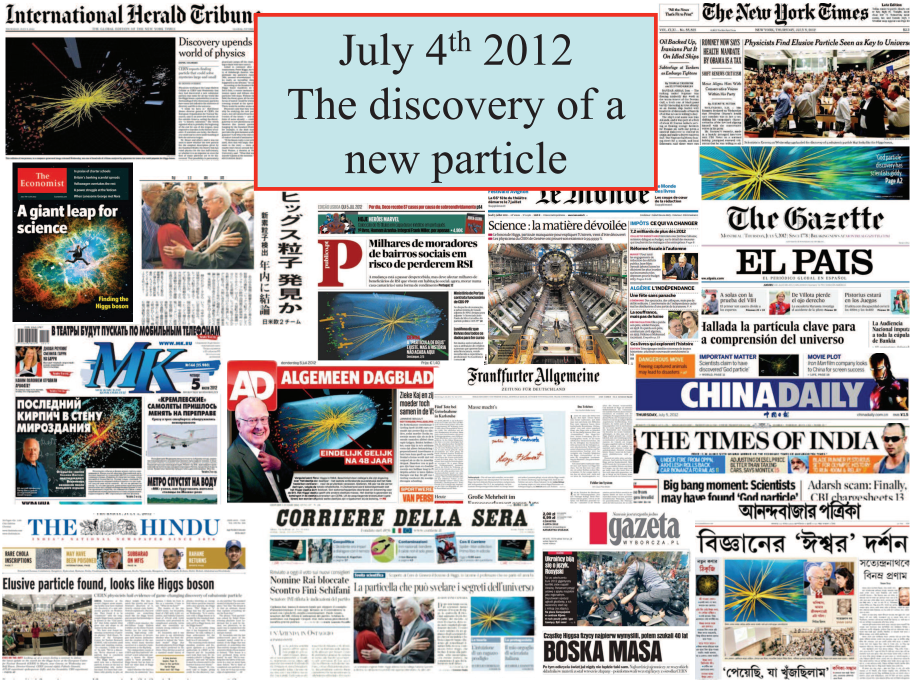
Excellent LHC performance

Number of events = Cross section $\times$ Luminosity

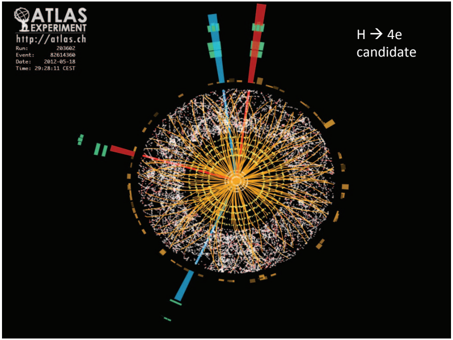


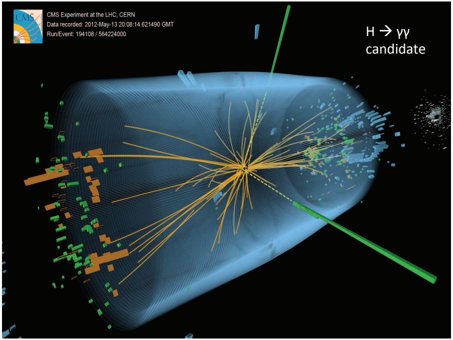


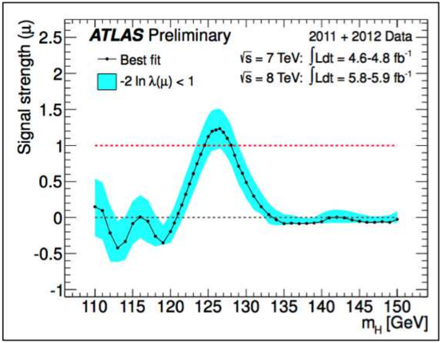
July 4th 2012
The discovery of a new particle

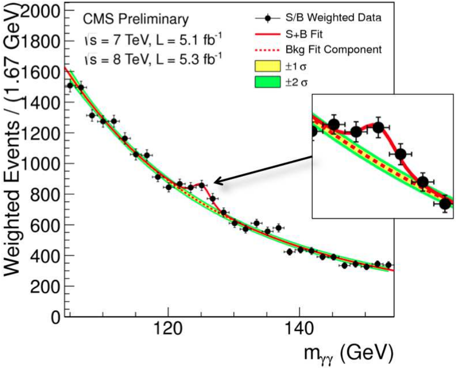


Possible Higgs boson events



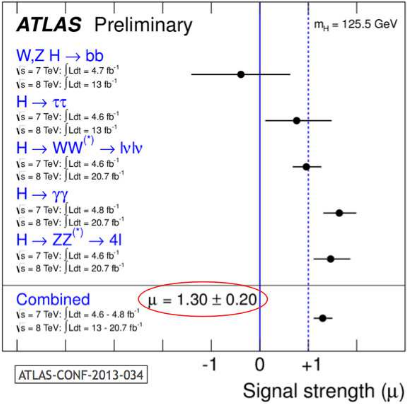


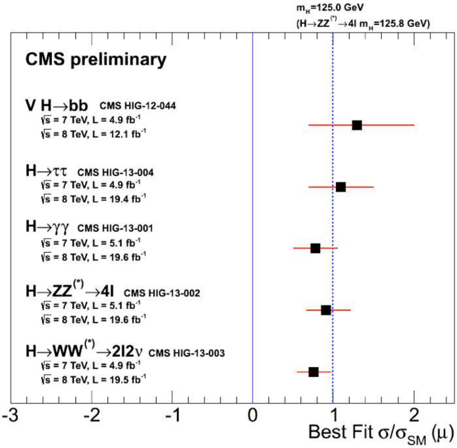




$m_H = 125.9 \pm 0.4$ GeV (average of Particle Data Group 2013)

Couplings of the new boson vs SM Higgs





- Agreement with Standard Model Higgs expectation at 1.5 σ
- Most compatible with scalar 0^+ hypothesis
- Measurement of its properties and decay rates currently under way

François Englert ↓ Peter Higgs ↓ Nobel Prize of Physics 2013

Why Beyond the Standard Model?

Experimental indications:

- Neutrino masses
- Unification of gauge couplings ?
- Dark matter [23]

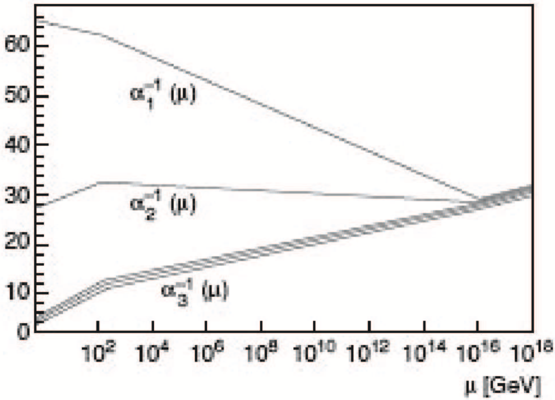
Two main theory reasons:

- Include gravity Quantum Mechanics + General Relativity ? [25]
- Mass hierarchy: $M_W/M_{\rm Planck} \simeq 10^{-17}$ [26]

Gauge coupling unification

Energy evolution of gauge couplings $\alpha_i = g_i^2/4\pi \Rightarrow$

low energy data $\rightarrow$ extrapolation at high energies:

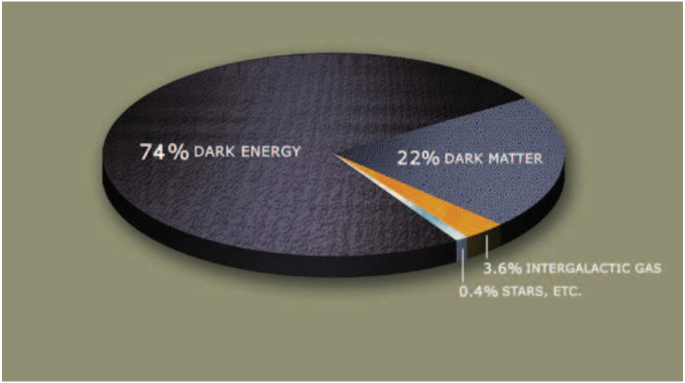


unification at $M_{GUT} \simeq 10^{15} - 10^{16}$ GeV [27]

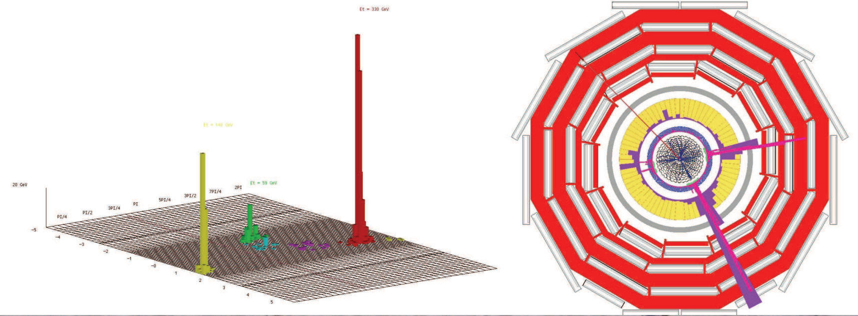
Observable Universe

- Ordinary baryonic matter: only a tiny fraction
- Non-luminous (dark) matter: 25%

  Natural explanation: new stable Weakly Interacting Massive Particle [21]



Classic Dark Matter Signature



Missing transverse energy
carried away by dark matter particles

Newton's law

$m \bullet \longleftarrow r \longrightarrow \bullet m \qquad F_{\rm grav} = G_N \frac{m^2}{r^2} \qquad G_N^{-1/2} = M_{\rm Planck} = 10^{19}$ GeV

Compare with electric force: $F_{\rm el} = \frac{e^2}{r^2} \Rightarrow$

effective dimensionless coupling $G_N m^2$ or in general $G_N E^2$ at energies E

$E = m_{\rm proton} \Rightarrow \frac{F_{\rm grav}}{F_{\rm el}} = \frac{G_N m^2_{\rm proton}}{e^2} \simeq 10^{-40} \Rightarrow$ Gravity is very weak !

At what energy gravitation becomes comparable to the other interactions?

$M_{\rm Planck} \simeq 10^{19}$ GeV $\rightarrow$ Planck length: 10^{-33} cm

$10^{15} \times$ the LHC energy! [21]

Mass hierarchy problem

Higgs mass: very sensitive to high energy physics

quantum corrections: $\delta m_H \sim$ scale Λ of new physics/massive particles

stability requires adjustment of parameters at very high accuracy

to keep the physical mass $(m_H^{tree})^2 + \delta m_H^2$ at the weak scale

$\Lambda = M_{GUT}$ or $M_P \Rightarrow$ fine tuning at 28-32 decimal places !

Why gravity is so weak compared to the other interactions? [32]

Standard picture: low energy supersymmetry

every particle has a superpartner with spin differ by $1/2$

cancel large quantum corrections to the Higgs mass

$\Rightarrow$ superpartner mass splittings must be not far from M_W

Advantages:

- natural elementary scalars
- gauge coupling unification [22]
- LSP: natural dark matter candidate
- prediction of light Higgs
- rich spectrum of new particles within LHC reach

Problems of supersymmetry

- too many parameters: soft breaking terms

  supersymmetry breaking mechanism: unknown

- Standard Model global symmetries are not automatic

  conditions on soft terms for suppression of flavor changing processes

- no satisfactory model of supersymmetric grand unification

- higgsino mass problem:

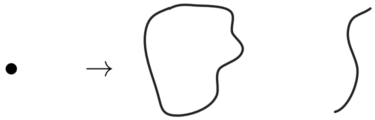
  supersymmetric mass parameter but of the order of the soft terms

- MSSM : already a % - ‰ fine-tuning

  'little' hierarchy problem

String theory: Quantum Mechanics + General Relativity

point particle $\to$ extended objects



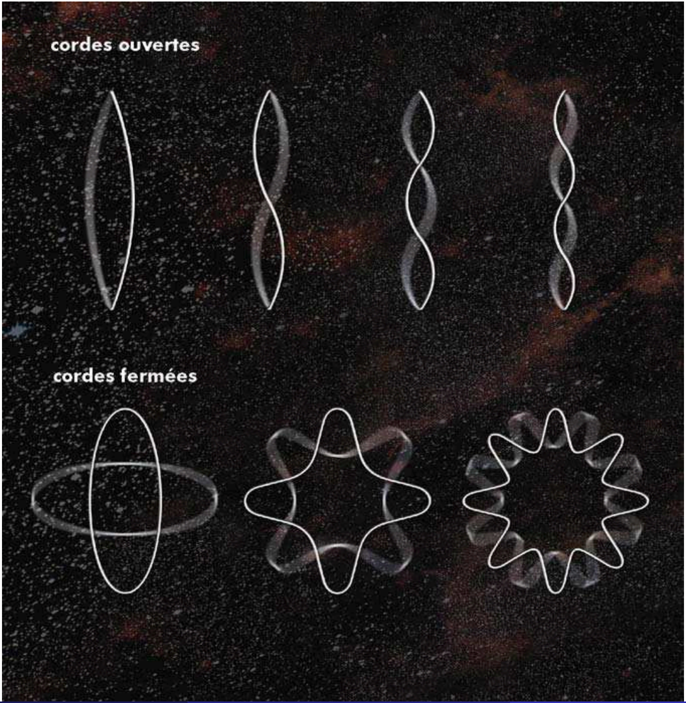
particles $\equiv$ string vibrations

- quantum gravity
- framework of unification of all interactions
- "ultimate" theory: · ultraviolet finite
  · no free parameters

mass scale (tension): $M_{\rm string} \leftrightarrow$ size: $l_{\rm string}$

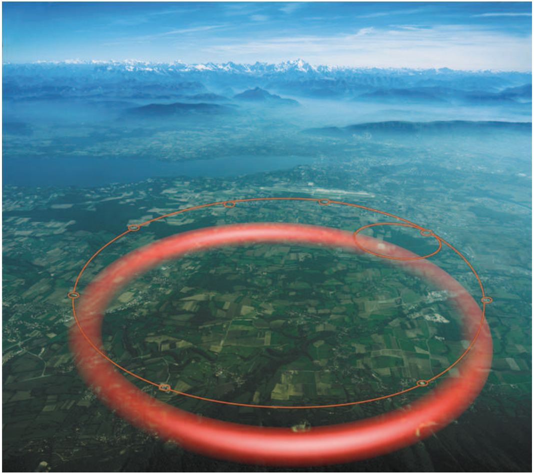
rigid string : known particles (massless)

vibrations : infinity of massive particles


cordes ouvertes
cordes fermées

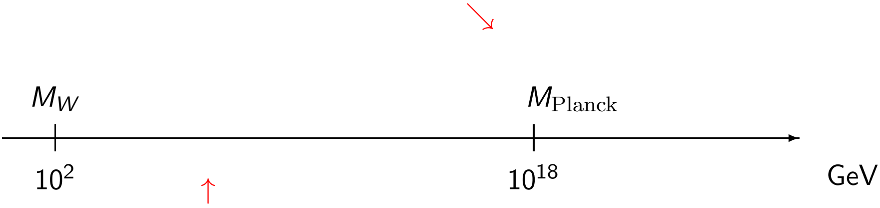
At what energies strings may be observed?

- Are there low energy string predictions testable at LHC ?



Very different answers depending mainly on the value of the string scale

Before 1994: M_{string} near M_{Planck} at $\sim 10^{18}$ GeV $l_{\mathrm{string}} \simeq 10^{-32}$ cm



After 1994: M_{string} is an arbitrary parameter

High string scale: natural for supersymmetry and unification

but no stringy test at LHC

Interesting possibility: $M_{\mathrm{string}} \sim M_W \Rightarrow$ nullify the hierarchy problem

low UV cutoff $\Lambda \simeq M_{\mathrm{string}}$ [26]

I.A.-Arkani Hamed-Dimopoulos-Dvali '98

Extra dimensions and braneworlds

Consistency of string theory $\Rightarrow$ 9 spatial dimensions !

$\Rightarrow$ **six new dimensions of space**

matter and gauge forces may be localized in less than 9 dimensions

$\Rightarrow$ **our universe on a extended membrane ?** [37]

p-brane: extended in p spatial dimensions

$p = 0$: particle, $p = 1$: string, $p = 2$: membrane,. . .

Extra dimensions

how they escape observation?

finite size R Kaluza and Klein 1920

energy cost to send a signal:

$E > R^{-1} \leftarrow$ compactification scale

experimental limits on their size

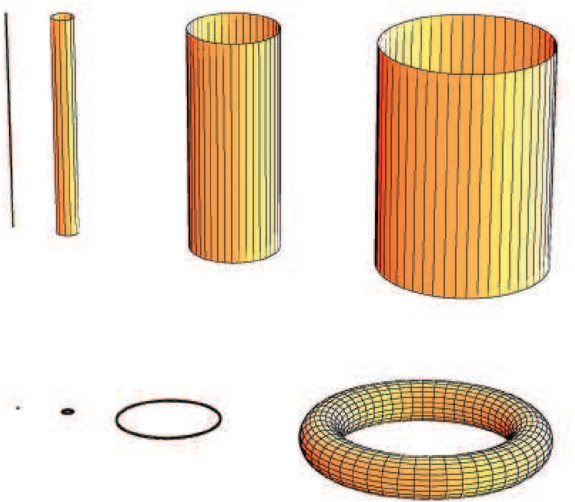
light signal $\Rightarrow$ $E \gtrsim 1$ TeV

$R \lesssim 10^{-16}$ cm

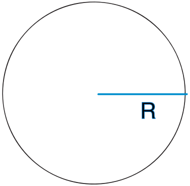
how to detect their existence?

motion in the internal space $\Rightarrow$ mass spectrum in 3d

How many dimensions ?



example: - one internal circular dimension
- light signal



plane waves e^{ipy} periodic under $y \to y + 2\pi R$

$\Rightarrow$ quantization of internal momenta: $p = \frac{k}{R}$; $k = 0, 1, 2, \dots$

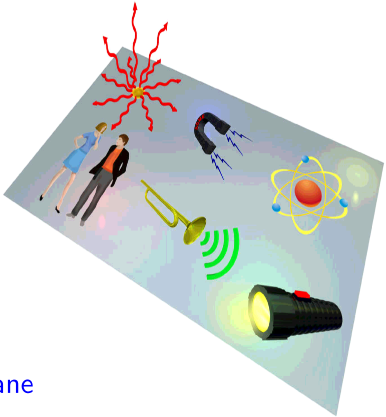
$\Rightarrow$ 3d: tower of Kaluza Klein particles with masses $M_k = k/R$

$$p_0^2 - \vec{p}^2 - p_5^2 = 0 \;\Rightarrow\; p_0^2 - \vec{p}^2 = p_5^2 = \frac{k^2}{R^2}$$

$E >> R^{-1}$: emission of many massive photons

$\Leftrightarrow$ propagation in the internal space [33]

Our universe on a membrane

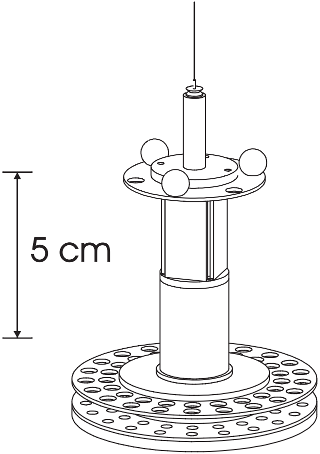


Two types of new dimensions:

- longitudinal: along the membrane
- transverse: “hidden” dimensions

  only gravitational signal $\Rightarrow R_\perp \lesssim 1$ mm !

Adelberger et al. '06



$R_\perp \lesssim 45\ \mu$m at 95% CL

- dark-energy length scale $\approx 85\mu$m [52]

Low scale gravity

Extra large $\perp$ dimensions can explain the apparent weakness of gravity

total force = observed force × volume $\perp$

$$\begin{array}{ccccc} \uparrow & & \uparrow & & \uparrow \\ G_N^* & = & G_N & \times & V_\perp \end{array}$$

n dimensions of size $R_\perp$

$\Rightarrow \; V_\perp = R_\perp^n$

$G_N^* = M_*^{-(2+n)}$: $(4+n)$-dim gravitational constant

total force $\simeq \mathcal{O}(1)$ at 1 TeV $\Rightarrow M_* \simeq 1$ TeV

$n = 1: \; R_\perp \simeq 10^8$ km excluded

$n = 2: \; R_\perp \simeq 0.1$ mm $(10^{-12}$ GeV$)$

possible

$n = 6: \; R_\perp \simeq 10^{-13}$ mm $(10^{-2}$ GeV$)$

String theory realization: D-brane world

- gravity: closed strings propagating in 10 dims
- gauge interactions: open strings with their ends attached on D-branes

Dimensions of finite size: n transverse $6-n$ parallel

calculability $\Rightarrow R_{\parallel} \simeq l_{\rm string}$; $R_{\perp}$ arbitrary

$G_N^* = g_s^2 \, l_s^{2+n}$ g_s : string coupling ($\simeq$ gauge coupling for D-branes)

$M_s \sim 1$ TeV $\Rightarrow R_{\perp}^n = 10^{32} \, l_s^n$

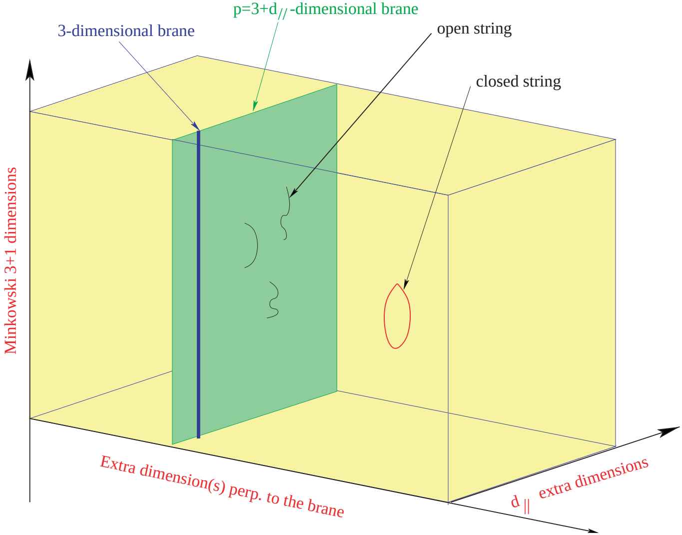
- distances $> R_{\perp}$: gravity 3d but for $< R_{\perp}$: gravity (3+n)d [42]
- strong gravity at 10^{-16} cm $\leftrightarrow 10^3$ GeV

$10^{30}\times$ stronger than thought previously! [43]

Braneworld

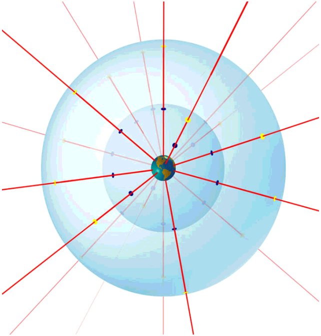
2 types of compact extra dimensions:

- parallel ($d_{\|}$): $\lesssim 10^{-16}$ cm (TeV) [45]
- transverse ($\perp$): $\lesssim 0.1$ mm (meV) [51]



Gravity modification at submillimeter distances

Newton's law: force decreases with area

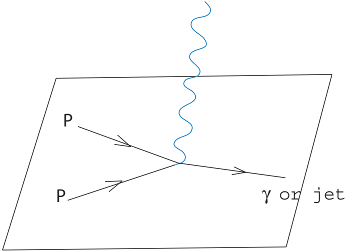


3d: force $\sim 1/r^2$

$(3+n)$d: force $\sim 1/r^{2+n}$

observable for $n = 2$: $1/r^4$ with $r << .1$ mm [40]

Gravitational radiation in the bulk ⇒ missing energy



present LHC bounds: $M_* \gtrsim 3-5$ TeV

Collider bounds on $R_\perp$ in mm			
	$n=2$	$n=4$	$n=6$
LEP 2	4.8×10^{-1}	1.9×10^{-8}	6.8×10^{-11}
Tevatron	5.5×10^{-1}	1.4×10^{-8}	4.1×10^{-11}
LHC	4.5×10^{-3}	5.6×10^{-10}	2.7×10^{-12}

Black hole production

Giddings-Thomas, Dimopoulos-Landsberg '01

String-size black hole energy threshold : $M_{\rm BH} \simeq M_s/g_s^2$

Horowitz-Polchinski '96, Meade-Randall '07

weakly coupled theory $\Rightarrow$ strong gravity effects occur much above M_s, M_*

$g_s \sim 0.1$ (gauge coupling) $\quad \Rightarrow \quad M_{\rm BH} \sim 100 M_s$

Comparison with Regge excitations : $M_j = M_s\sqrt{j} \;\Rightarrow$

production of $j \sim 1/g_s^4 \sim 10^4$ string states before reach $M_{\rm BH}$

Other accelerator signatures

- Large TeV dimensions   seen by SM gauge interactions

  $\Rightarrow$ KK resonances of SM gauge bosons [41]   I.A. '90

$$M_n^2 = M_0^2 + \frac{k^2}{R^2} \quad ; \quad k = \pm 1, \pm 2, \ldots$$

- string physics and possible strong gravity effects

  Massive string vibrations $\Rightarrow$ e.g. resonances in dijet distribution [49]

$$M_j^2 = M_0^2 + M_s^2\, j \quad ; \quad \text{maximal spin} : j + 1$$

  higher spin excitations of quarks and gluons with strong interactions

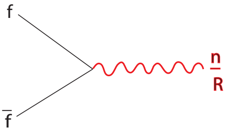
  Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08

- extra $U(1)$'s and anomaly induced terms [50]

  masses suppressed by a loop factor from M_s

Localized fermions (on brane intersections)

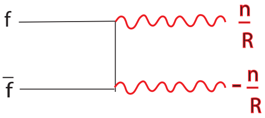
⇒ single production of KK modes I.A.-Benakli '94



- strong bounds indirect effects: $R^{-1} \gtrsim 4\,\mathrm{TeV}$
- new resonances [48]

Otherwise KK momentum conservation

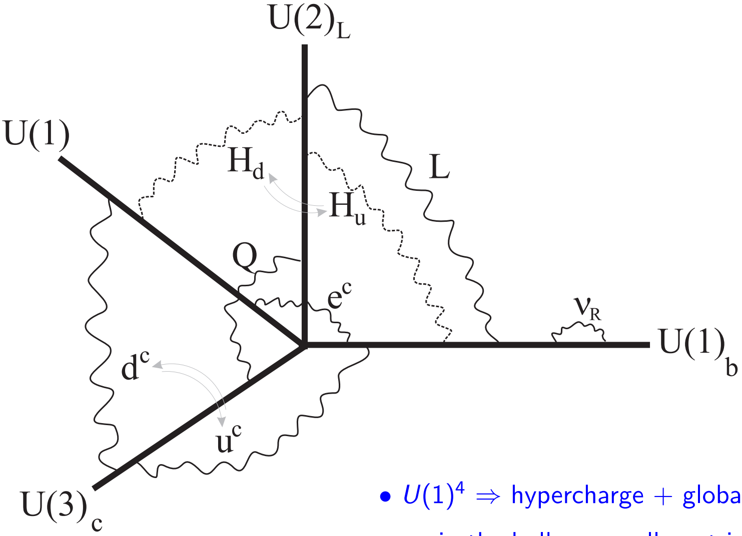
⇒ pair production of KK modes (universal dims)



- weak bounds $R^{-1} \gtrsim 500$ GeV
- no resonances
- lightest KK stable ⇒ dark matter candidate

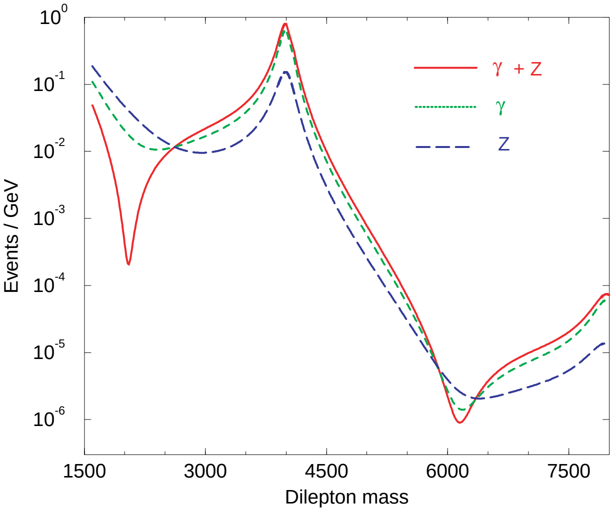
Servant-Tait '02

Standard Model on D-branes I.A.-Kiritsis-Rizos-Tomaras '02



- $U(1)^4 \Rightarrow$ hypercharge + global symmetries
- ν_R in the bulk $\Rightarrow$ small neutrino masses

$R^{-1} = 4$ TeV [46] I.A.-Benakli-Quiros '94, '99

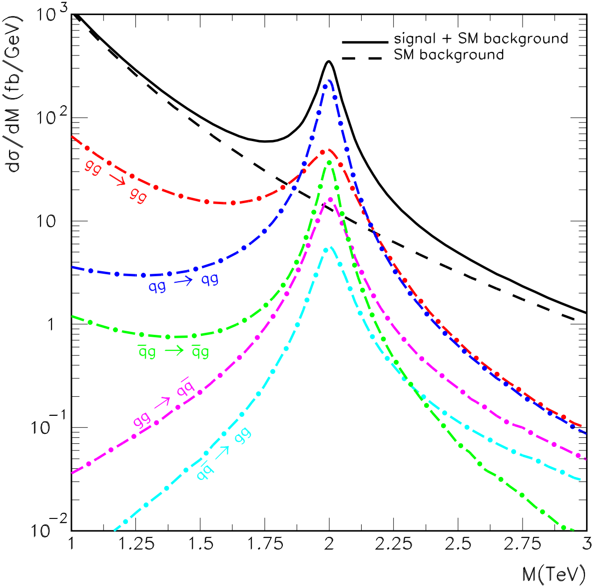


Universal deviation from Standard Model in jet distribution

$M_s = 2$ TeV

Width = 15-150 GeV

Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger ’08 [45]



present LHC limits (2010 data): $M_s \gtrsim 5$ TeV

Extra $U(1)$'s and anomaly induced terms

masses suppressed by a loop factor

usually associated to known global symmetries of the SM

(anomalous or not) such as (combinations of)

Baryon and Lepton number, or PQ symmetry

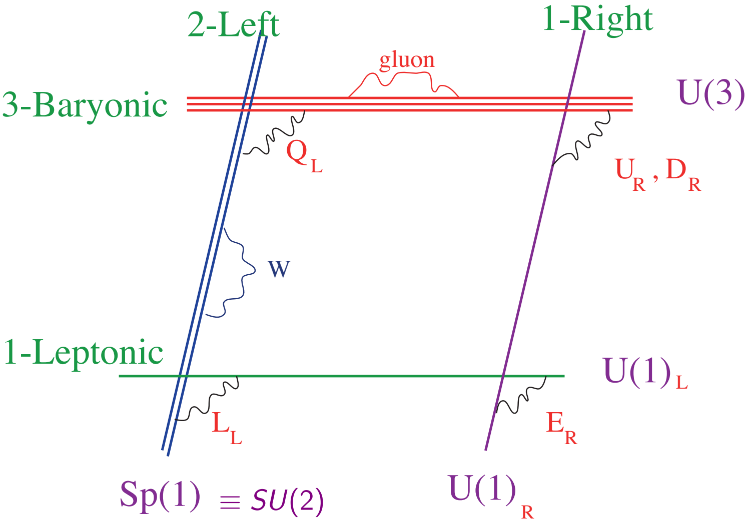
- in general they become massive due to anomalies

  but global symmetries remain in perturbation

  - Baryon number $\Rightarrow$ proton stability

  - Lepton number $\Rightarrow$ protect small neutrino masses

Standard Model on D-branes



$U(1)^3 \Rightarrow$ hypercharge + B, L global

microgravity experiments

- change of Newton's law at short distances [38]

  detectable only in the case of two large extra dimensions

- new short range forces

  light scalars and gauge fields if SUSY in the bulk

  or broken by the compactification on the brane

  I.A.-Dimopoulos-Dvali '98, I.A.-Benakli-Maillard-Laugier '02

  such as radion and lepton number

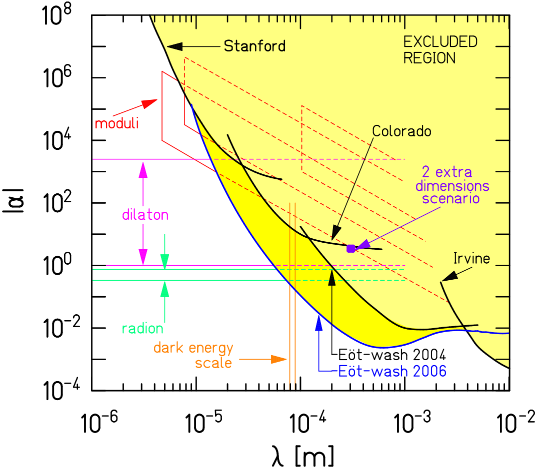
  volume suppressed mass: $(\mathrm{TeV})^2/M_P \sim 10^{-4}$ eV $\rightarrow$ mm range

  can be experimentally tested for any number of extra dimensions

  - Light $U(1)$ gauge bosons: no derivative couplings

    $\Rightarrow$ for the same mass much stronger than gravity: $\gtrsim\ 10^6$

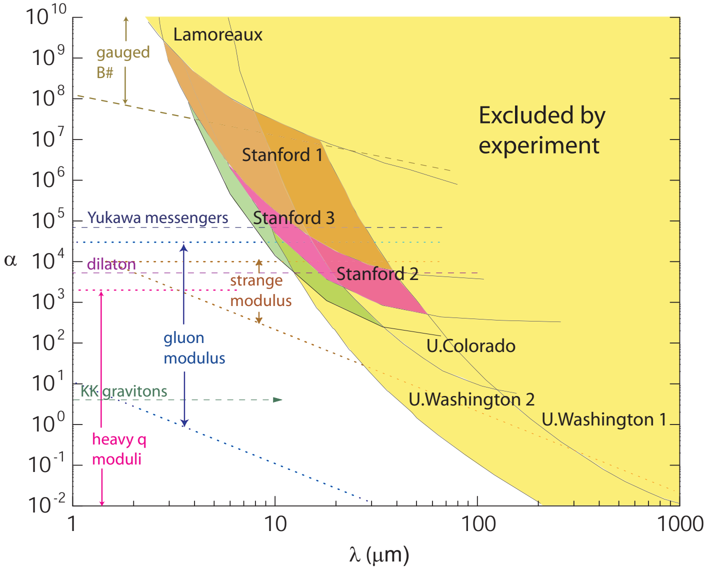
$$V(r) = -G\,\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

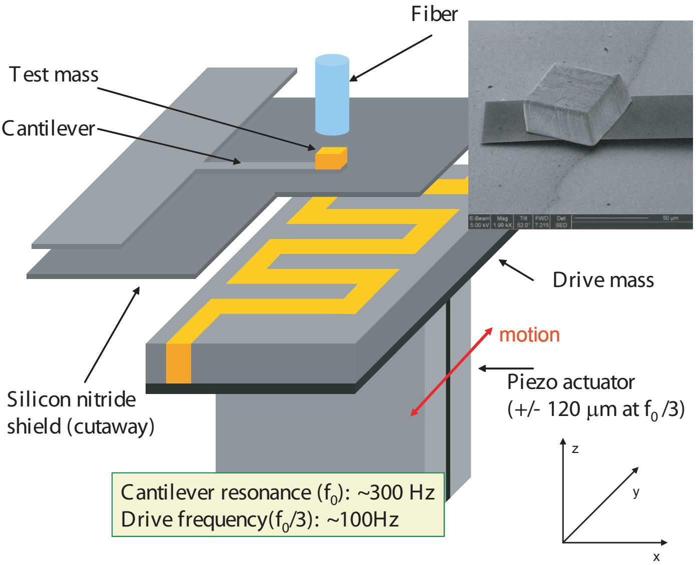


Radion $\Rightarrow M_* \gtrsim 6$ TeV 95% CL Adelberger et al. '06

improved bounds in the range 5-15 μm

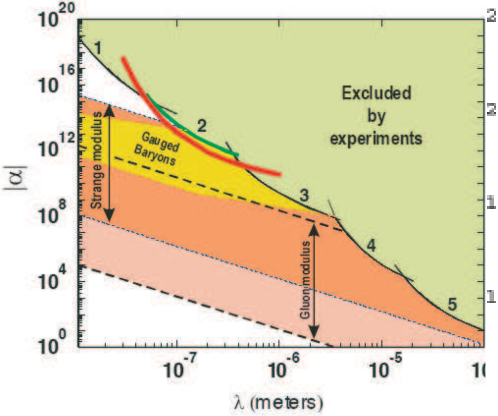
Geraci-Smullin-Weld-Chiaverini-Kapitulnik '08

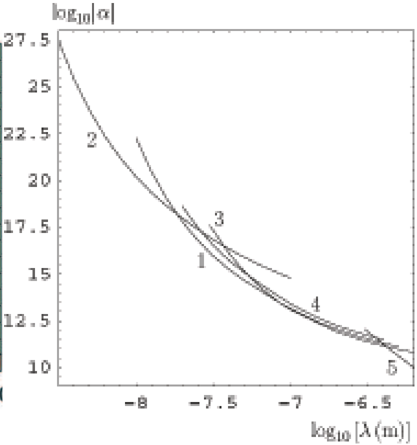



Fiber
Test mass
Cantilever
Drive mass
motion
Silicon nitride
shield (cutaway)
Piezo actuator
(+/- 120 μm at f_0 /3)
z
y
x
Cantilever resonance (f_0): ~300 Hz
Drive frequency(f_0/3): ~100Hz

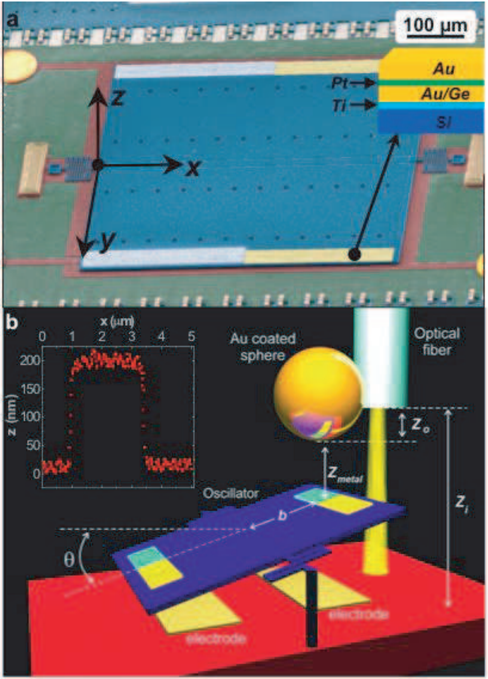
improved bounds from Casimir effect in the nm range

Decca-Fischbach et al '07, '08



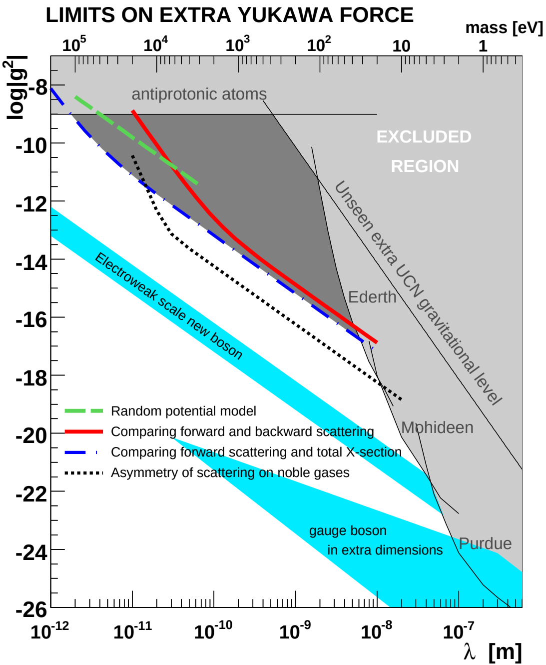


5: Colorado   4: Stanford   3: Lamoureaux   1: Mohideen et al.


a
100 μm
Au
Pt
Au/Ge
Ti
Si
Z
x
y
b
x (μm)
0 1 2 3 4 5
200
150
100
50
0
z (nm)
Au coated sphere
Optical fiber
Z_o
Z_{metal}
Z_i
Oscillator
b
θ
electrode
electrode

Neutron scattering: bounds in the range $\sim$ 1pm - 1nm

Nesvizhevsky-Pignol-Protasov '07



Conclusions

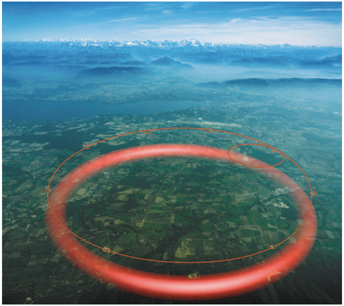
- Confirmation of the Higgs scalar discovery at the LHC :

  important milestone of the LHC research program

- LHC and Particle physics in a new era with possible new discoveries

  unveiling the fundamental laws of Nature

- Future plans to explore the 10-100 TeV energy frontier



The LHC timeline

LS1 Machine Consolidation

LS2 Machine upgrades for high Luminosity

- Collimation
- Cryogenics
- Injector upgrade for high intensity (lower emittance)
- Phase I for ATLAS : Pixel upgrade, FTK, and new small wheel

LS3 Machine upgrades for high Luminosity

- Upgrade interaction region
- Crab cavities?
- Phase II: full replacement of tracker, new trigger scheme (add L0), readout electronics.

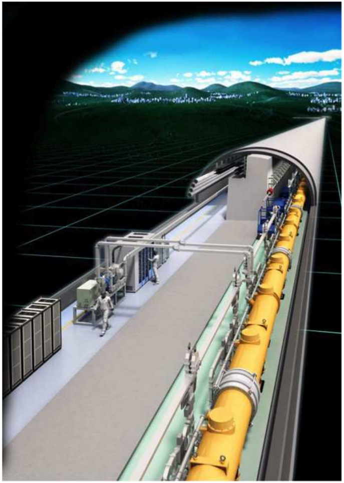
Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.

LHC timeline

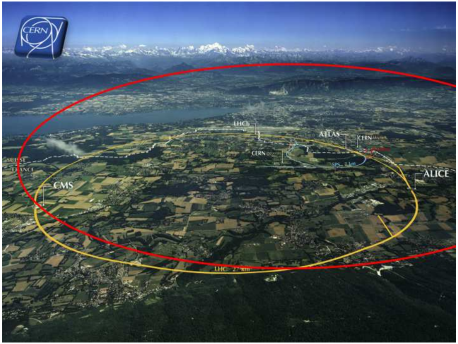
2009	Start of LHC	
	Run 1, 7+8 TeV, ~25 fb^{-1} int. lumi	
2013/14	Prepare LHC for design *E* & lumi	**LS1**
	Collect ~30 fb^{-1} per year at 13/14 TeV	
2018	Phase-1 upgrade ultimate lumi	**LS2**
	Twice nominal lumi at 14 TeV, ~100 fb^{-1} per year	
~2022	Phase-2 upgrade to HL-LHC	**LS3**
	~300 fb^{-1} per year, run up to > 3 ab^{-1} collected	
~2030		

Future accelerators

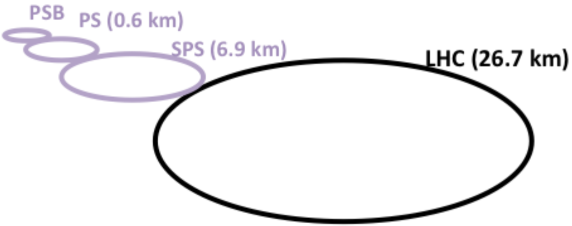
ILC project



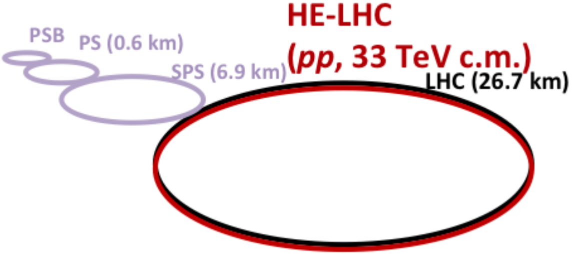
The future of LHC



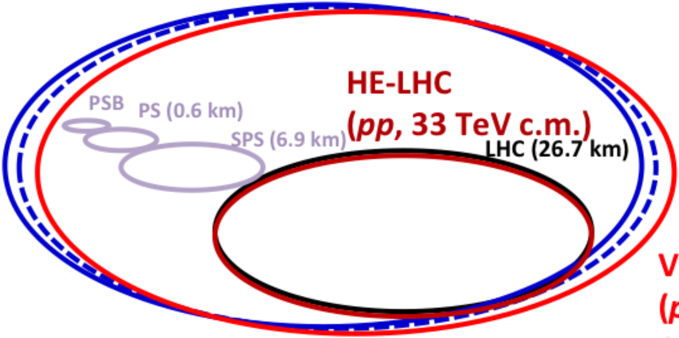
possible long-term strategy



possible long-term strategy

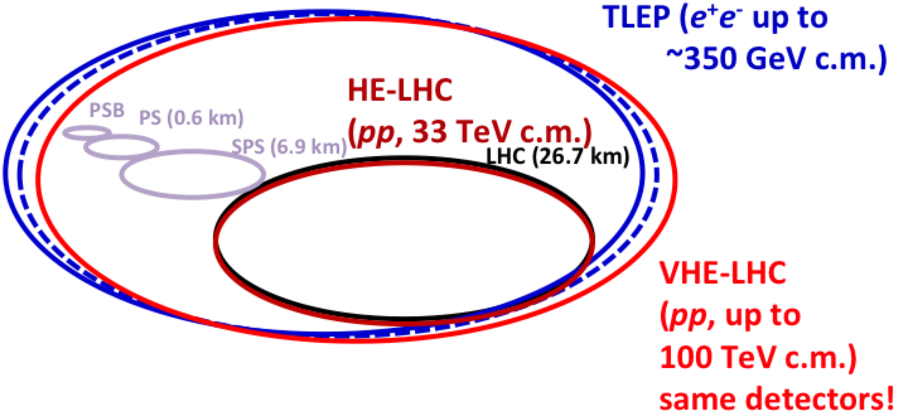


possible long-term strategy



VHE-LHC
(*pp*, up to
100 TeV c.m.)
same detectors!

possible long-term strategy



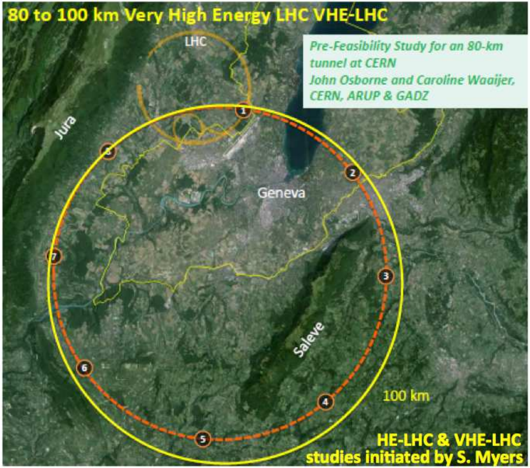
also: $e^{\pm}$ (120 GeV) – *p* (7 & 50 TeV) collisions

≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

VHE-LHC: location and size

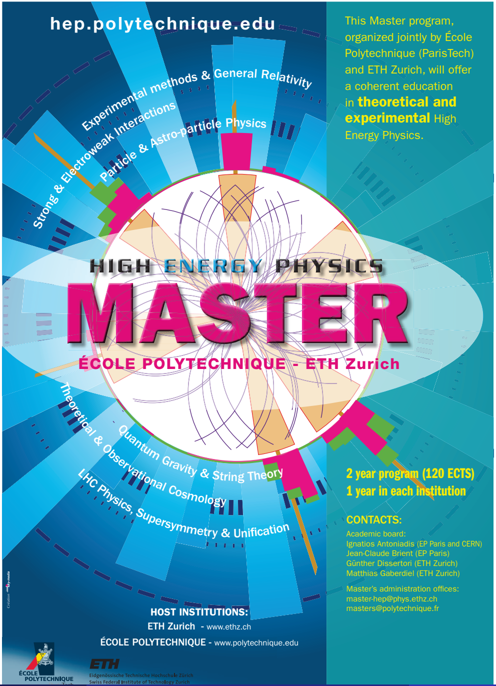
- 100 TeV p-p collider
- CDR and cost review to be ready for next European Strategy Update
- The tunnel could also house a e^+- e^- Higgs factory (TLEP)

	TLEP
circumference	80 km
Beam energy up to	370 GeV c.m.
max no. of IPs	4
Luminosity/IP at 350 GeV c.m.	1.3×10^{34} $cm^{-2}s^{-1}$
Luminosity/IP at 240 GeV c.m.	4.8×10^{34} $cm^{-2}s^{-1}$
Luminosity/IP at 160 GeV c.m.	1.6×10^{35} $cm^{-2}s^{-1}$
Luminosity/IP at 90 GeV c.m.	$5.6\ 10^{35}$ $cm^{-2}s^{-1}$



A circumference of 100 km is being considered for cost-benefit reasons

20T magnet in 80 km / 16T magnet in 100 km $\rightarrow$ 100 TeV



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