Large Hadron Colliders:

blackhole apocalypse
or
the future of
particle physics?

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Tufts University, October 15th 2010

what is elementary particle physics ?

science trying to find answers to a few fundamental questions:

what is the world made of?

how does the world work?

what is world?

classical physicist's view of the world

- Time
- Space
- Matter
- Forces

particle physicist's view of the world

- space-time
- quarks and leptons
- Interactions = quantum gauge fields

ideas about the structure of matter

- 5^{th} century BC: Lencippus and Democritus (Greece) developed a concept of ATOM, the smallest, invisible element out of which every other form of matter (gold, water…) was made (~2500 years ago!!)

- 4^{th} century BC: this very modern (by today's standards) view was pushed aside in by Aristotle (Greece) who thought of 4 basic elements out of which everything was made:
HEAT, COLD, MOISTURE and DRYNESS

ideas about the structure of matter

- Since heat and cold can mix and interchange, it was thought that other substances also can change from one to another. Many tried to find a way to obtain gold from other, less expensive, materials. Nobody succeeded, but the experiments contributed to our knowledge of what is now known as chemistry

- By the XIXth century alchemists and chemists have identified many basic elements, in addition to known metals (gold, silver, copper, zinc, tin, lead, iron) they knew sulphur, sodium, carbon, potassium, chlorine, hydrogen, oxygene, nitrogene and many others

structure of matter: XIX century

- ~1802:

John Dalton (English chemist) introduced a concept of a molecule, the "smallest" amount of any substance. The term ATOM re-appeared in scientific terminology as a smallest indivisible portion of an element, e.g. a water molecule is made of two hydrogen atom and one oxygen atom

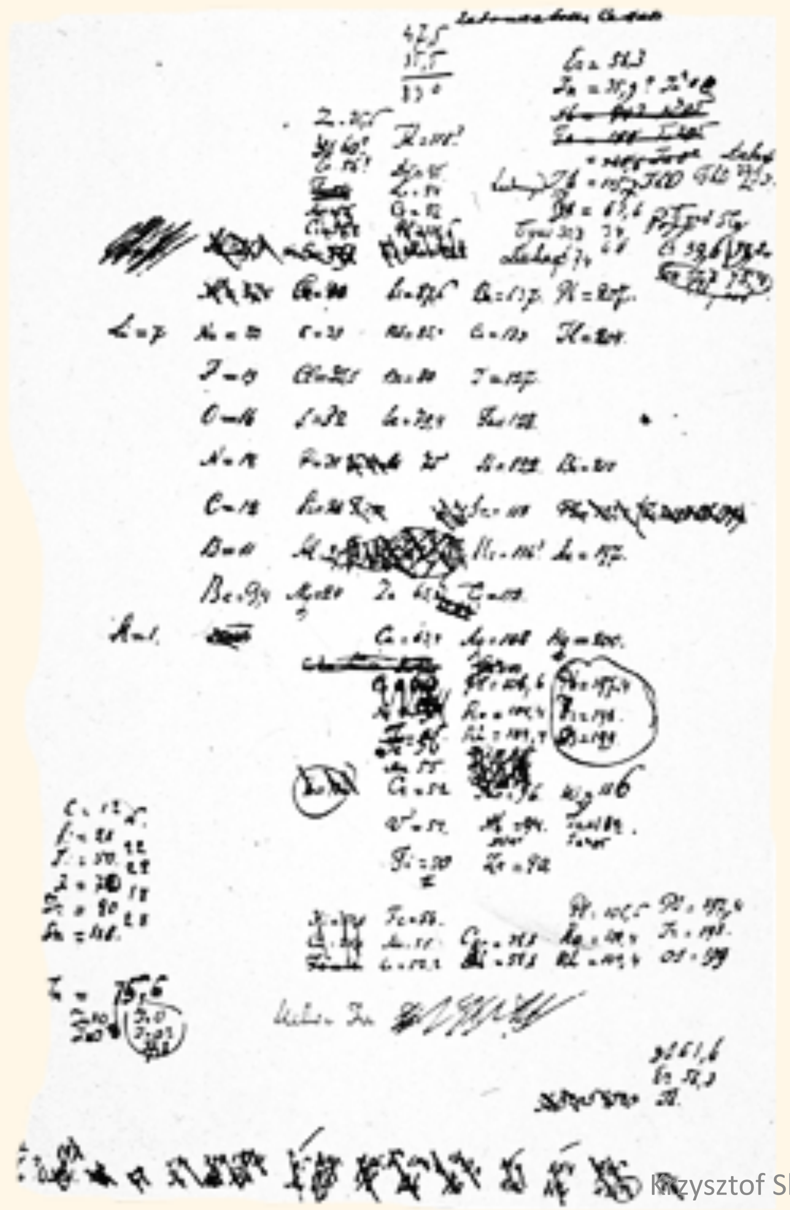
- 1815 Prout (English): suggested that all atoms are composed of hydrogen atoms, based on pattern of atomic weights, abandoned with more accurate data

structure of matter: XIX century

- In 1869 Dimitrii Mendeleev (Russia) published the periodic table of chemical elements. There were more than 90 of them, far too many to think of them as of elementary building blocks of matter.

- There was also a peculiar regularity. If one ordered the light elements according to the mass of the atom, hydrogen being the lightest, elements separated by 2,8 and (for heavier elements) 18 positions on the list had similar chemical properties

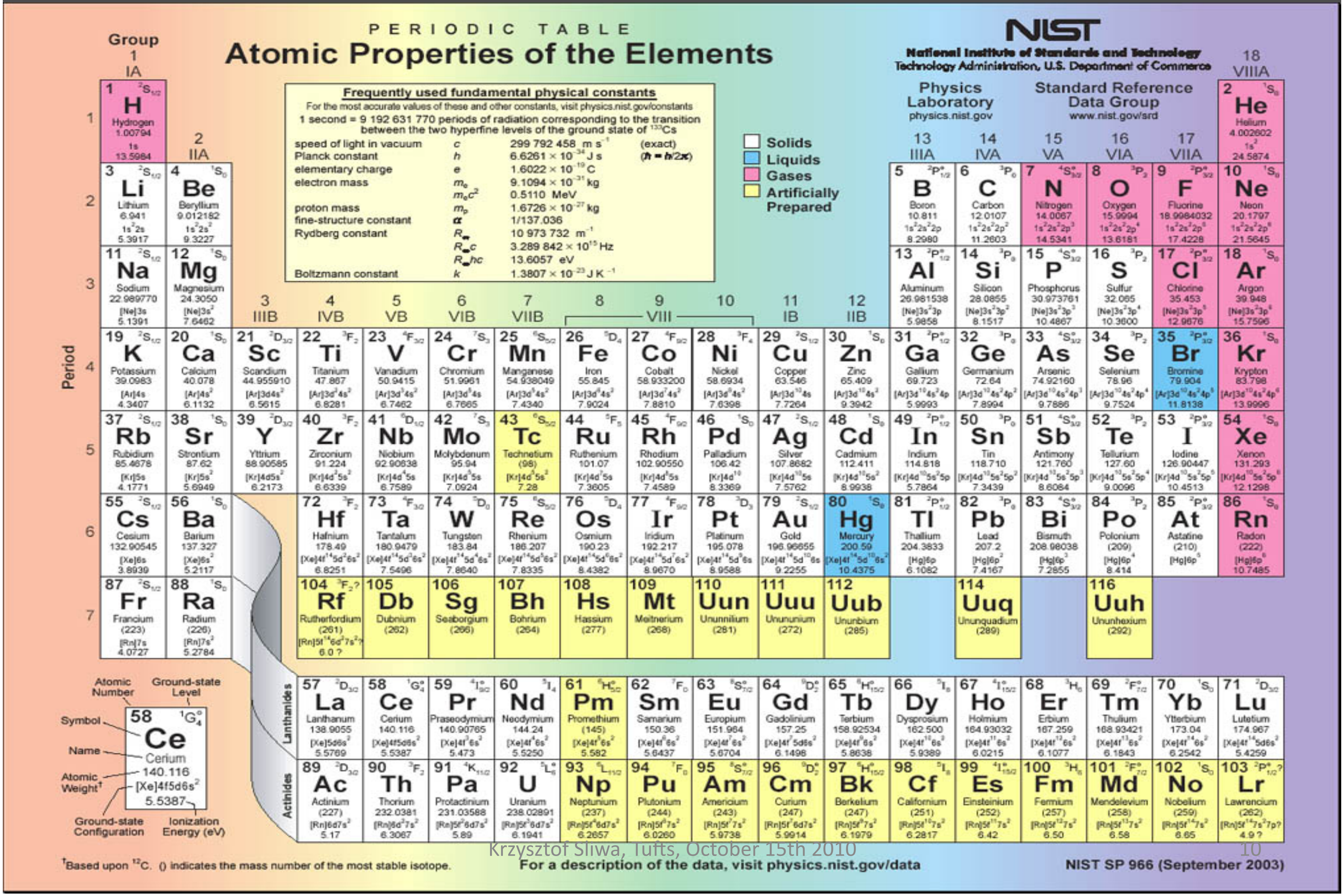
Mendeleev table



THE PERIODICITY OF THE ELEMENTS

The Elements	Their Properties in the Free State: t [1]	a [2]	d [3]	A/d [4]	The Composition of the Hydrogen and Organo-metallic Compounds: RH_m or $R(CH_3)_m$ [5]	Symbols and Atomic Weights: R [6]	A	The Composition of the Saline Oxides: R_2O_n [7]	The Properties of the Saline Oxides	d' [8]	$\frac{(2A+n'16)}{d'}$ [9]	V [10]	Small Periods or Series [11]
Hydrogen	<−200°	—	<0·05>	20	m = 1	H	1	1 = n		0·917	19·6	<−20	1
Lithium	180°	—	0·59	12		Li	7	1†		2·0	15	− 9	2
Beryllium	(900°)	—	1·64	5·5		Be	9	— 2		3·06	16·3	+ 2·6	
Boron	(1300°)	—	2·5	4·4	3 — —	B	11	— — 3		1·8	39	10	
Carbon	>(2500°)	—	<2·0 >	6	4 — — —	C	12	— — — 4		>1·0	<88	<19	
Nitrogen	−203°	—	<0·7 >	20	3 — —	N	14	1 — 3* — 5*		1·64	66	< 5	
Oxygen	<−200°	—	<1·0 >	16	2 —	O	16			—	—	—	
Fluorine	—	—	—	—	1	F	19			—	—	—	
Sodium	96°	071	0·98	23	1	Na	23	1†	Na_2O	2·6	24	−22	3
Magnesium	500°	027	1·74	14	2 —	Mg	24	— 2†		3·6	22	− 3	
Aluminium	600°	023	2·6	11	3 — —	Al	27	— — 3	Al_2O_3	4·0	26	+ 1·3	
Silicon	(1200°)	008	2·3	12	4 — — —	Si	28	— — 3 4		2·65	45	5·2	
Phosphorus	44°	128	2·2	14	3 — —	P	31	1 — 3* 4* 5*		2·39	59	6·2	
Sulphur	114°	067	2·07	15	2 —	S	32	— 2 — 4* 5* 6*		1·96	82	8·7	
Chlorine	−75°	—	1·3	27	1	Cl	35½	1 — 3 — 5* — 7*		—	—	—	
Potassium	58°	084	0·87	45		K	39	1†		2·7	35	−55	4
Calcium	(800°)	—	1·6	25		Ca	40	— 2†		3·15	36	− 7	
Scandium	—	—	(2·5)	(18)		Sc	44	— — 3†		3·86	35	(0)	
Titanium	(2500°)	—	(5·1)	(9·4)		Ti	48	— — 3 4		4·2	38	(+5)	
Vanadium	(2000°)	—	5·5	9·2		V	51	— 2 3 4 5		3·49	52	6·7	
Chromium	(2000°)	—	5·5	8·0		Cr	52	— 2 3 — — 6*		2·74	73	9·5	
Manganese	(1500°)	—	7·5	7·3		Mn	55	— 2† 3 4 — 6* 7*		—	—	—	
Iron	1400°	012	7·8	7·2		Fe	56	— 2† 3 — — 6*		—	—	—	
Cobalt	(1400°)	013	8·6	6·8		Co	58½	— 2† 3 4		—	—	—	
Nickel	1350°	017	8·7	6·8		Ni	59	— 2† 3		—	—	—	
Copper	1054°	029	8·8	7·2		Cu	63	1† 2†	Cu_2O	5·9	24	9·8	5
Zinc	433°	—	7·1	9·2	2 —	Zn	65	— 2†		5·7	28	4·8	
Gallium	30°	—	5·96	12	3 — —	Ga	70	— — 3	Ga_2O_3	(5·1)	(36)	(4·0)	
Germanium	900°	—	5·47	13	4 — — —	Ge	72	— 2 — 4		4·7	44	4·5	
Arsenic	500°	006	5·7	13	3 — —	As	75	— — 3 — 5*		4·1	56	6·0	
Selenium	217°	—	4·8	16	2 —	Se	79	— — — 4 — 6*		—	—	—	
Bromine	−7°	—	3·1	26	1	Br	80	1 — — — 5* — 7*		—	—	—	
Rubidium	39°	—	1·5	57		Rb	85	1†		—	—	—	6
Strontium	(600°)	—	2·5	35		Sr	87	— 2†		4·3	48	−11	
Yttrium	—	—	(3·4)	(26)		Y	89	— — 3†		5·05	45	(−2)	
Zirconium	(1500°)	—	4·1	22		Zr	90	— — — 4		5·7	43	−0·2	
Niobium	—	—	7·1	13		Nb	94	— — 3 — 5*		4·7	57	+6·2	
Molybdenum	—	—	8·6	12		Mo	96	— 2 3 4 — 6*		4·4	65	6·8	
						(1)							
Ruthenium	(2000°)	010	12·2	8·4		Ru	103	— 2 3 4 — 6 — 8		—	—	—	
Rhodium	(1900°)	008	12·1	8·6		Rh	104	— 2 3 4 — 6		—	—	—	
Palladium	1500°	012	11·4	8·3		Pd	106	1† 2 — 4		—	—	—	
Silver	950°	019	10·5	10		Ag	108	1†	Ag_2O	7·5	31	11	7
Cadmium	320°	031	8·6	13	2 —	Cd	112	— 2†		8·15	31	2·5	
Indium	176°	046	7·4	14	3 — —	In	113	— 2 3	In_2O_3	7·18	38	2·7	
Tin	230°	023	7·2	16	4 — — —	Sn	118	— 2 — 4		6·95	43	2·8	
Antimony	432°	012	6·7	18	3 — —	Sb	120	— — 3 4 5		6·5	49	2·6	8
Tellurium	455°	017	6·4	20	2 —	Te	125	— — — 4 — 6*		5·1	68	4·7	
Iodine	114°	—	4·9	26	1	I	127	1 — 3 — 5* — 7*		—	—	—	
Cæsium	27°	—	1·88	71		Cs	133	1†		—	—	—	
Barium	—	—	3·75	36		Ba	137	— 2†		5·1	60	−6·0	
Lanthanum	(600°)	—	6·1	23		La	138	— — 3†		6·5	50	+1·3	
Cerium	(700°)	—	6·6	21		Ce	140	— — 3 4		6·74	50	2·0	
Didymium	(800°)	—	6·5	22		Di	142	— — 3 — 5		—	—	—	
						(14)							
Ytterbium	—	—	(6·9)	(25)		Yb	173	— — 3		9·18	43	(−2)	10
						(1)							
Tantalum	—	—	10·4	18		Ta	182	— — — — 5		7·5	59	4·6	
Tungsten	(1500°)	—	19·1	9·6		W	184	— — — 4 — 6		6·9	67	8	
						(1)							
Osmium	(2500°)	007	22·5	8·5		Os	191	— — 3 4 — 6 — 8		—	—	—	
Iridium	2000°	007	22·4	8·6		Ir	193	— — 3 4 — 6		—	—	—	
Platinum	1775°	005	21·5	9·2		Pt	196	— 2 — 4		—	—	—	
Gold	1045°	014	19·3	10		Au	198	1 — 3	Au_2O	(12·5)	(33)	(13)	11
Mercury	−39°	—	13·6	15	2 —	Hg	200	1† 2†		11·1	39	4·5	
Thallium	294°	031	11·8	17	3 — —	Tl	204	1† — 3	Tl_2O_3	(9·7)	(47)	(4·3)	
Lead	326°	029	11·3	18	4 — — —	Pb	206	— 2† — 4		8·9	53	4·2	
Bismuth	268°	014	9·8	21	3 — —	Bi	208	— — 3 — 5		—	—	—	
						(5)							
Thorium	—	—	11·1	21		Th	232	— — — 4		9·86	54	20	12
						(1)							
Uranium	(800°)	—	18·7	13		U	240	— — — 4 — 6		(7·2)	(80)	(9)	

Mendeleev table (modern version)



structure of matter: XIX century

• Through very clever measurements scientists measured the size of the molecules, their diameters are of the order of 1/10 000 000 000 = 10^{-10} m

10^{-10} m/1m = 1/10 000 000 000 = 1 second / 320 years

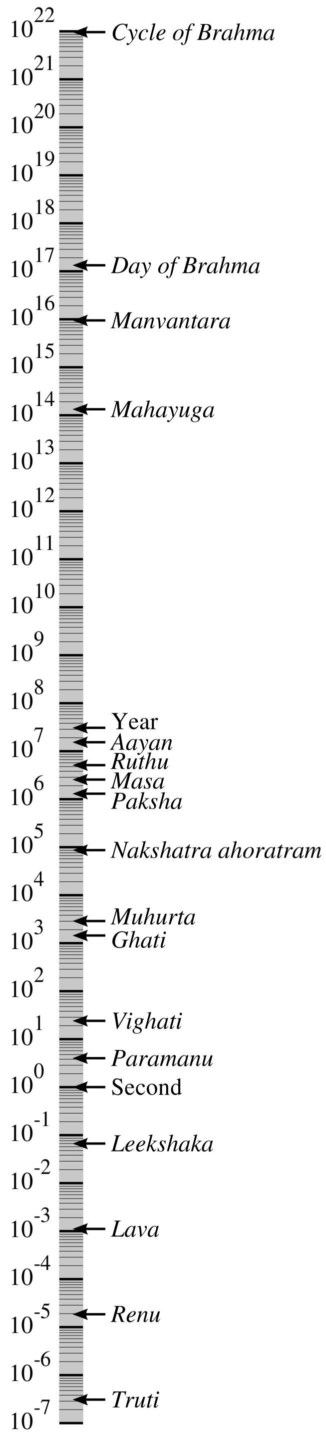
• This is why the number of molecules in our bodies is large, about 1 000 000 000 000 000 000 000 000 000 ~ 10^{27} in each of us. Atoms are a bit smaller than molecules, but not by much

Forces

- contact forces known via everyday experience, objects falling on Earth, electric forces, magnetic

- 1686 Newton universal theory of gravitation, the same for Moon and on Earth; action at the distance, no contact, mutual interaction between any pair of masses

- 1861 Maxwell equations unified electrical and magnetic forces, two aspects of the same fundamental phenomena, which one is observed depends on the choice of reference frame; also action at the distance



time

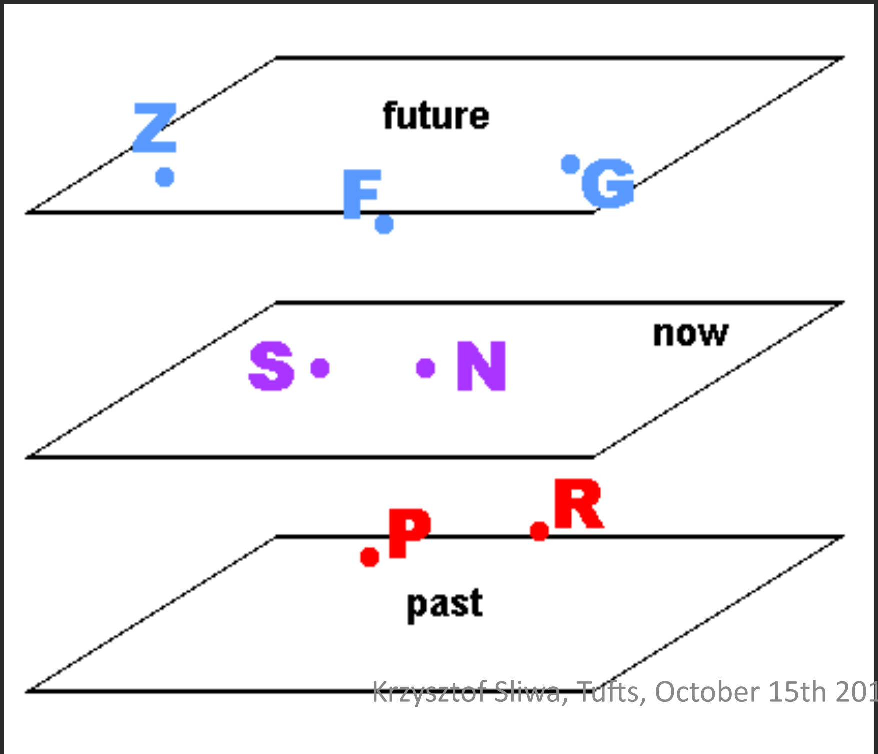
- 24 hours/day, 60 min/hour, 60 sec/min Babylonian units
- in most ancient cultures (Babylon, Hindu, Inca, Maya, ancient Greece..) time is cyclical
- Bible : linear with a beginning and an end
- is it “real” or is it an “illusion”?
- Newton: absolute space and time, continuous
- Leibniz: time and space are relational, based on objects and events, discrete
- Kant: neither, a framework in which experiences can be organized

time and space (end of XIX century)

- classical mechanics uses absolute space and time of Galileo and Newton
- space and time independent of each other, both continuous

space modeled by R^3 (3 dimensional Euclidean space)

time modeled by R^{1*} (arrow of time, for some reason we cannot reverse the time flow)



physics laws invariant under Galilean transformations

is physics finished?

Such opinions were voiced not infrequently by the end of XIXth century. All matter was understood to be composed of different atoms

one could *in principle*, given the knowledge of initial conditions and the Physics Laws (Newton's three laws of mechanics, Newton's law of gravity and Maxwell's laws of electromagnetism) calculate positions of particles in a system COMPLETELY DETERMINISTICALLY at any moment of time

maybe there were too many of chemical elements for atoms to be really elementary, black-body radiation was unexplained and it was strange that Lorentz transformations (not Galilean) were needed to keep Maxwell equations invariant

breakthroughs

- 1895 Thomson: discovered electrons, particles with negative electric charge, and mass ~2000 smaller than the hydrogen atom, the lightest known element. Electric current is a flow of electrons

- 1896 Becquerel: discovered radioactivity; Maria Curie-Sklodowska isolated several new radioactive elements

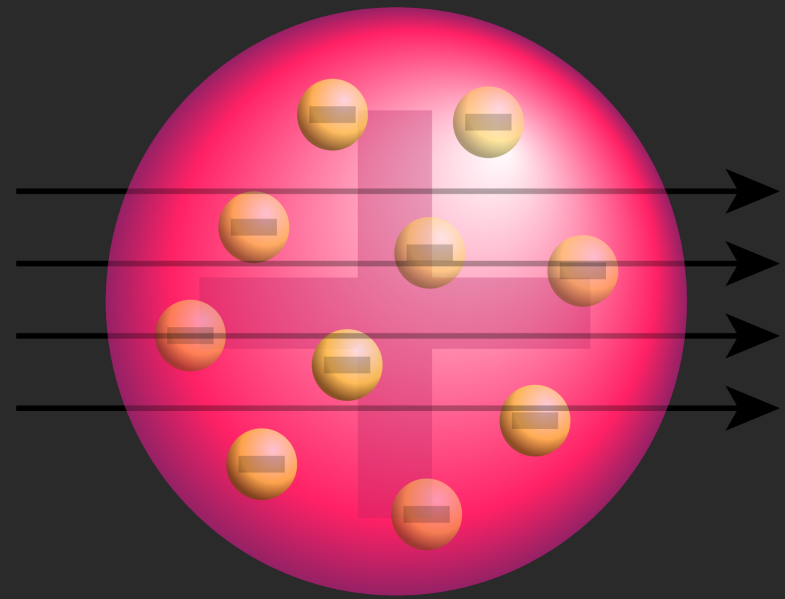
breakthroughs

- 1898-1903 Rutherford: identified 3 types of radiation; one could transform one element another with α and β (even into gold, except it would be very expensive) but not with γ radiation

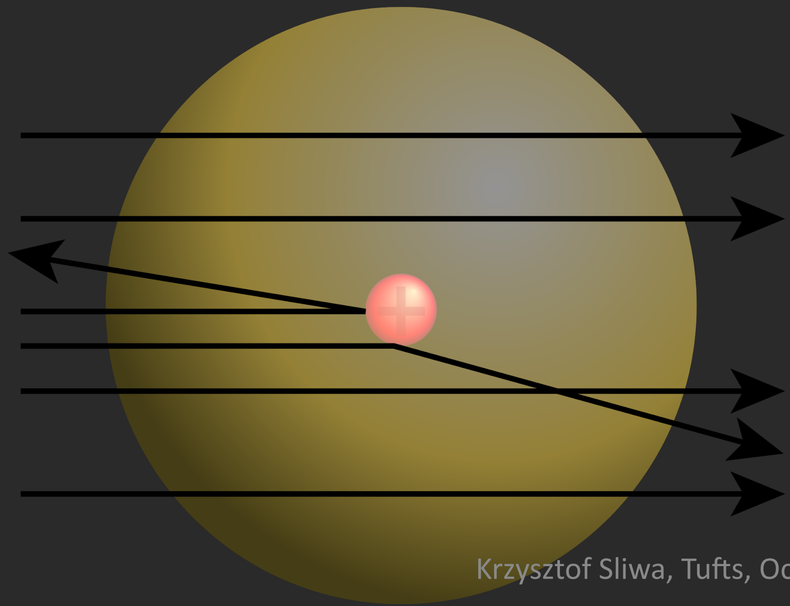
- 1907 Rutherford proved that α radiation are just ionized helium atoms

- 1909 Geiger and Marsden demonstrated existence of large angle scattering when directing α radiation at gold foil (Rutherford gold experiment)

Geiger–Marsden gold experiment



expected in Thomson
“plum pudding” model



experiment => Rutherford
model of atomic nucleus

atomic nucleus

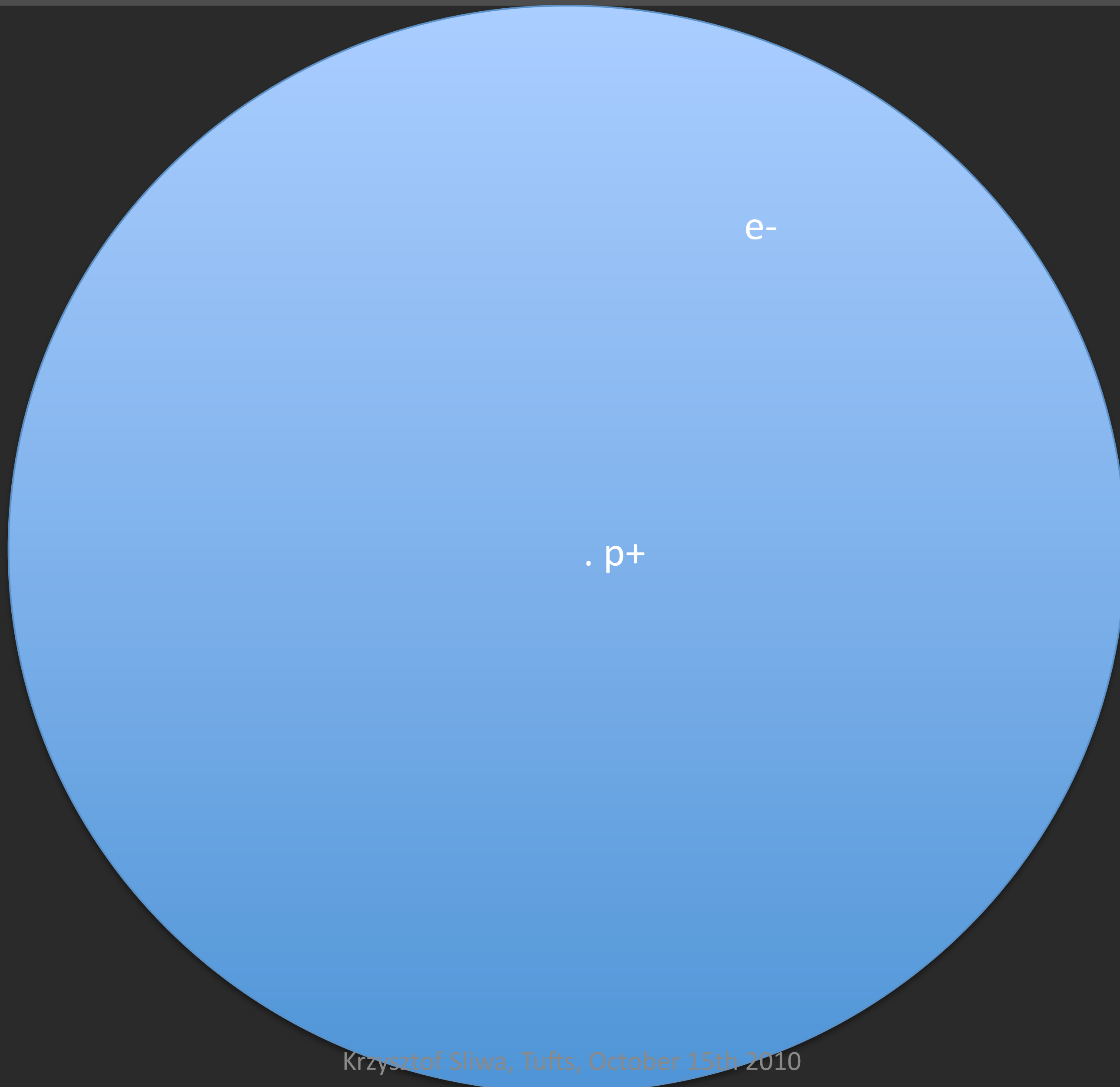
- 1911 Rutherford postulated that atoms have their positive charge confined to a small NUCLEUS surrounded by electron cloud to make atoms electrically neutral

- nucleus is extremely small, only 1/100000 = 10^{-5} of atom size:

  if atom was the size of football field the nucleus would be only 1 mm across

we are made of almost empty space with almost all our mass in tiny nuclei

matter we see is made of almost empty space...



H atom
(not to scale)

size of atoms =
size of electron
clouds

Quantum Mechanics

- 1900 Planck – introduced a concept of quantum of energy to explain the black-body radiation – did not like the idea!
- 1905 Einstein explained the photo-electric effect using the same concept
- to explain atomic emission and absorption spectra a new theory was developed - QUANTUM MECHANICS – by Schrodinger and Heisenberg in 1926 (Dirac, Jordan, Born, Bohr..)

Quantum Mechanics

- PHYSICS ON ATOMIC SCALE IS GOVERNED BY QUANTUM MECHANICS - no longer completely deterministic as in classical physics (Feynman : nobody understands quantum mechanics)

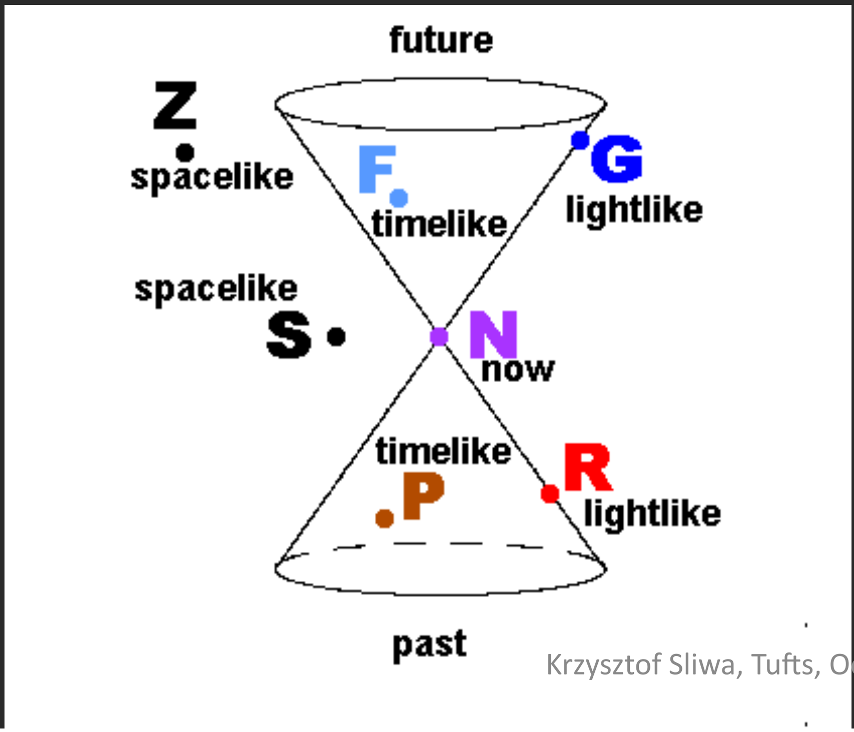
- periodicity of chemical elements is a quantum effect observable on macroscopic scale (spacings of 2,8,8,18,18 elements in Mendeleev table)

Minkowski space-time

- special theory of relativity (SR) proposed by Einstein in 1905

  Lorentz transformations <=> time and space no longer absolute because of the finite, and the same for all observers, speed of propagation of light or any signal

- Minkowski : interpreted SR a consequence of time and space being an unseparable 4-dimensional space-time entity (“world”) 1907

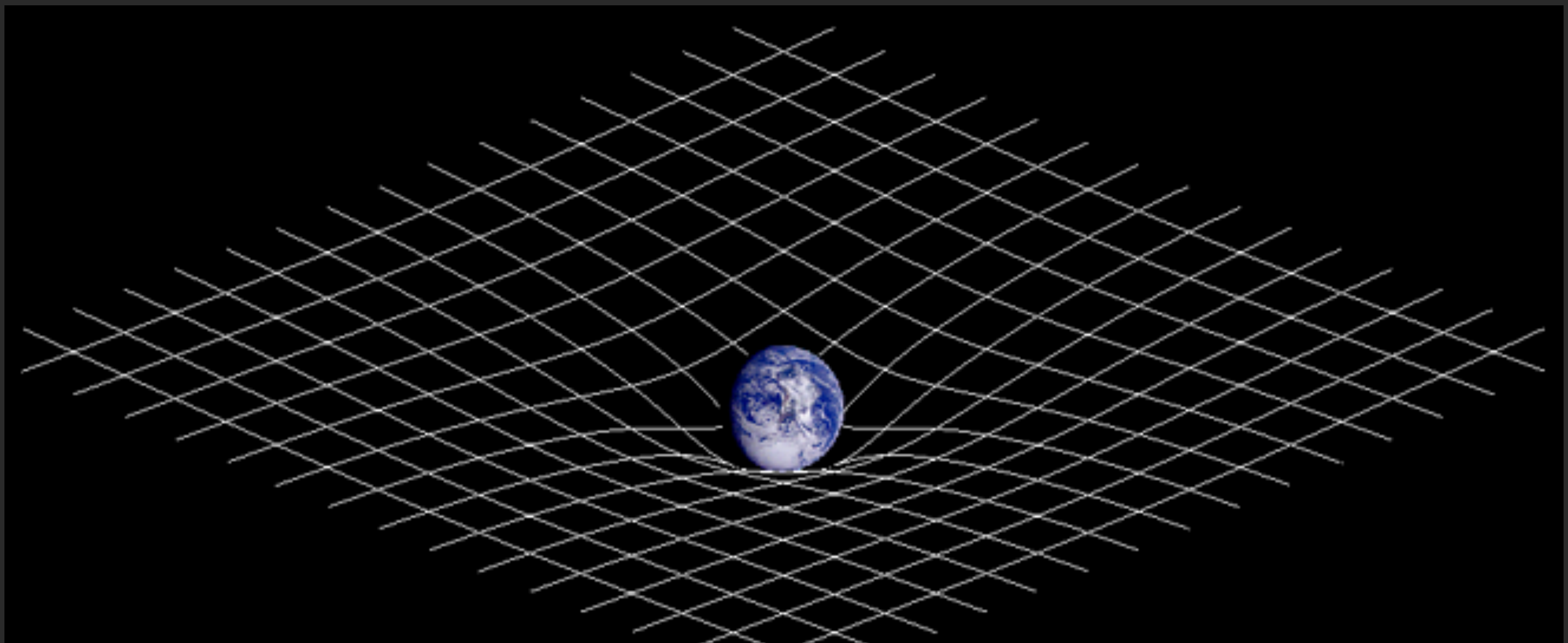


Physics laws invariant under Poincare group of transformations:

- space translations
- space rotations
- time translations
- Lorentz boosts = rotations in 4-dim “world” or spacetime which mix time and space coordinates

General Relativity

- General Theory of relativity Einstein 1907-1915 – a new relativistic and geometric theory of gravity: matter tells spacetime how to curve, and curved spacetime tells matter how to move" (Wheeler)



early attempts at Unification

- 1918 Weyl's theory of gravitation and electricity, he introduced term gauge invariance; unification was unsuccessful; however, his idea applied to quantum mechanic became what we now call gauge theories (complex scale factor rather than real)

- 1921 Kaluza and Klein suggested that gravitation and electricity can be unified in a theory of gravity in 5-dimensional Riemannian geometry; not much support, mainly because it was introducing new dimension (Ockham's razor principle)

structure of matter/ early XX century

- For about 20 years in the beginning of XXth century scientists thought that electron and proton are true building blocks of matter

proton	q=+1e (1.6×10^{-19} C)	$m=m_P$ (1.67×10^{-27} kg)
electron	q=-1e	$m=m_P/2000$

- In particle physics a different system of units is used rather than SI: c=1, $\hbar$=1

1 eV=1.6×10^{-19} J (scale in which WE live)
$m_P = 1.67 \times 10^{-27}$ kg ~ 1 GeV/c^2 (c=1, just to remind that m is mass)
m_e=0.5 MeV/c^2

elementary particles ~1920

- 1919 Rutherford proved that the lightest atom, hydrogen, is also part of nitrogen atom (first "atom splitting")

$$^{14}N + \alpha \rightarrow {}^{17}O + p$$

- 1928 Rutherford postulated that hydrogen atom is built of a single proton and an electron; he also postulated existence of a neutron – particle with mass of a proton and no electric charge

  all atoms are build of three elementary particles (isotopes explained):

proton	q=+1e (1.6 x 10^{-19} C)	$m=m_P$ (1.67 x 10^{-27} kg)
neutron	q=0	$m=m_P$
electron	q=-1e	$m=m_P/2000$

New particles

1928 Dirac, *as a result of purely mathematical studies*, postulated existence of an anti-particle to the electron, a positron

1931 a neutrino, neutral particle with zero (or almost zero) mass was postulated by Pauli to account for "missing energy" in β decays

1932 a positron was discovered by Anderson, and a neutron by Chadwick

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New particles -> not elementary?

antiprotons postulated in 1930 were discovered in 1955

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more and more "elementary" particles were being discovered

π, ρ, μ, Σ, Λ, θ, K, K*, Ω, ω, η…….

~1960, the number of "elementary particles" was about 70, and growing; it became clear that they cannot be elementary, very much as it was the case with chemical elements less than a 100 years earlier

New Interactions

- to explain existence of nuclei a strong force was proposed to counteract the electric repulsion between protons

- a weak force was suggested to account for radioactive β decays

STRENGTH OF INTERACTIONS

Interaction	gravity	weak	em	strong
Coupling constant C^2 *(J · m)*	$1.87 x 10^{-64}$	$3.22 x 10^{-31}$	$2.31 x 10^{-28}$	$2.5 x 10^{-27}$
Range *(m)*	∞	$2 x 10^{-18}$	∞	$1.5 x 10^{-15}$

(between two protons)

Quarks

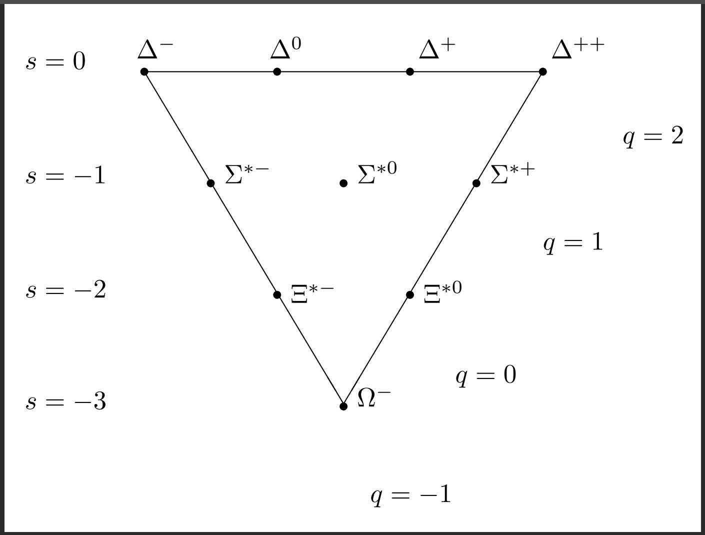
- Gell-Mann and Zweig 1964

- Baryons (heavy) and mesons (intermediate) particles were
forming "multiplets" with particles of similar mass and properties

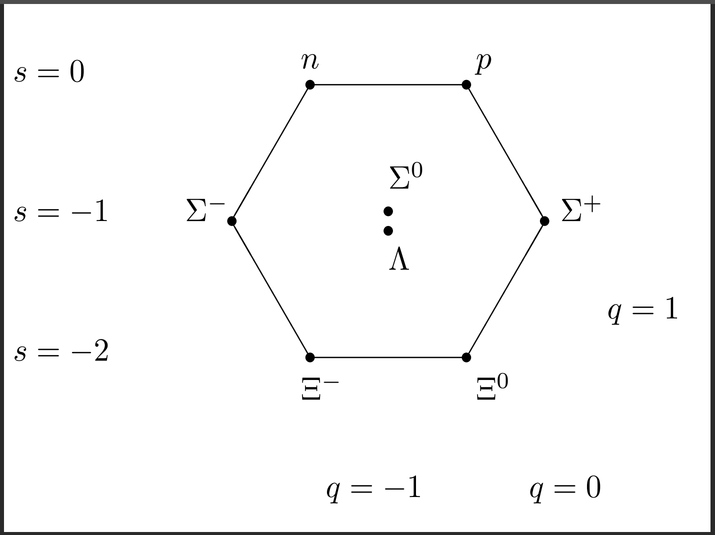
9	spin-0 mesons (nonet)
9	spin-1 mesons (nonet)
8	spin ½ baryons (octet)
10	spin 3/2 baryons (decaplet)

Other than electric charge, several new quantum numbers were introduced: spin, isospin, strangeness, hypercharge….

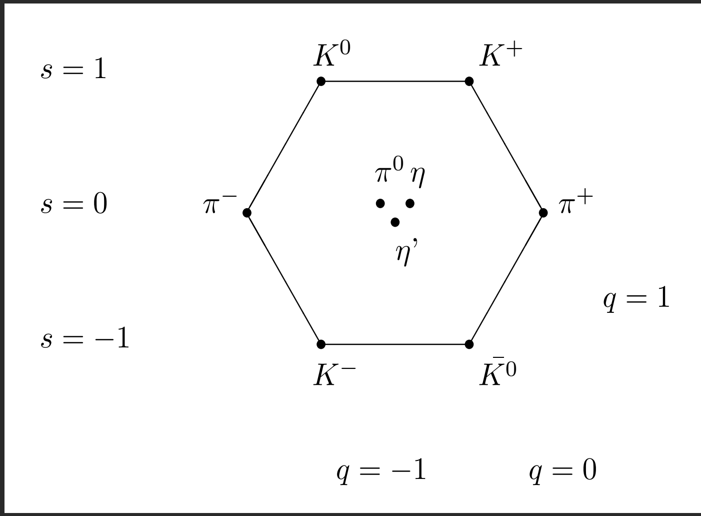
Quarks



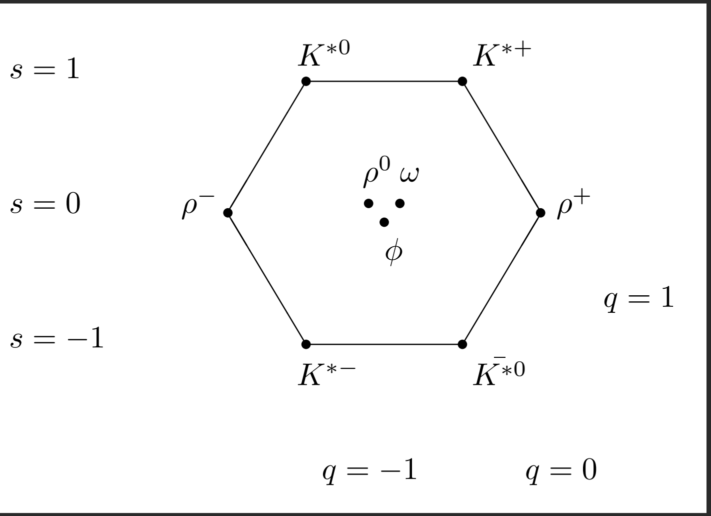
s = 0
s = −1
s = −2
s = −3
Δ⁻ Δ⁰ Δ⁺ Δ⁺⁺
Σ*⁻ Σ*⁰ Σ*⁺
Ξ*⁻ Ξ*⁰
Ω⁻
q = 2
q = 1
q = 0
q = −1



s = 0
s = −1
s = −2
n p
Σ⁻ Σ⁰ Σ⁺
Λ
Ξ⁻ Ξ⁰
q = 1
q = −1
q = 0



s = 1
s = 0
s = −1
K⁰ K⁺
π⁻ π⁰ η π⁺
η'
K⁻ K̄⁰
q = 1
q = −1
q = 0



s = 1
s = 0
s = −1
K*⁰ K*⁺
ρ⁻ ρ⁰ ω ρ⁺
φ
K*⁻ K̄*⁰
q = 1
q = −1
q = 0

Quarks

If one assumes existence of three new fundamental objects (quarks) u,d,s (up, down and strange) which belong to a fundamental representation of SU(3) called 3**,** with the antiquarks belonging to 3/bar, then one can identify the observed octets, nonets and decaplets with representations of SU(3) flavour symmetry group obtained by forming tensor products of the fundamental representations

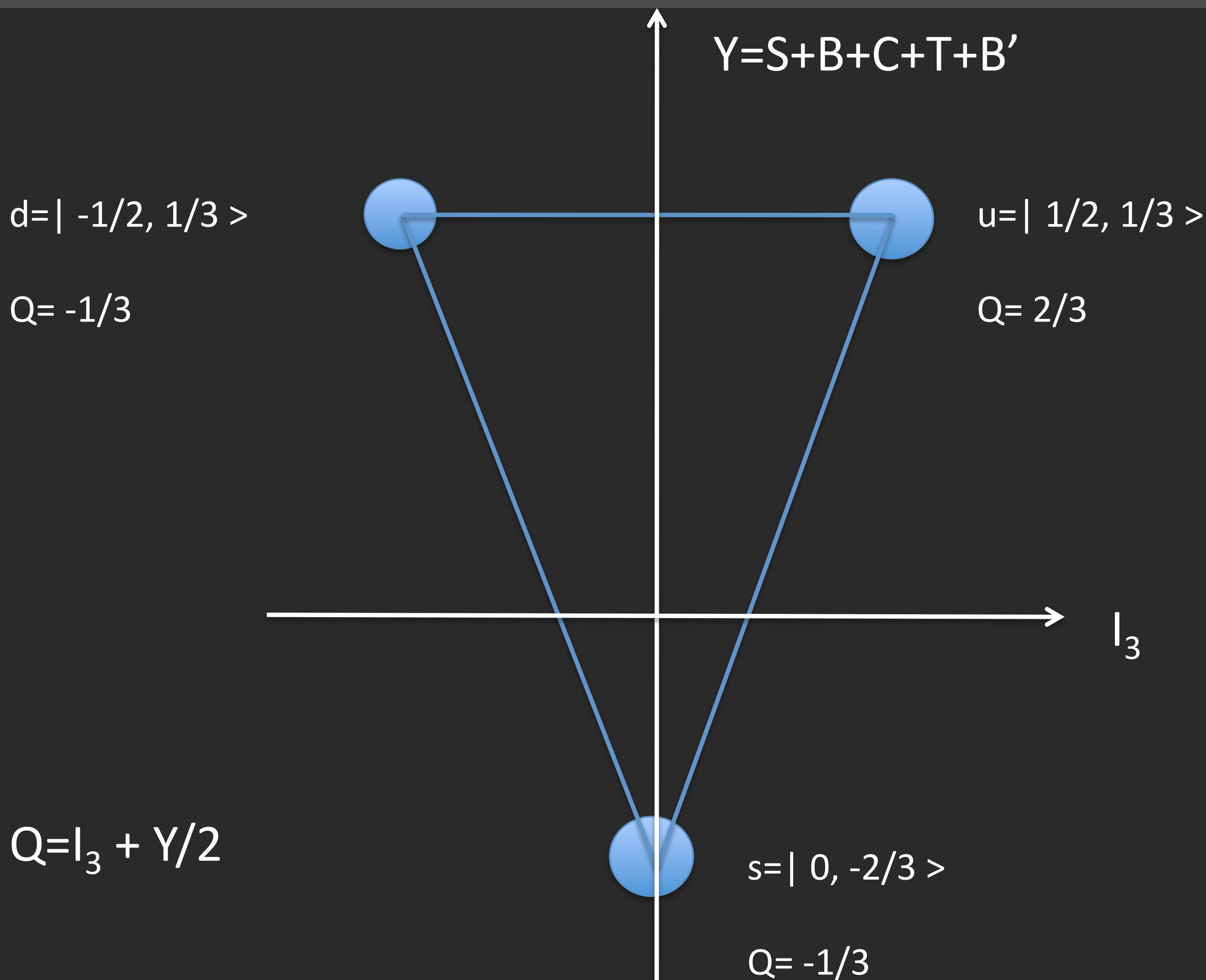
3 × 3/bar = 1 + 8 => mesons are made of quark-antiquark
3 x 3 x 3 = 1 + 8 + 8 + 10 => baryons are made of three quarks

but not

3 x 3 = 1 + 6 (such multiplets were never observed)

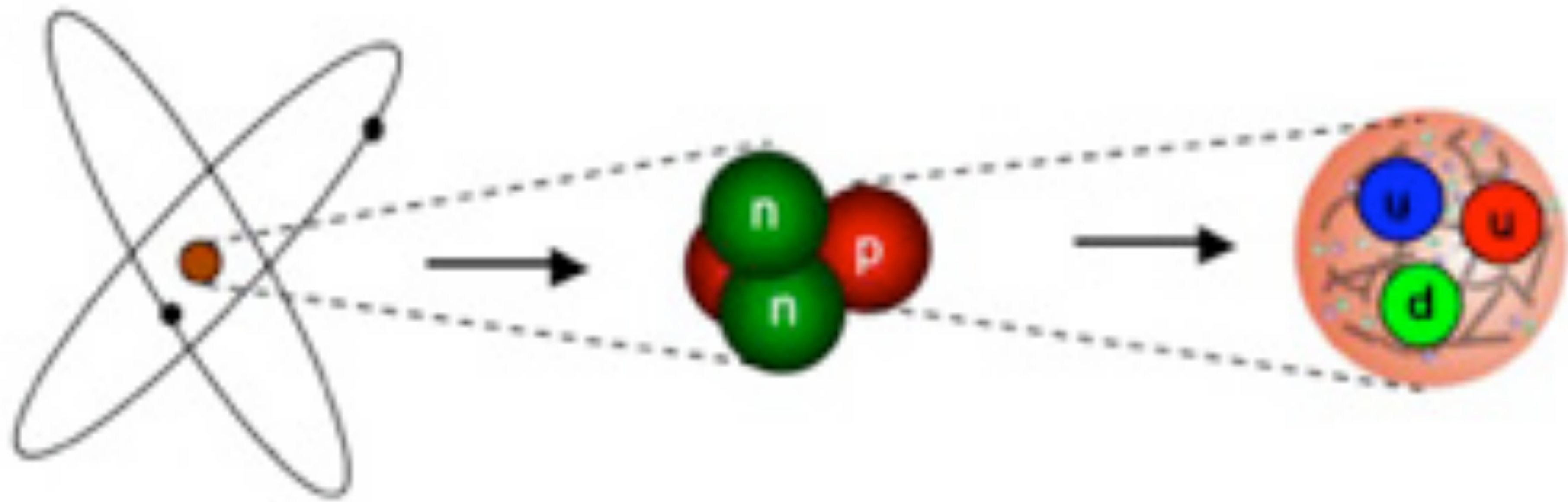
If masses of u,d,s quarks were equal, SU(3) flavor symmetry would be perfect, and the masses of all particles would be the same when SU(3) rotations exchange quarks

quarks (u,d,s)



$$Q = I_3 + Y/2$$

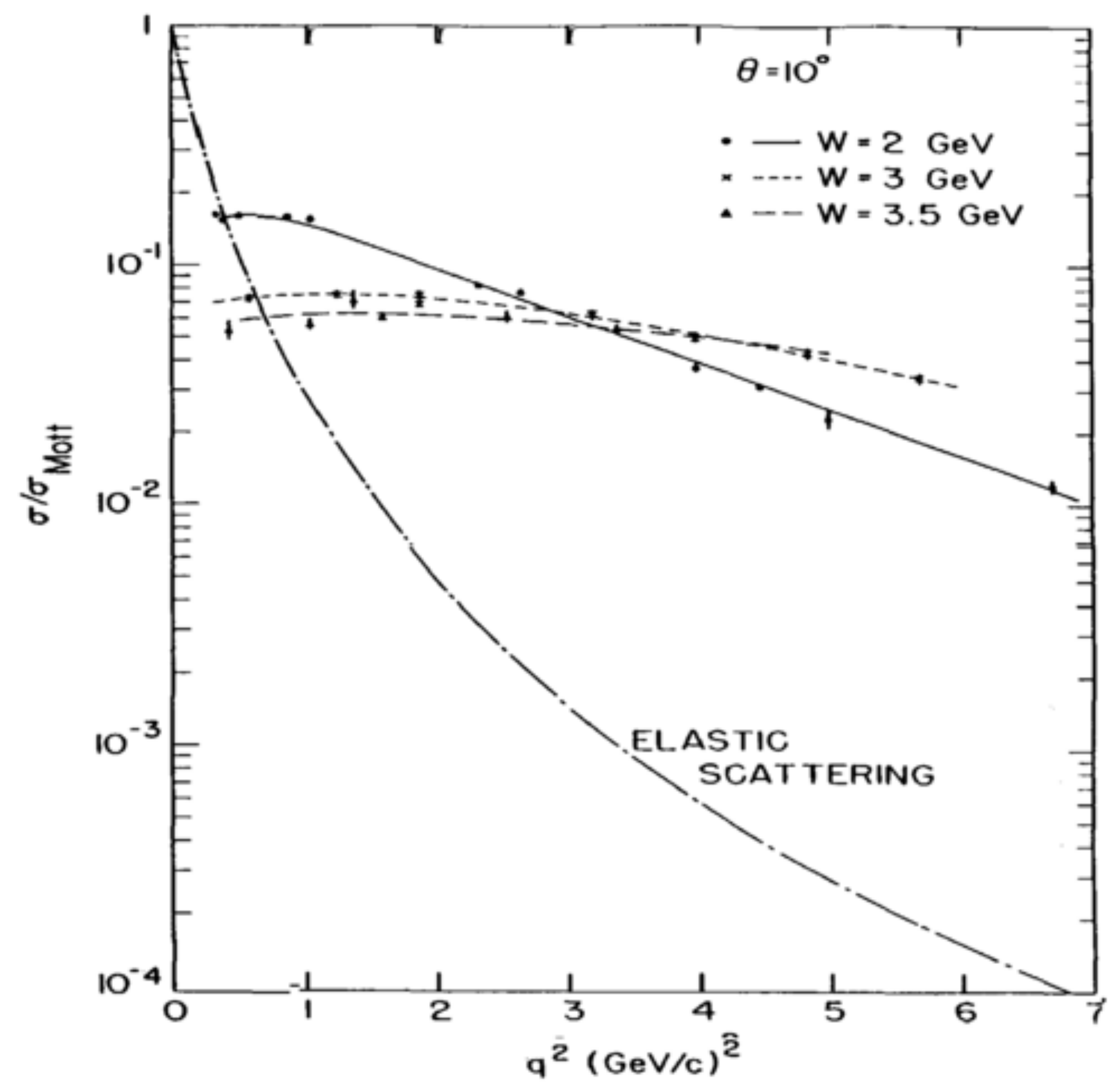
Quarks



Quarks – are they real?

For a while many physicists were reluctant to accept existence of fractionally charged quarks.

However, SLAC-MIT experiment (1970), very similar in concept to Rutherford gold experiment (e+p) proved that quarks really exist in a proton



symmetries ⇔ conservation laws

Emmy Noether discovered the connection between symmetries and conservation laws while working with David Hilbert and Felix Klein in Gottingen

In 1918 she proved two theorems, for finite continuous groups and infinite continuous groups which are the foundations of the modern (XXth century) physics. The theorems are collectively known as “Noether’s theorem”

Informally, Noether’s theorem says:

differentiable symmetry generated by local actions <=> conserved current

or

there is one-to-one correspondence between symmetries and conservation laws

symmetry <=> conservation law

symmetries ⇔ conservation laws

examples (symmetries of space-time)

energy is conserved if and only if (iff) the physical laws are invariant under time translations (if the form of physics laws do not depend on time)

linear momentum is conserved only iff the physical laws are invariant under space translations (if the form of physics laws do not depend on the position)

angular momentum is conserved iff the physical laws are invariant under rotations (if the physics laws do not depend on orientation; if only true about a particular direction <=> only the component of angular momentum in that direction is conserved)

symmetries ⇔ conservation laws

Symmetries observed in physics:

Symmetries of discrete space-time transformations: parity, time-reversal, charge conjugation

Symmetries of continuous space-time transformations: translational and rotational invariance and Lorentz (space-time rotations) invariance

Symmetries of permutations: lead to two kind of particles: bosons (spin=0,1,2..), which obey Bose-Einstein statistics, and fermions (spin=1/2,3/2…), which obey Fermi-Dirac statistics

Gauge symmetries: "internal" symmetries inherent from the nature of the field associated with a given particle carrying such attributes as electric charge - U(1), color - SU(3) et cetera (conservation of electric charge <=> invariance under the global phase transformation in the "internal" space; electromagnetic field <=> invariance under the local phase transformation; et cetera….)

symmetries ⇔ conservation laws

Modern particle physics is based entirely on the idea of underlying internal symmetries

- relativistic quantum gauge theories

The electro-weak sector is based upon the "internal" symmetries which the electromagnetic and weak interactions obey - U(1) and SU(2)

The strong sector of the Standard Model (SM), quantum chromodynamics (QCD) is based on the "internal" SU(3) color symmetry, different symmetry than flavor symmetries observed in hadron spectroscopy

Spontaneous symmetry breaking has been proposed to explain massive weak bosons (Z, W) and the massless photon. The prediction of the W and Z bosons came from symmetry arguments and the discovery of these particles at CERN was one of the greatest successes of modern particle physics

STANDARD MODEL

Current understanding of elementary particles and their strong and electro-weak interactions is given by Standard Model, a gauge theory based on the following "internal" symmetries:

$$SU(3)_c \times SU(2)_l \times U(1)_Y$$

The SU(3) is an unbroken symmetry, it gives Quantum Chromo-Dynamics (QCD), a quantum theory of strong interactions, whose carriers (gluons) are massless, couple to color (strong force charge)

SU(2)×U(1) (quantum theory of electroweak interactions) is spontaneously broken by the Brout-Englert-Higgs mechanism; which gives mass to electroweak bosons (W^+, W^-, Z^o and a massless photon) and all fermions

In the Minimal Standard Model, the Higgs sector is the simplest possible: contains two complex Higgs fields, which after giving masses to W^+, W^-, Z^o leaves a neutral scalar Higgs particle which should be observed - the ONLY particle not yet discovered in MSM

MINIMAL STANDARD MODEL

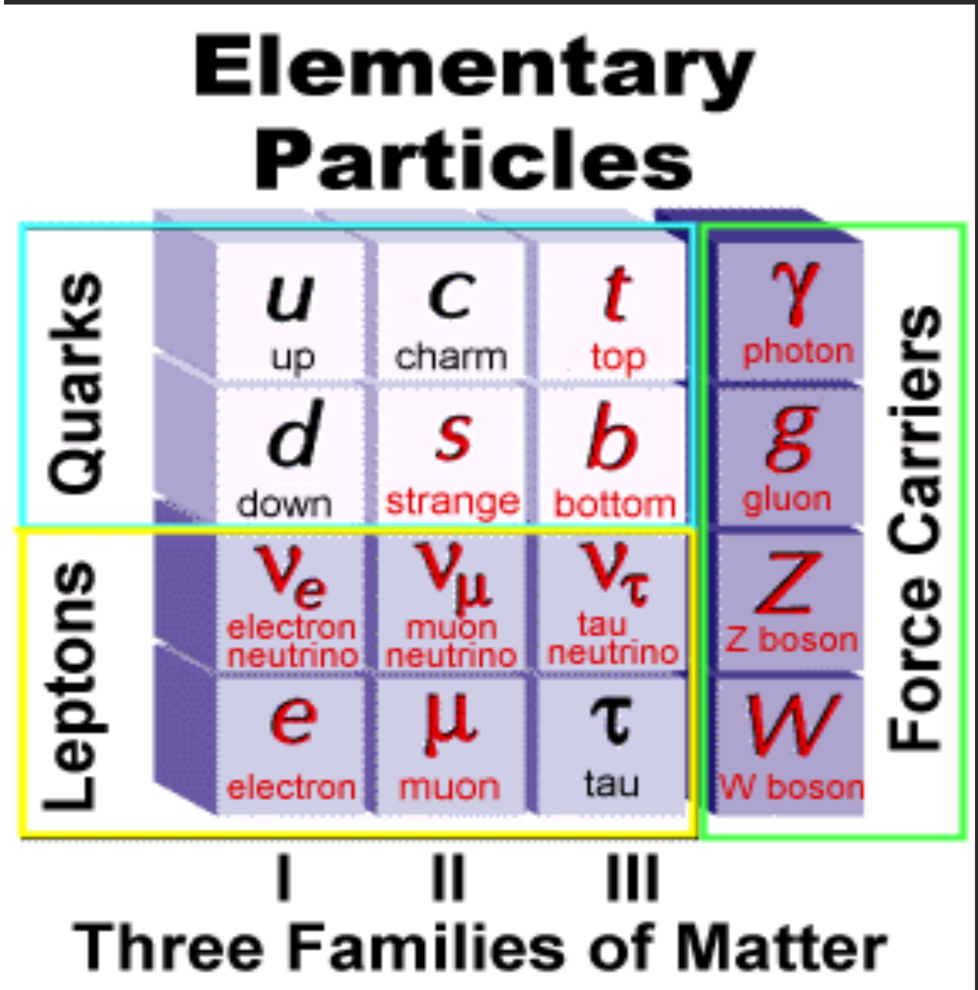
Matter is build of fermions - quarks and leptons, three families of each, with corresponding antiparticles; quarks come in three colors, leptons are color singlets, do not couple to gluons

Bosons are carriers of interactions: 8 massless gluons, 3 heavy weak bosons (W,Z) and 1 massless photon

A massive neutral scalar Higgs field permeates the Universe and is (in some way) responsible for masses of other particles (they originate from couplings to Higgs field)

HIGGS SCALAR IT IS THE ONLY PARTICLE MISSING IN THE MINIMAL STANDARD MODEL

STANDARD MODEL



26 parameters NOT predicted by SM:

- masses of 6 quarks
- masses of 6 leptons
- coupling constants of SU(3), SU(2) and U(1)
- Higgs mass and vacuum expectation value
- Cabibbo-Kobayashi-Maskawa quark mixing angles and complex phase
- Maki-Nakagawa-Sakata lepton mixing matrix angles and complex phase
- QCD phase θ

ALL MUST BE MEASURED !!!

STANDARD MODEL – QUESTIONS???

- why so many free parameters: all masses, all couplings, all mixing angles and CP-violating phases

- why 6 quarks and 6 leptons - is there an additional symmetry?

- why quarks and and leptons come in three pairs (generations)?

- why is CP not an exact symmetry (or why are laws of physics not symmetrical between matter and antimatter?) perhaps related $\Rightarrow$ why is our Universe matter-dominated?

- are quarks and leptons elementary or do they have structure at scale smaller than we can see ($<10^{-18}$ m)?

- Muon and electron look identical, except for their masses, could muon be an “excitation” of what constitutes a “pointlike” electron??

STANDARD MODEL – QUESTIONS???

- neutrinos - Dirac or Majorana ? why neutrino masses are so small?

- is proton stable?

- QCD - confinement of quarks and gluons was never proven; if we live in low temperatures where confinement works is there a phase transition at higher temperatures where quarks become free?

- what is the nature of spontaneous symmetry breaking of electroweak theory?

- do strong and electroweak interactions become one at very high energies ?

- HOW TO INCLUDE GRAVITY ???

BEYOND STARDARD MODEL??

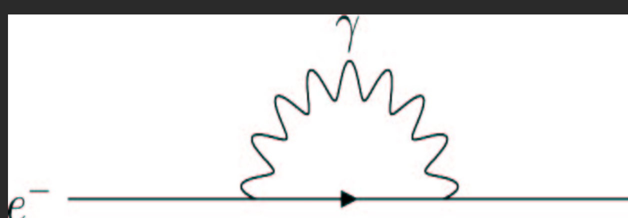
- SUPERSYMMETRY
- TECHNICOLOR
- GRAND UNIFIED THEORIES based on larger symmetry groups, e.g. SU(5), SO(10), E_8, Monster group…
- STRING THEORY, SUPERSTRING THEORIES, BRANES, M-theory
- new models, extensions of Kaluza-Klein theory
- EXPERIMENTAL DATA NEEDED BADLY !!!!

SM problems: spontaneous breaking of the electroweak symmetry by Higgs mechanism

This part of SM is the only remaining untested part of SM. Higgs has not been observed as of yet; remember, the EW symmetry could be broken in a different way, not necessarily like in MSM

Difficulties with the elementary Higgs sector: suppose that SM is just an effective theory and that NEW physics is at some scale Λ.

the quantum corrections to fermion masses would depend only logarithmically on scale Λ:



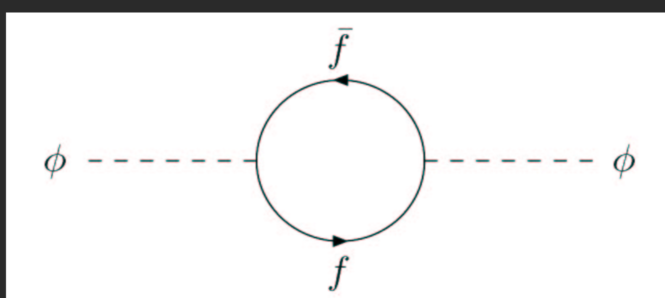
$\delta m_f \sim m_f \ln\Lambda$

SM problems: spontaneous breaking of the electroweak symmetry by Higgs mechanism

Difficulties with the elementary Higgs sector: the analogous quantum corrections to scalar particle (Higgs) would exhibit a quadratic dependence on scale Λ. This means that Higgs mass is VERY sensitive to the scale of the NEW physics => FINE TUNING PROBLEM (for m_o) as m_H=O(100) GeV in SM !!

$$m_H^2 = - m_0^2 + g^2\Lambda^2$$

SM cannot be valid for very large momenta, the scale Λ serves as a cutoff above which physics not contained in SM becomes important. At least one such scale, Planck scale at which gravity becomes relevant, Λ=O(10^{19}) GeV, must be present in any theory.



$$\delta m_H^2 \sim \Lambda^2$$

SM problems: spontaneous breaking of the electroweak symmetry by Higgs mechanism

This fine tuning has to be performed for each order of perturbation theory; this is a very unpleasant feature of SM

This sensitivity is called also the GAUGE HIERARCHY PROBLEM, as the Higgs mass is related to the weak boson masses in the spontaneously broken gauge theory. One may say that the original problem of how to give masses to weak gauge bosons in a gauge invariant way was only partially solved by Higgs mechanism, and the problem was transferred to a new level, where the new puzzle is how to keep Higgs mass stable against large quantum corrections from the higher energy scales

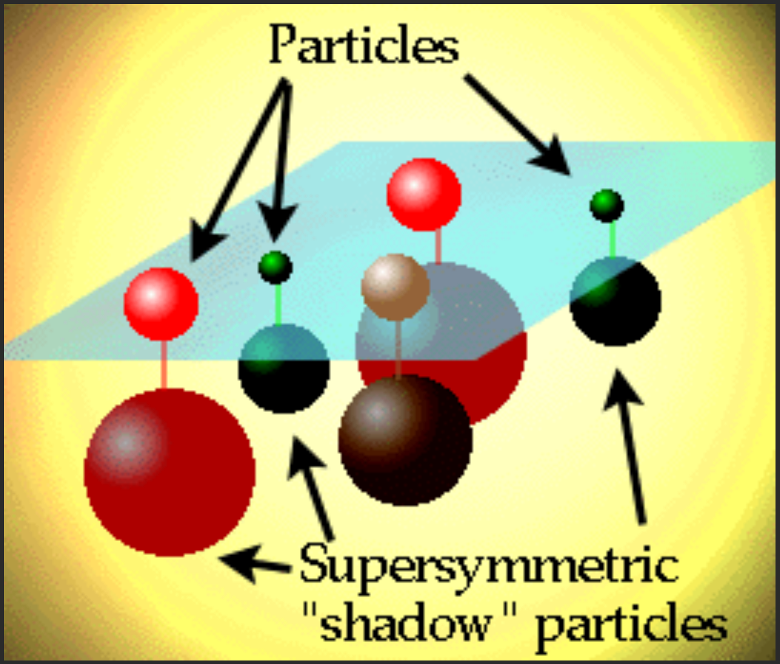
A method of controlling Higgs mass divergence other than fine tuning of parameters would be very welcomed

supersymmetry - the most elegant solution?

interesting thing about the scalar mass divergencies from virtual particle loops (quantum corrections) is that the *virtual fermions and virtual bosons contribute with opposite signs and would cancel each other exactly if for every boson there was a fermion of the same mass and charge - divergencies would cancel without any fine tuning and in all orders of perturbation theory !!*

supersymmetry is such a symmetry: it connects bosons to fermions, it introduces a fermionic partner to every boson and vice-versa, identical in all quantum numbers; such boson <=> fermion connection is unique to supersymmetry; all the symmetries listed before provide no such connection

SUPERSYMMETRY



supersymmetry - the most elegant solution?

Obviously, if supersymmetry were real, it must be somehow broken as we have not yet observed superparticles. One needs to allow such breaking of supersymmetry while still keeping the ability of such a theory to solve the gauge hierarchy problem. Not easy, depends on the scale at which SUSY is broken, and on how it is broken. To some extent it remains still an open question

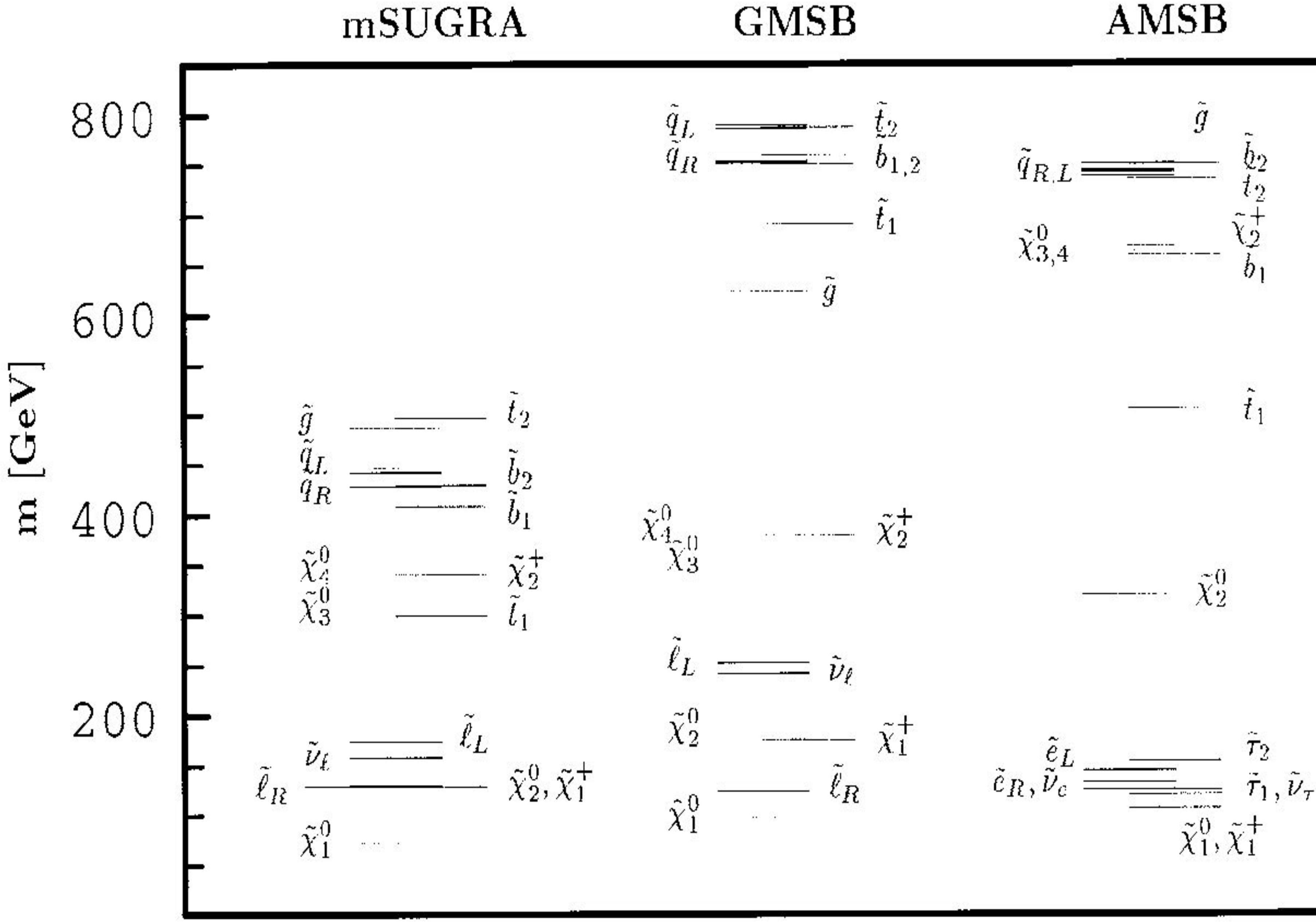
Another reason for SUSY theories being attractive is that in string theories the most viable versions are supersymmetric

Local supersymmetry could also be a viable theory of gravity, supergravity.

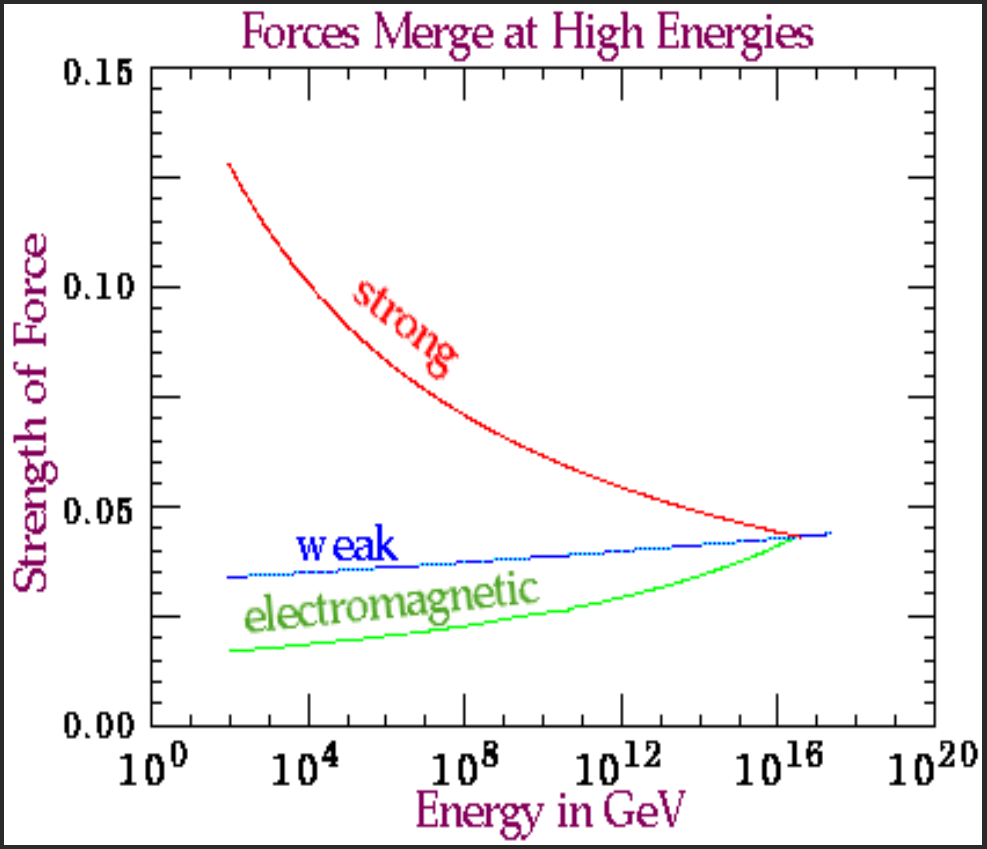
SM and MSSM particle spectrum

Standard Model Particles		SUSY Partners		
Particles	States	Sparticles	States	Mixtures
quarks (q)	$\binom{u}{d}_L, u_R, d_R$	squarks ($\tilde q$)	$\binom{\tilde u}{\tilde d}_L, \tilde u_R, \tilde d_R$	
(spin-$\frac{1}{2}$)	$\binom{c}{s}_L, c_R, s_R$	(spin-0)	$\binom{\tilde c}{\tilde s}_L, \tilde c_R, \tilde s_R$	
	$\binom{t}{b}_L, t_R, b_R$		$\binom{\tilde t}{\tilde b}_L, \tilde t_R, \tilde b_R$	$\tilde t_{1,2}, \tilde b_{1,2}$
leptons (l)	$\binom{e}{\nu_e}_L, e_R$	sleptons ($\tilde l$)	$\binom{\tilde e}{\tilde\nu_e}_L, \tilde e_R$	
(spin-$\frac{1}{2}$)	$\binom{\mu}{\nu_\mu}_L, \mu_R$	(spin-0)	$\binom{\tilde\mu}{\tilde\nu_\mu}_L, \tilde\mu_R$	
	$\binom{\tau}{\nu_\tau}_L, \tau_R$		$\binom{\tilde\tau}{\tilde\nu_\tau}_L, \tilde\tau_R$	$\tilde\tau_{1,2}$
gauge/Higgs bosons	g, Z, γ, h, H, A	gauginos/Higgsinos	$\tilde g, \tilde Z, \tilde\gamma, \tilde H_1^0$	$\tilde\chi^0_{1,2,3,4}$
(spin-1, spin-0)	$W^\pm, H^\pm$	(spin-$\frac{1}{2}$)	$\tilde W^\pm, \tilde H^\pm$	$\tilde\chi^\pm_{1,2}$
graviton (spin-2)	G	gravitino (spin-$\frac{3}{2}$)	$\tilde G$	

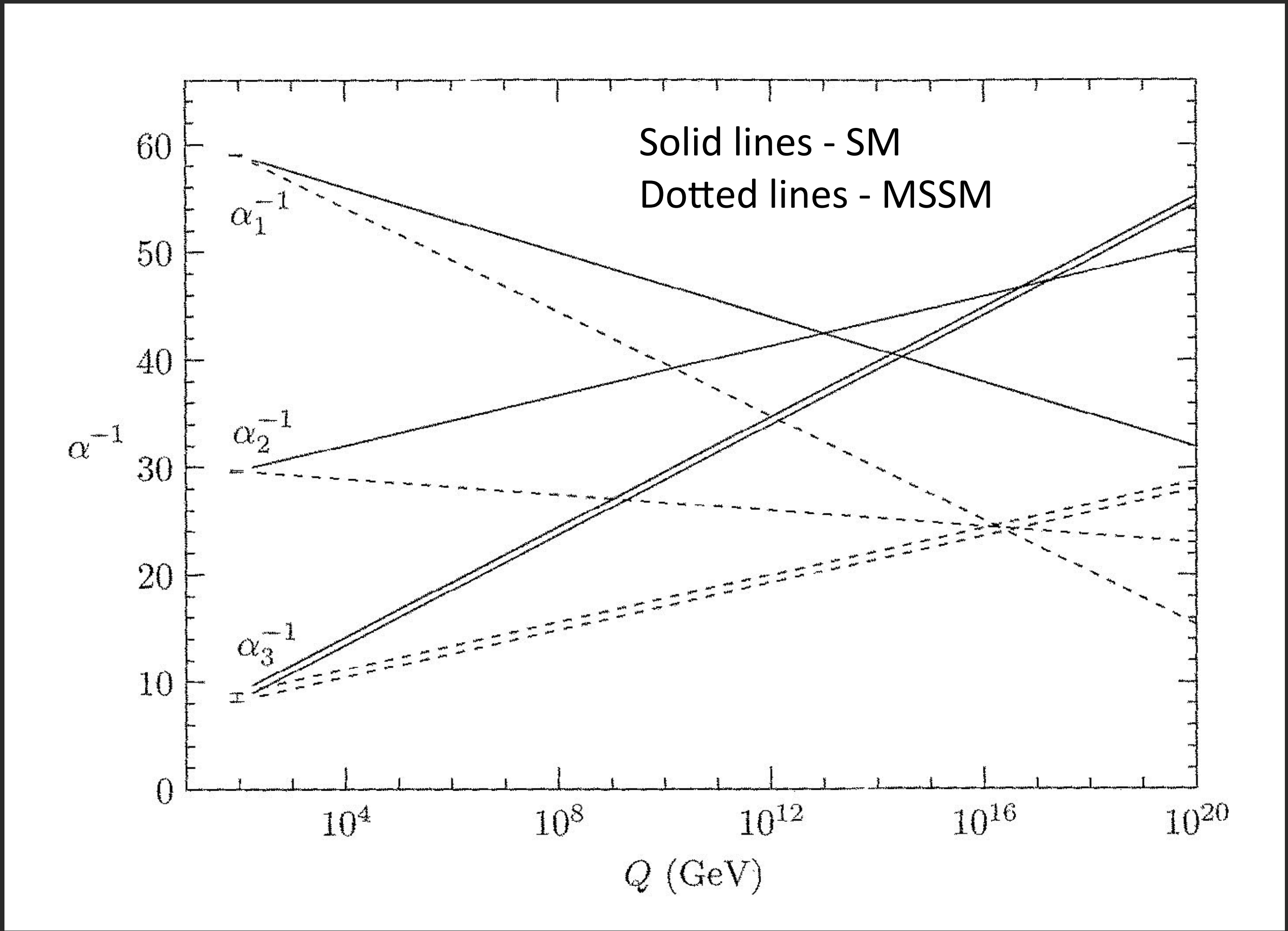
spectrum of particle masses in SUSY models



merging forces



running coupling constants in SM and MSSM models



gauge theories and fibre bundles

Geometrical picture (from ~1970: Attiyah, Singer, Donaldson, Witten, Bott…)

In the mathematical language of fibre bundles, a gauge potential (e.g. 4-vector potential of electrodynamics, or Yang-Mills potentials for Electroweak Theory) is a connection in a fibre bundle, an abstract state-space of internal structure, described by a given gauge group: U(1) of EM, SU(2) of Yang-Mills theory, superimposed on space-time. The curvature of the connection is the gauge field (e.g the field strength tensor $F_{\mu\nu}$ of electrodynamics).

gauge theories and fibre bundles

It is a very similar (geometrical) picture to Einstein's gravity, except the distortion measured by curvature is not taking place in the geometry of space-time but in the geometry of the more-dimensional abstract "total space", imposed over space-time.

Gauge (phase) transformations are analogous to co-ordinate transformations in Riemannian geometry of Einstein's GR (Hilbert derived Einstein's equations from a postulate that action is invariant under general co-ordinate transformation)

Fiber bundles provide a geometrical picture of all interactions; some physicists and mathematicians think that fiber bundles will have to be part of any future progress in particle physics

The remaining problem is to quantize gravity

gauge theories and extra dimensions

In 1980 Scherk, Schwartz and Cremmer revived interest in Kaluza-Klein theories. They advocated that the extra dimensions should be regarded as physical, not abstract, just like the four dimensions that we are aware of.

Cremmer and Scherk suggested that the difference between the four observed and the unobserved ones has its origin in a process of "spontaneous compactification" of the extra dimensions.

The N=8 supersymmetry gives a successful theory of gravity (supergravity)

gauge theories and extra dimensions

1981 Witten noticed a remarkable fact (could be a concidence):
the minimum number of dimensions of a manifold with SU(3)xSU(2)xU(1) symmetry is 7, so to construct a Kaluza-Klein theory in which those symmetries arise as components of gravity in more than 4 dimensions, one must have at least 11 dimensions. At the same time, 11 is probably the maximum number of dimensions for supergravity.

1984 Green and Schwartz: string theories consistent only in 26 dimensions (bosonic) and 10 (supersymmetric)

1990 M-theory – Sen, Duff, Witten: in 11 dimensions, unites all types of 10 dimensional superstring theories

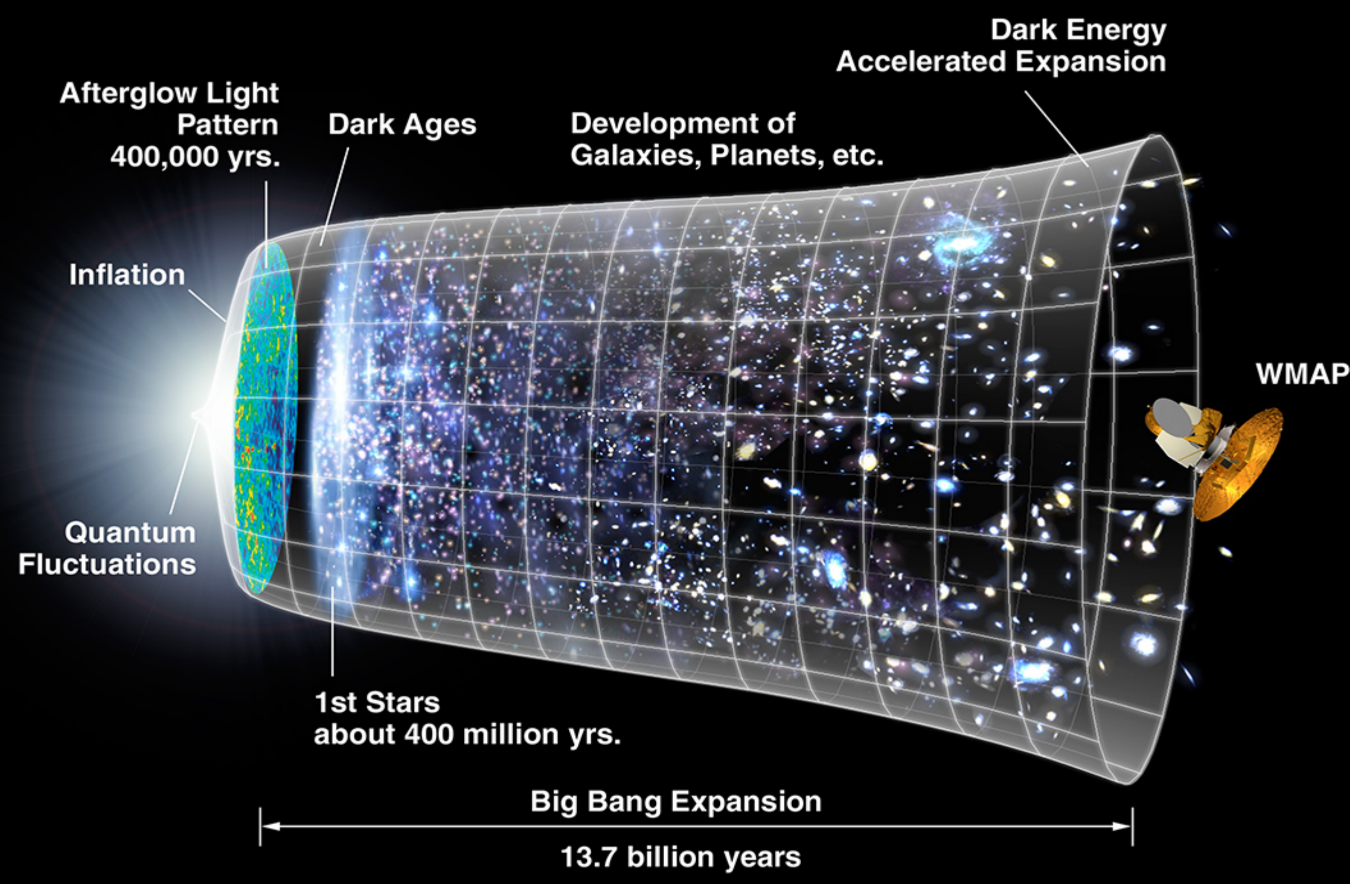
HOW TO STUDY THOSE QUESTIONS???

- Precision low energy experiments - compare with precise calculations where tiny deviations from predictions based on SM may point to "new physics"

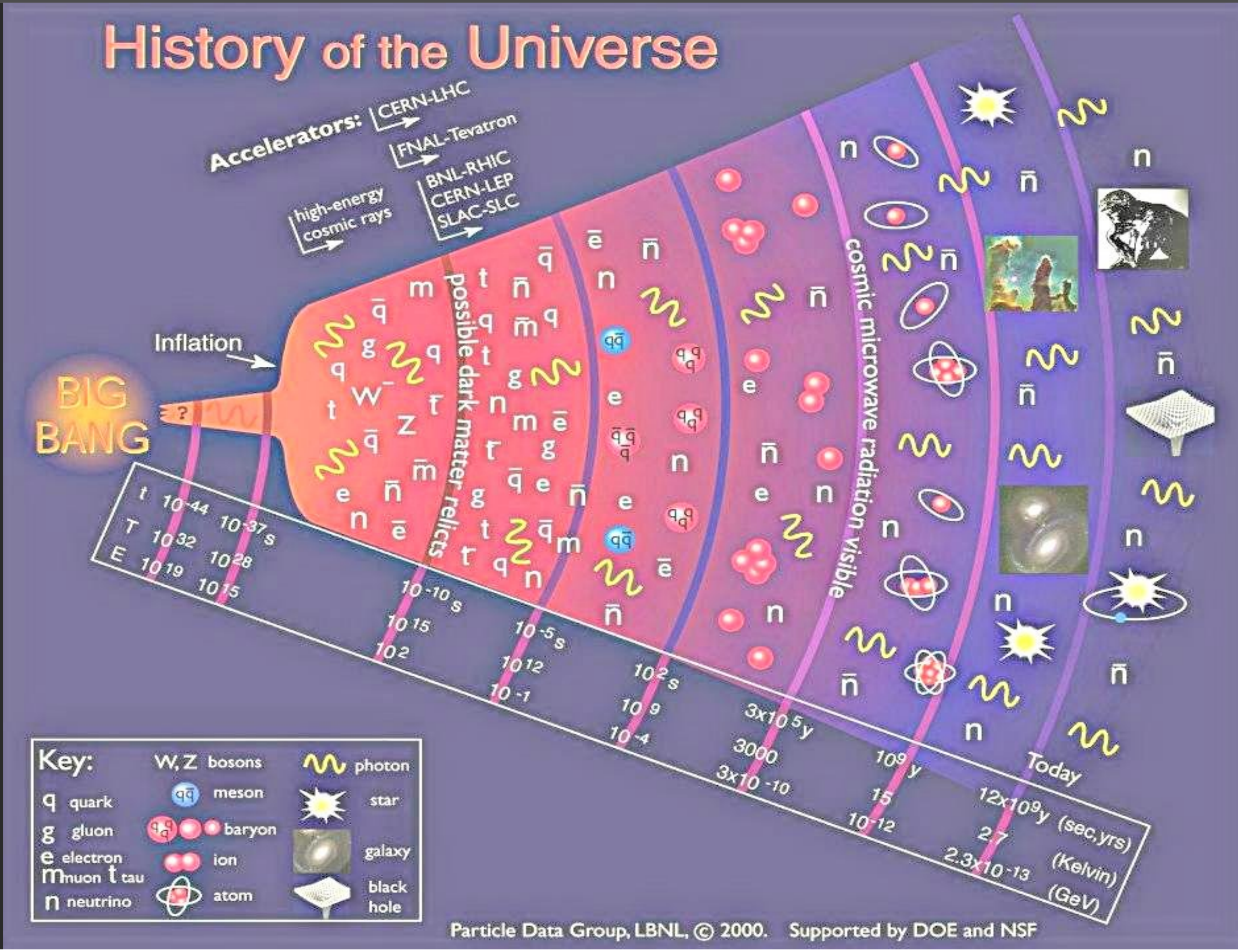
- astrophysics + cosmology: look at the Universe, the farther out one looks, the more back in time one sees, one can extrapolate from very early Universe to present assuming known physics laws, and compare the predicted sky with reality = ASSUMES VALIDITY OF KNOWN PHYSICS LAWS AT ALL TIMES, also violates the scientific principle = ONE CANNOT REPEAT THE EXPERIMENT !! (our Universe is the only one we know!)

- ACCELERATOR EXPERIMENTS - collide particles (protons, antiprotons, electrons, positrons) at as high energies as possible, study particles that emerge from collisions; deviations from SM will be, hopefully, "new physics"

Big bang cosmology

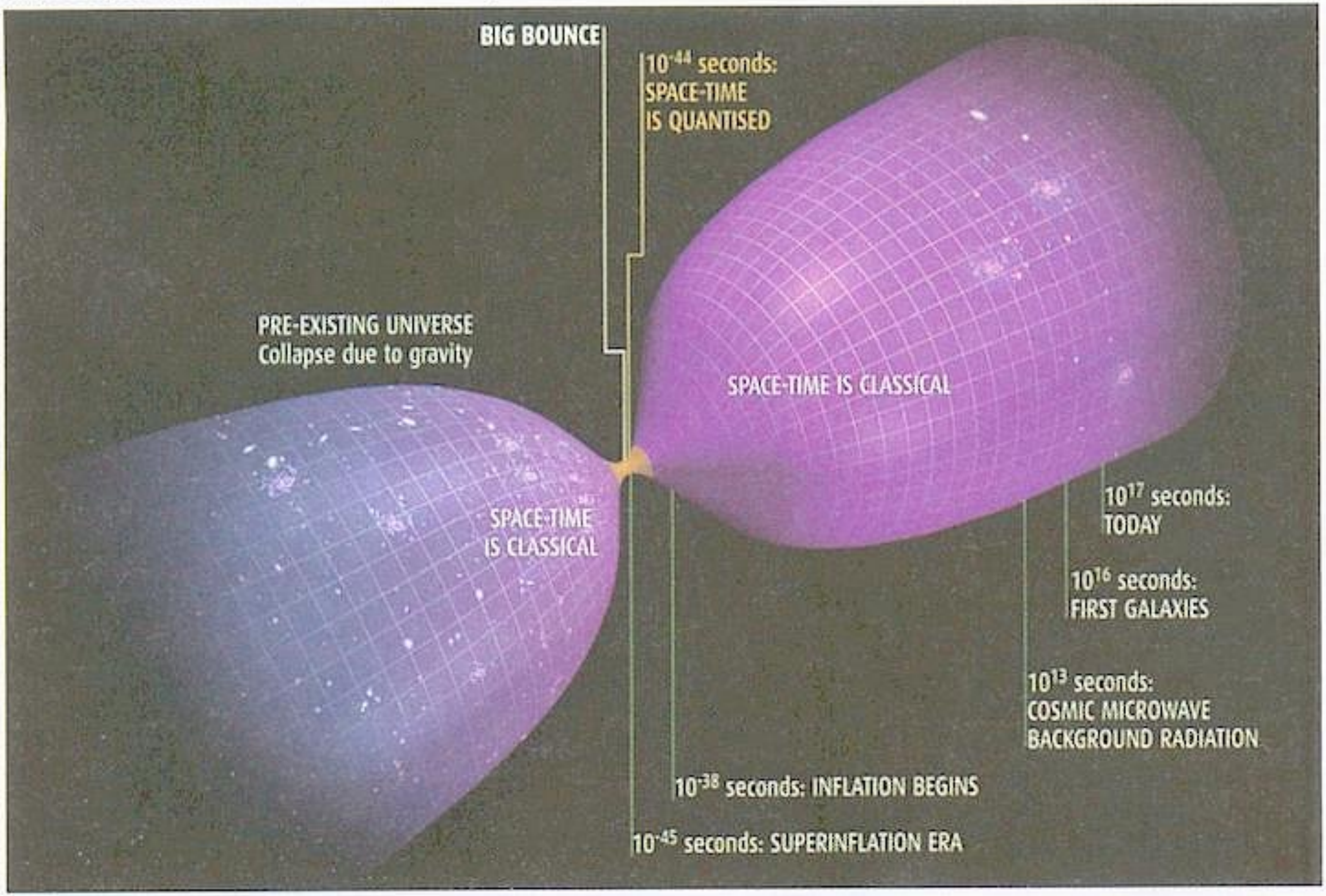


big bang cosmology=applied particle physics

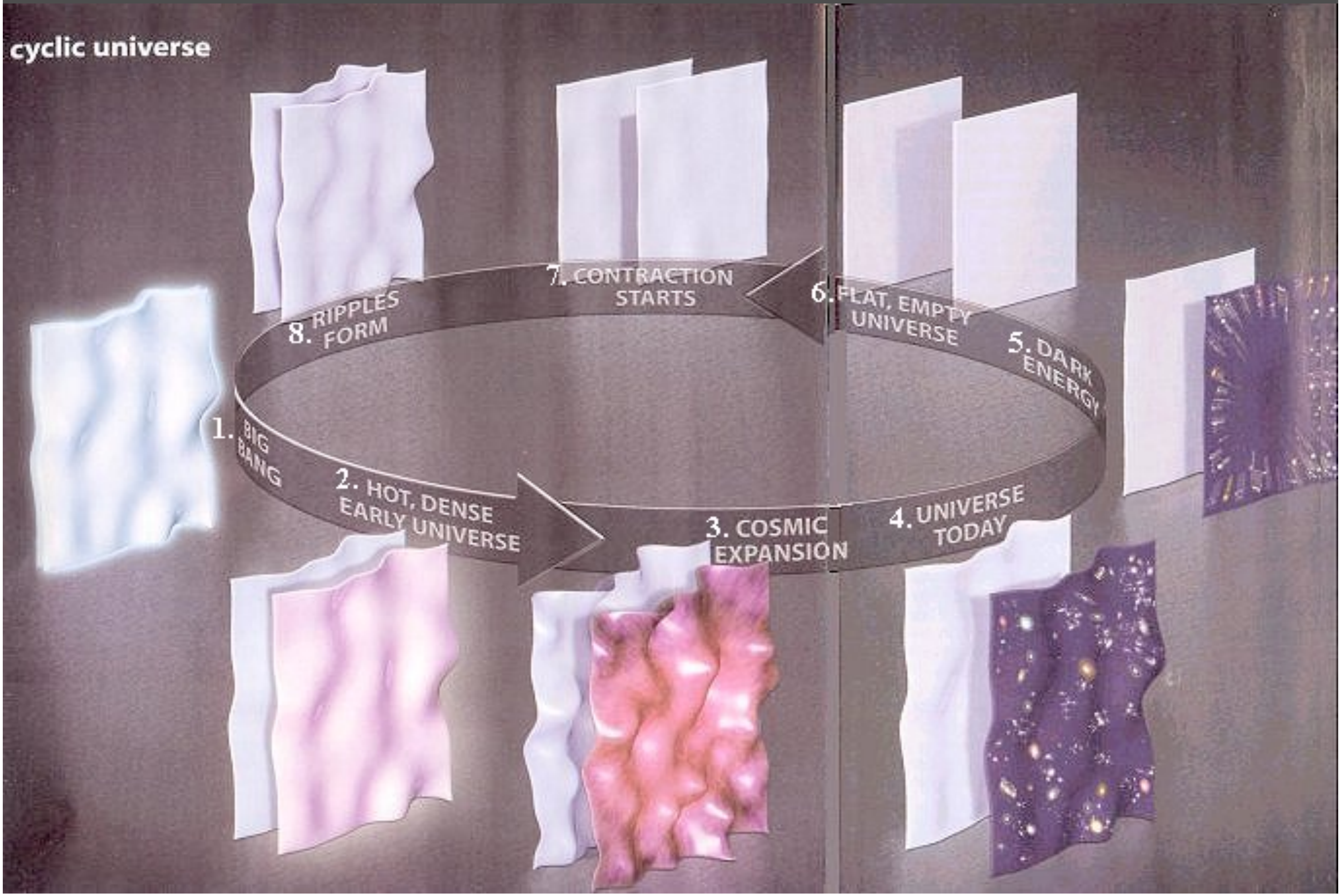


THE BIG BOUNCE

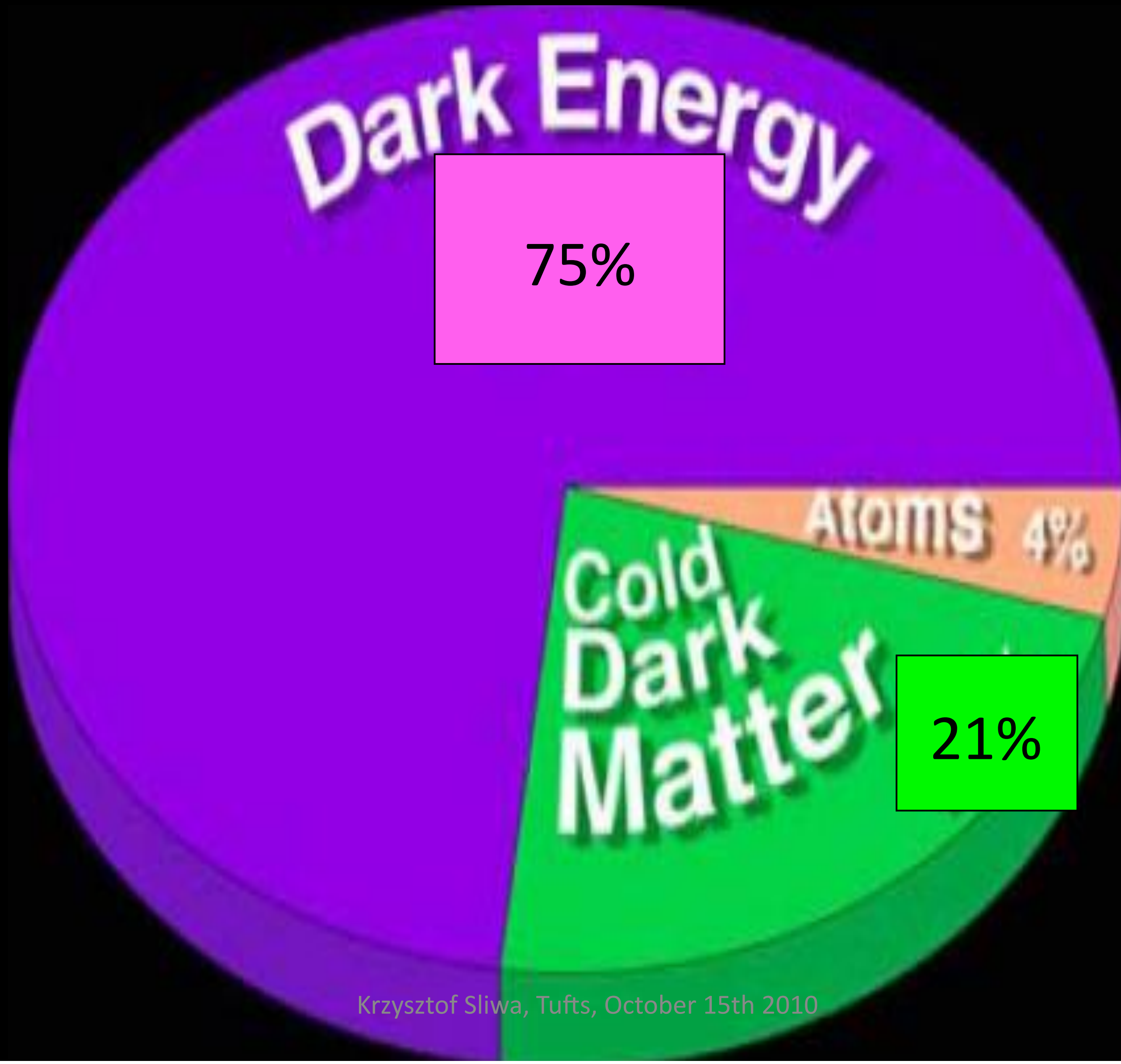
Loop quantum cosmology predicts that the universe did not arise from nothing in a big bang. Instead it grew from the collapse of a pre-existing universe that bounced back from oblivion



cyclic cosmology



Constraints from "standard cosmology"



Dark matter most likely is a weakly interacting (massive?) particle maybe WIMP or Lightest Supersymmetry Particle (stable)

Favoured SUSY candidate is a WIMP in mass range 0.1-10 TeV

ACCELERATORS = MICROSCOPES OF PARTICLE PHYSICS

- What particles to collide?

electrons+positrons :	all kinematics known, all energy transformed into produced particles difficult to accelerate, either very long, or large radius machines (large energy loss because of small mass) SLAC, LEP
proton machines:	easy to built; messy collisions as protons can be viewed as bags filled with quarks and gluons not all proton energy available in the collision Tevatron at Fermilab, LHC at CERN

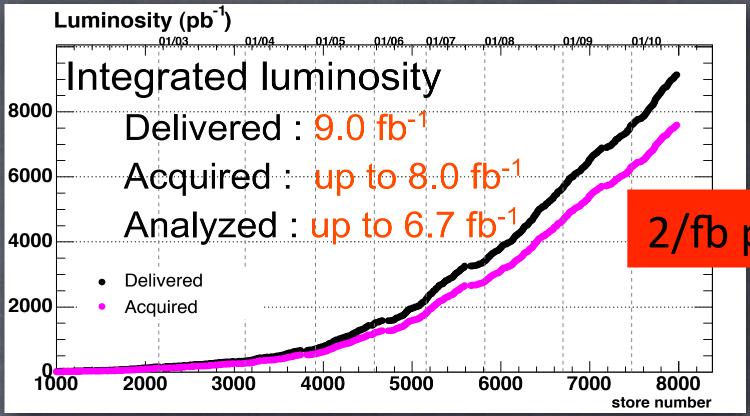
- beam energy (or, rather, energy available in collision)

- Luminosity (related to beam intensity)

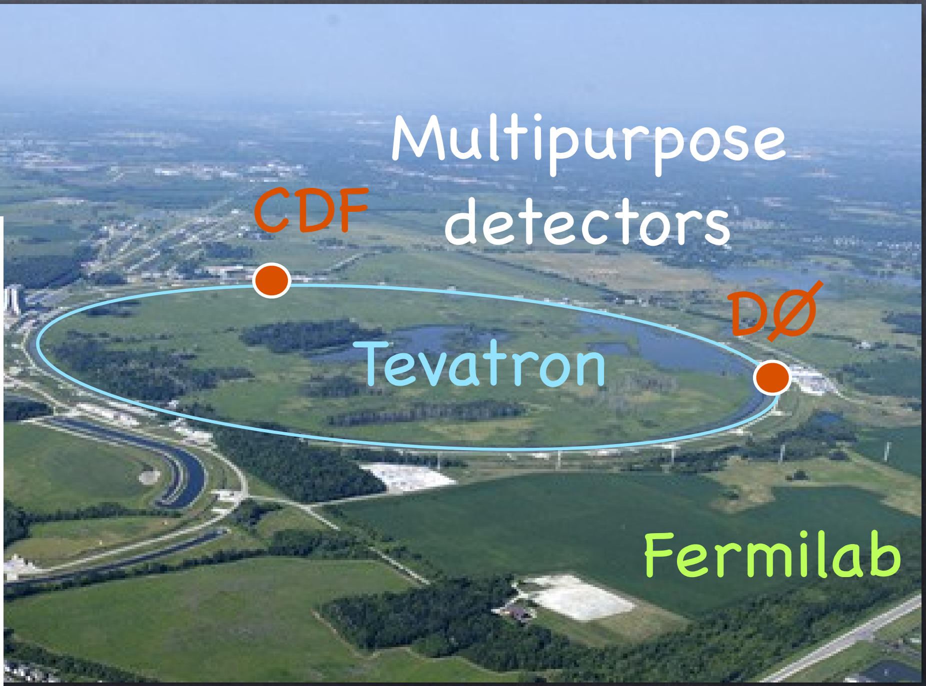
ACCELERATORS = MICROSCOPES OF PARTICLE PHYSICS

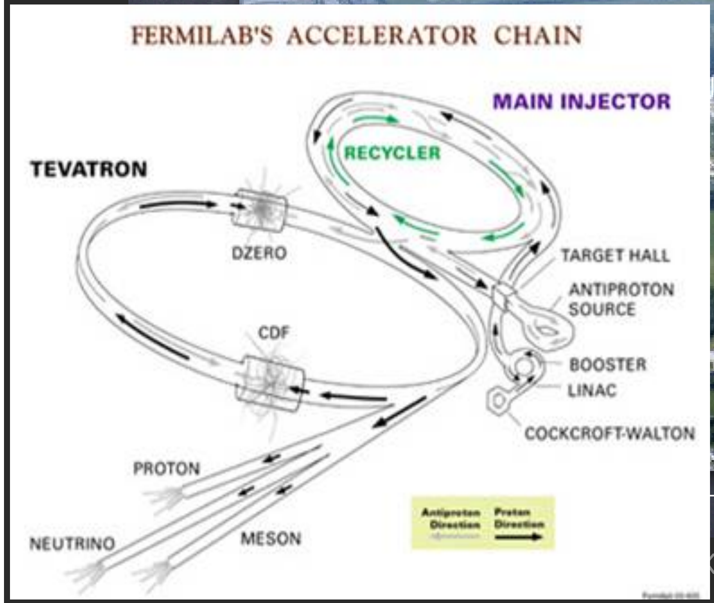
Tevatron

- $p\bar{p}$ collisions with $\sqrt{s}$ = 1.96 TeV
- Two collider experiments, CDF & DO

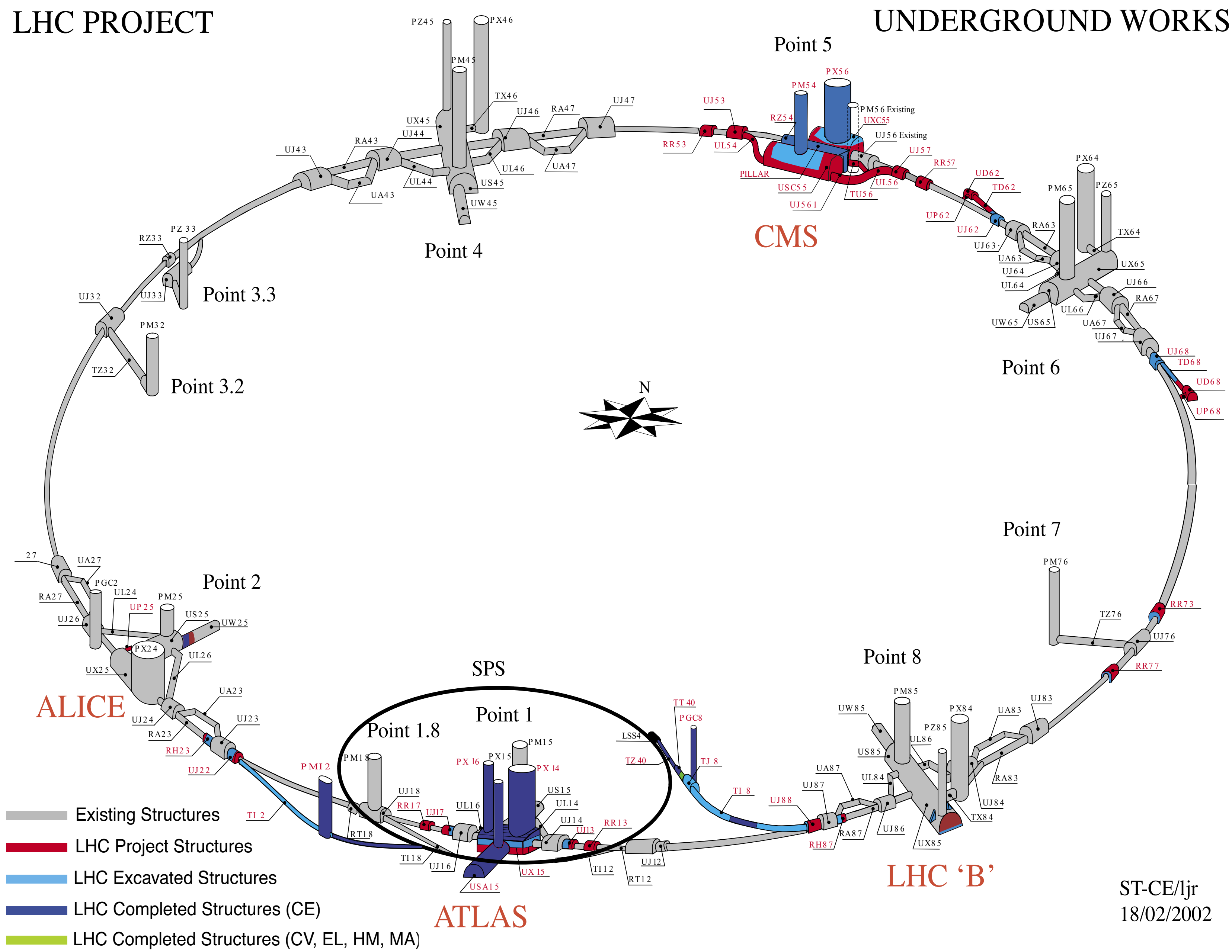


2/fb per year

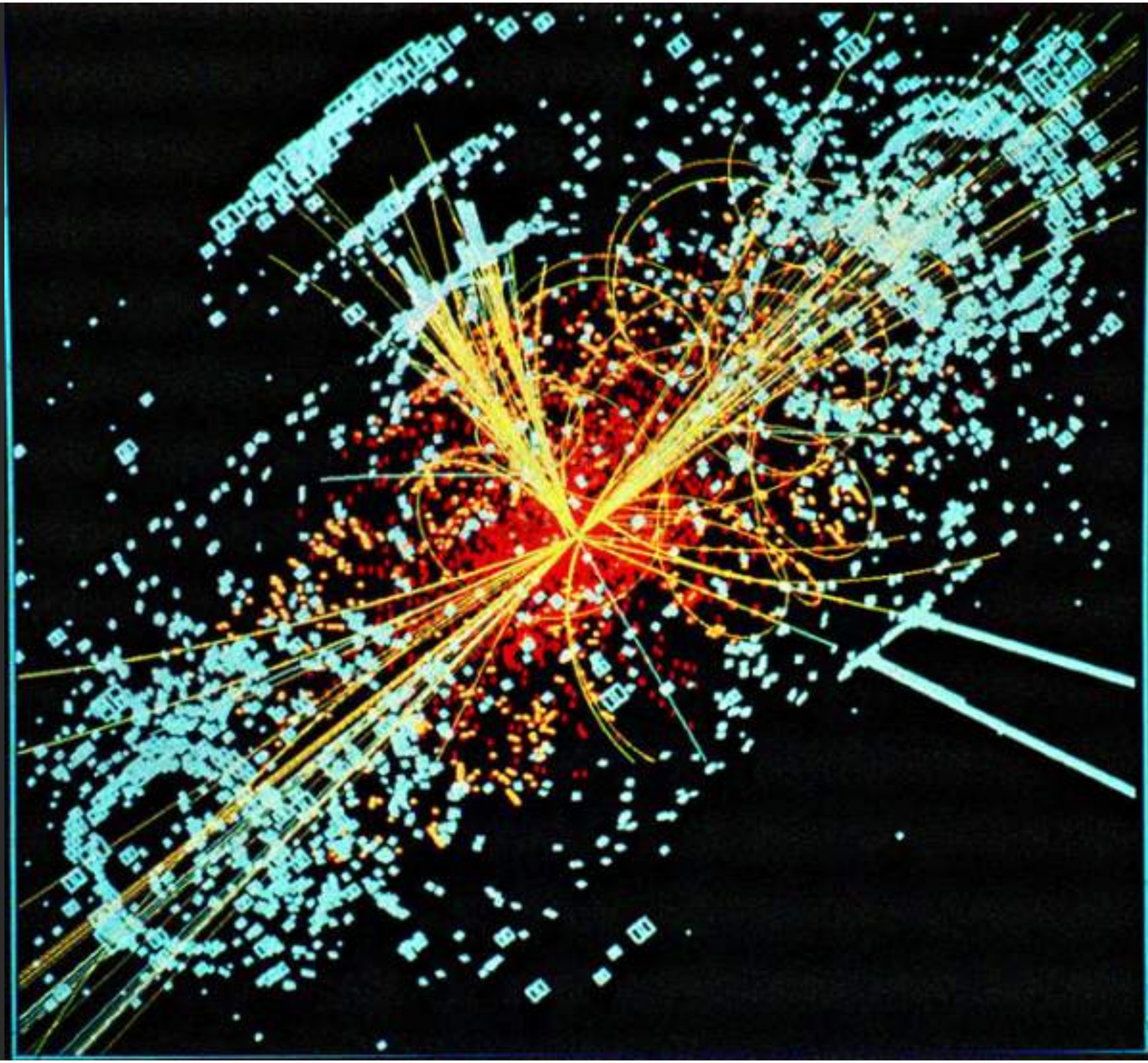




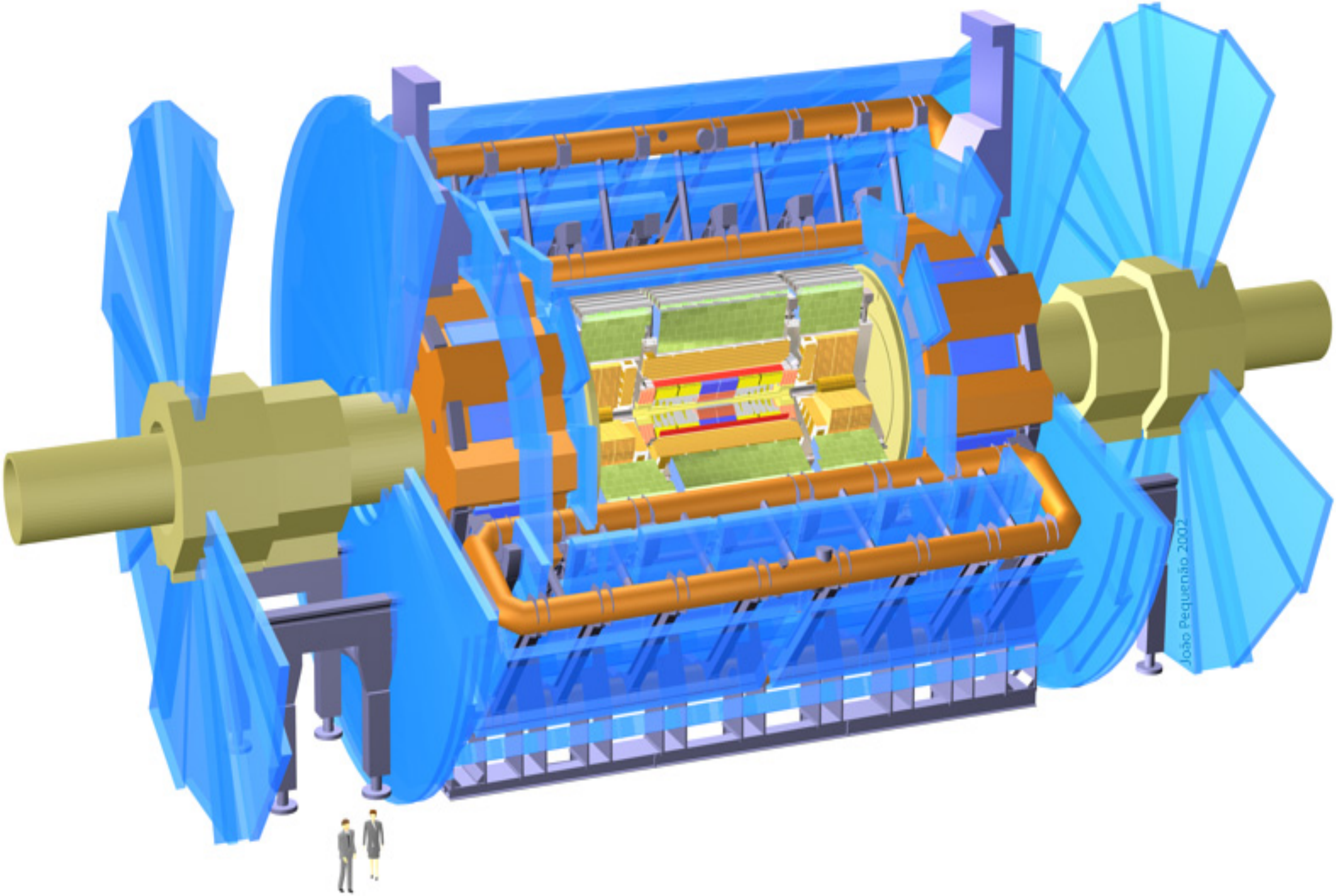

Large Hadron Collider at CERN
European Centre for Particle Physics, Geneva, Switzerland
Superconducting Proton Accelerator and Collider
installed in a 27km circumference underground tunnel (tunnel cross-section diameter 4m) at CERN
Tunnel was built for LEP collider in 1985
First operation in Fall 2008

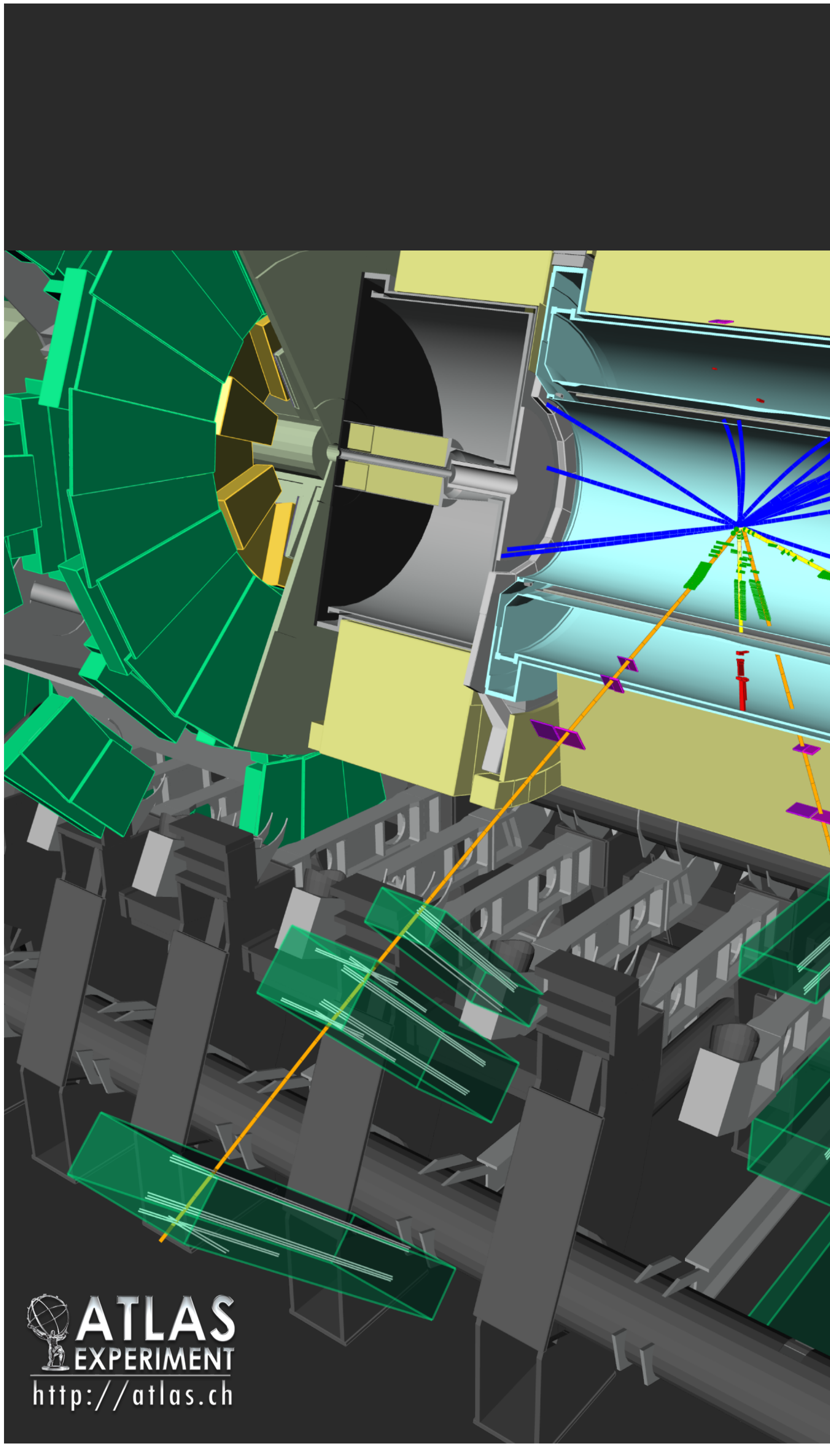
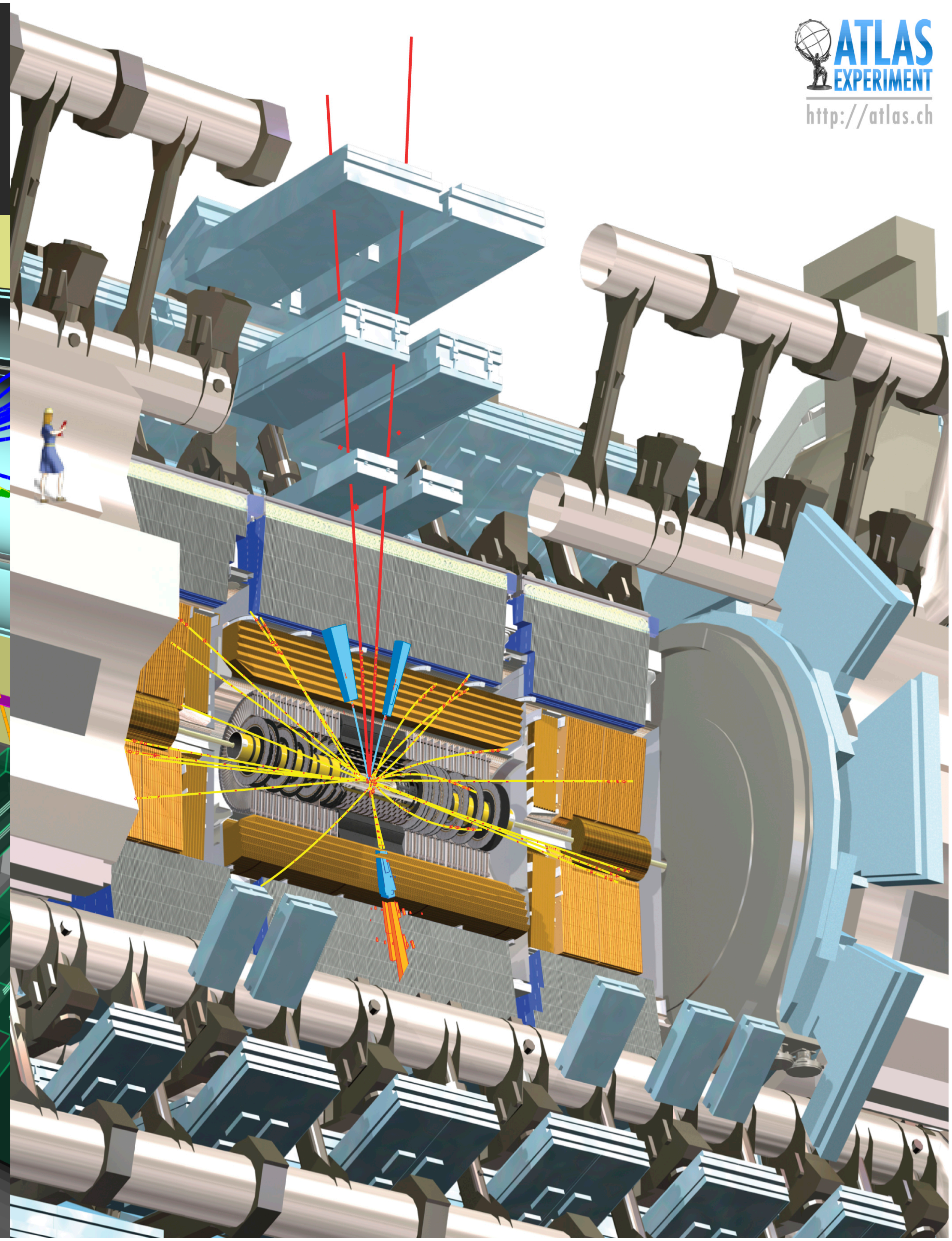


LHC PROJECT
UNDERGROUND WORKS
Point 5
CMS
Point 4
Point 3.3
Point 3.2
Point 6
Point 7
Point 2
ALICE
SPS
Point 1
Point 1.8
ATLAS
Point 8
LHC 'B'
N
Existing Structures
LHC Project Structures
LHC Excavated Structures
LHC Completed Structures (CE)
LHC Completed Structures (CV, EL, HM, MA)
ST-CE/ljr
18/02/2002



ATLAS DETECTOR AT LHC




ATLAS
EXPERIMENT
http://atlas.ch

ATLAS
EXPERIMENT
http://atlas.ch

THE INDEPENDENT

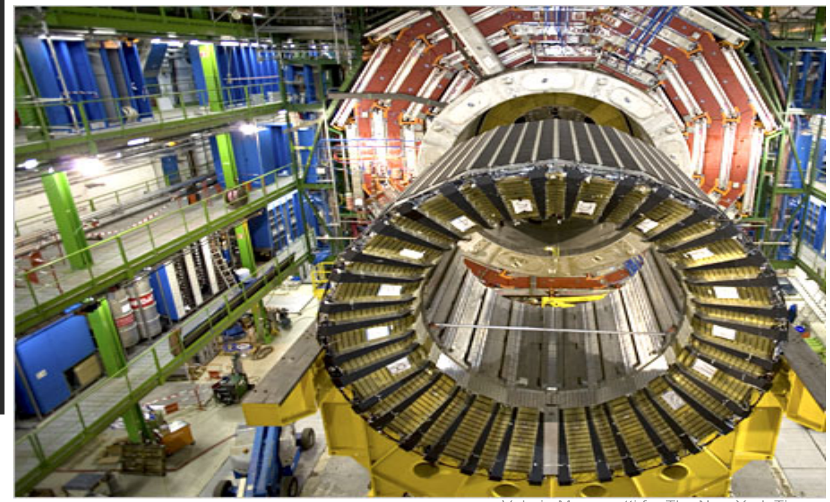
The Large Hadron Collider: End of the world, or God's own particle?

bewildered Cole Moreton goes

The experiment that could blow up the planet

The New York Times

Asking a Judge to Save the World, and Maybe a Whole Lot More



Valerio Mezzanotti for The New York Times

Part of a detector to study results of proton collisions by a particle accelerator that a federal lawsuit filed in Hawaii seeks to stop.

By DENNIS OVERBYE
Published: March 29, 2008

Mail Online

Landmark experiment to unlock secrets of B Bang could cause end of the world, say scientists in court bid to halt it

By Fiona Macrae
Last updated at 4:44 PM on 1st September 2008

It has cost £4.4billion and is designed to unlock the secrets of the Big Bang.

But rather than providing vital information about the beginning of life, the world's biggest experiment could cause the world, say scientists.

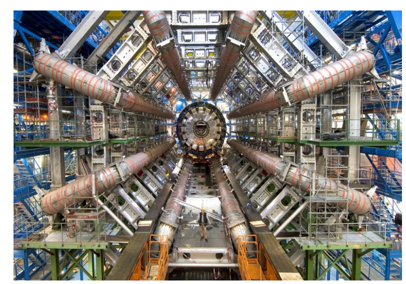
They fear that the Large Hadron Collider - due to be switched on in nine days' time - will create a black hole that could swallow the planet.

Mostly Movies, Comics, TV and Science Fiction with some randomness thrown in.

- Home

Will CERN Destroy The World? (Updated)

May 11, 2008
tags: alice, atlas, backwards causation, Big Bang, blackholes, cern, cern doomsday, CMS, dr. brian cox, end of the world, god particle, higgs boson, large hadron collider, LHC, quantum mechanics, rap, TPC
by David M.



No it wont, but a pretty provocative thought eh? Let's do some research. Bear with me, it'll be fun, really.

BLACK HOLE APOCALYPSE ?????

Extra dimensions and low energy scale gravity

- Observed 3-space = 3-brane on which SM charges and fields are confined

  (this is where WE live)

- Embedded in a *D*-dimensional bulk = 3+N+1 spacetime dimensions

- Only graviton propagates in the extra dimensions

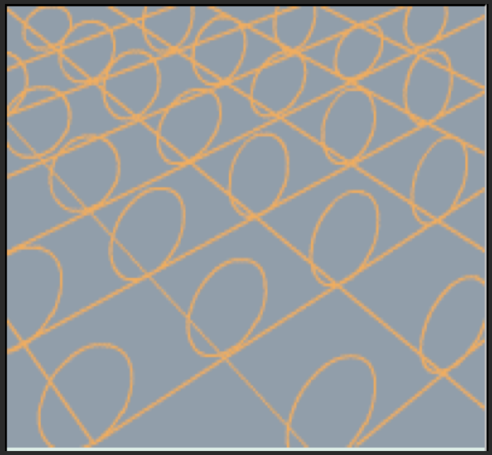
- String theory ⇒ branes on which some fields (open strings) are confined and others (closed strings) are not ⇒ prefers N = 7

Extra dimensions and low energy scale gravity

Examples of possible scenarios:

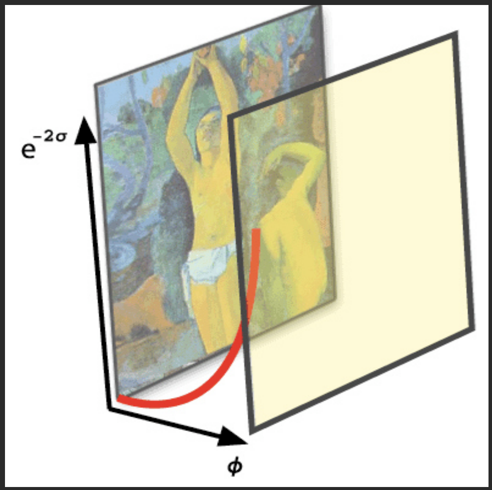
Arkani-Hamed, Dimopoulos, Dvali (ADD)*

Large volume of <u>compact</u> (flat) extra dimensions generates the hierarchy ⇒ gravitational field lines spread through bulk.



Randall, Sundrum (RS)†

Strong <u>curvature</u> (warping) of small AdS single extra dimension generates the hierarchy ⇒ gravity localized on a second brane bounding the extra dimension.



** Phys. Lett. B 429, 263 (1998)*

† Phys. Rev. Lett. 83, 3370 (1999)

Extra dimensions and low energy scale gravity

SIGNATURES (warning: calculations are at least a bit hand-waving; at most semi-classical)

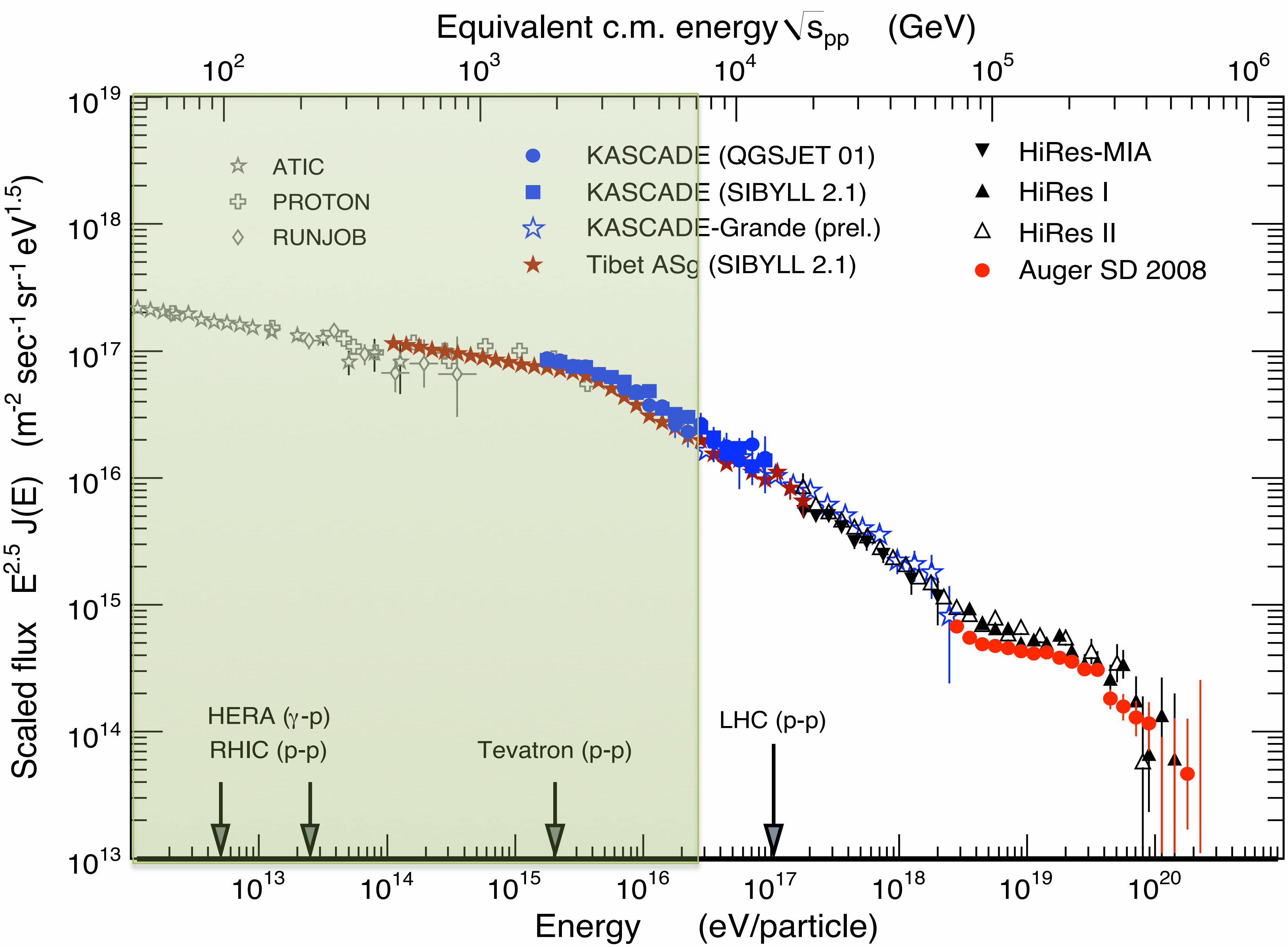
- Deviations from Newton's Law at short distance (torsion-balance "Cavendish" expts.)

- Direct or virtual emission of gravitons by SM particles in accelerator experiments

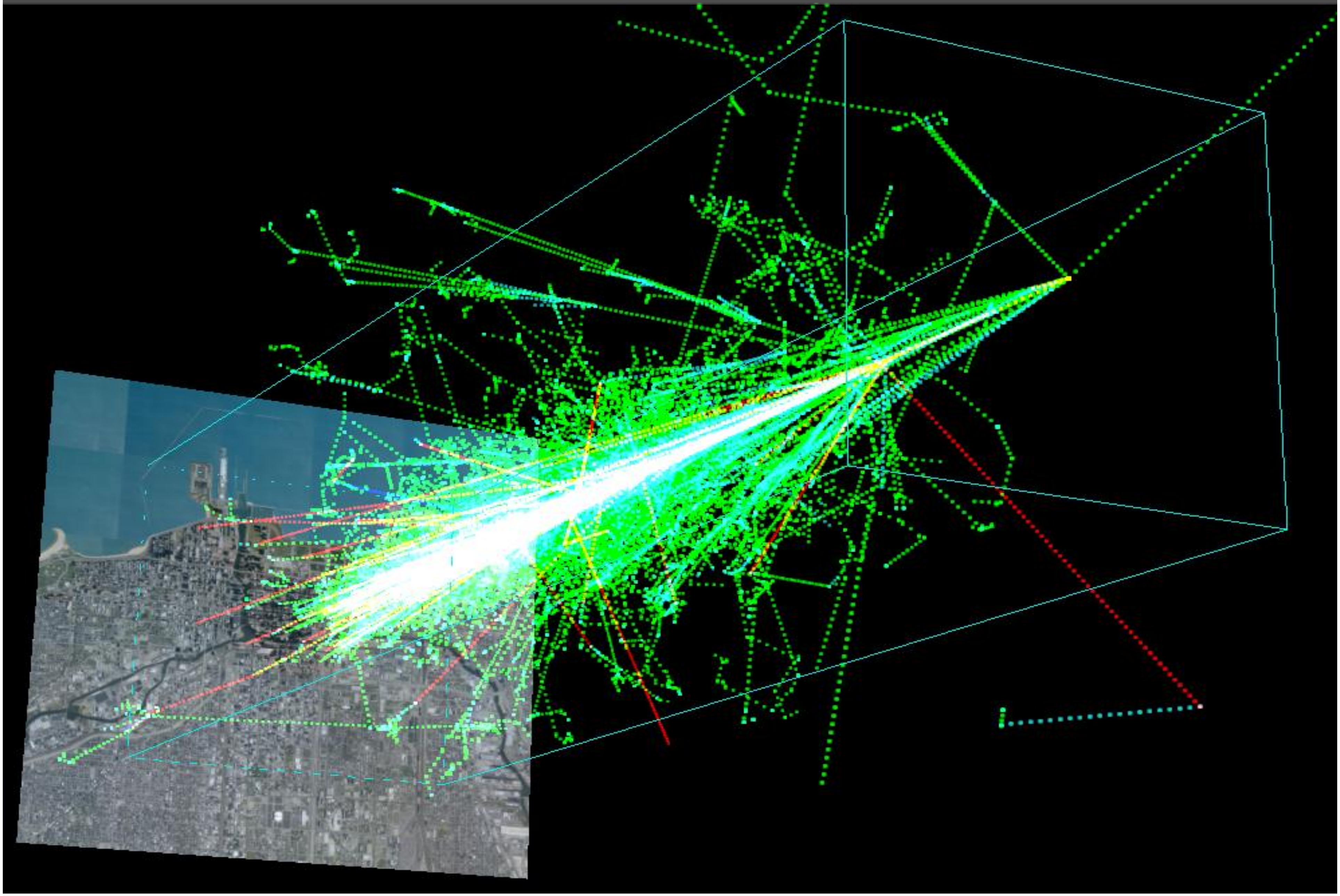
- Enhanced production of gravitons in early universe and in certain astrophysical processes

- Large cross section for black hole production at TeV collision energies

NO BLACK HOLE APOCAPLYPSE !!!



cosmic ray shower



LHC: Some Technical Challenges

Circumference (km)	26.7	100-150m underground
Number of superconducting twin-bore Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K) (cryogenics system)	1.9	Superconducting magnets needed for the high magnetic field Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field 1ppm resolution
Beam Intensity (A)	0.5	$2.2.10^{-6}$ loss causes quench
Beam Stored Energy (MJoules)	362	Results from high beam energy and high beam current 1MJ melts 1.5kg Cu
Magnet Stored Energy (MJoules)/octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

Incident of September 19th 2008

- A very impressive start-up with beam on September 10, 2008

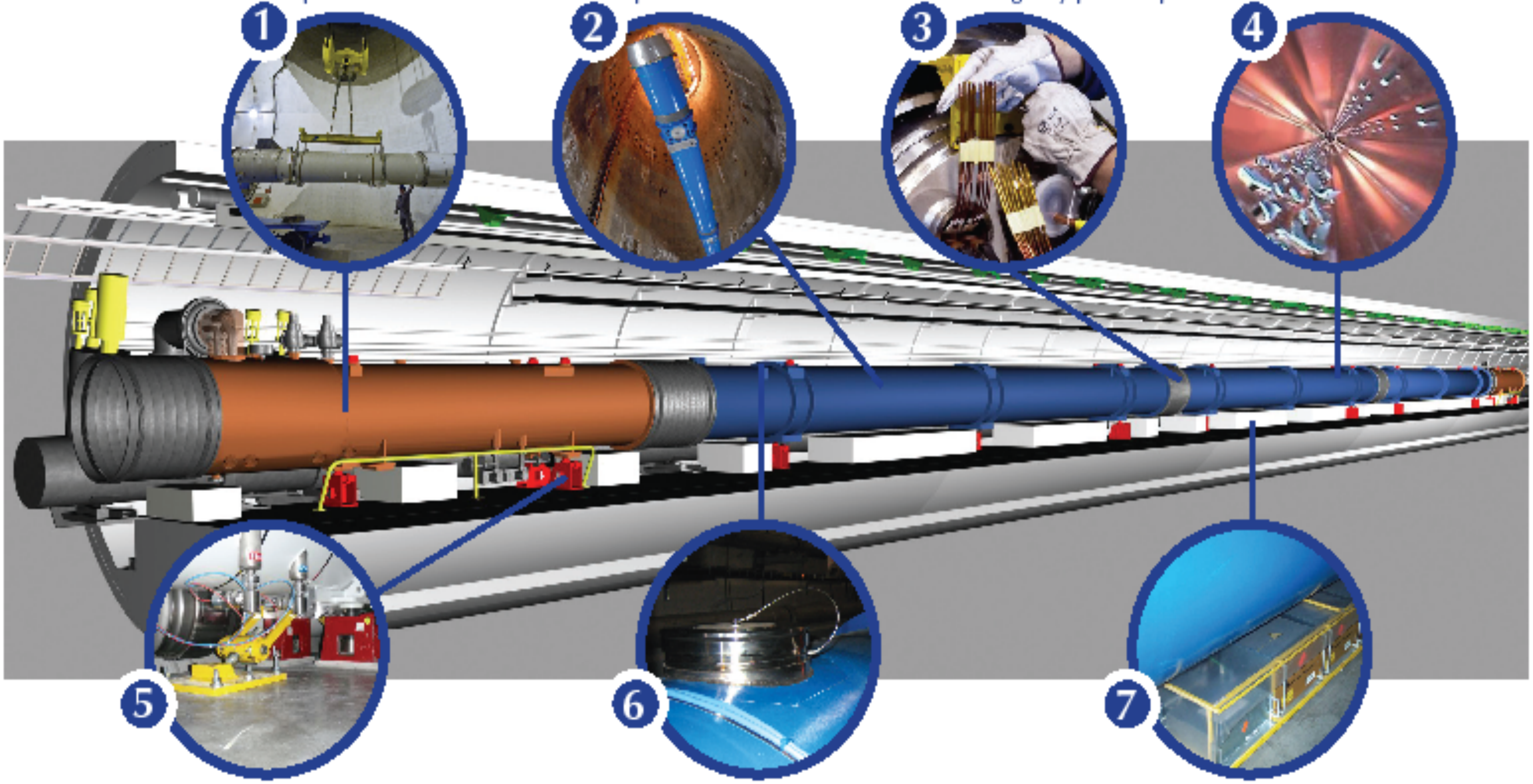
- During a few days period without beam making the last step of dipole circuit in sector 34, to 9.3kA, at 8.7kA, development of resistive zone in the dipole bus bar splice between Q24 R3 and the neighbouring dipole

- Electrical arc developed which punctured the helium enclosure

Phase 1 +2

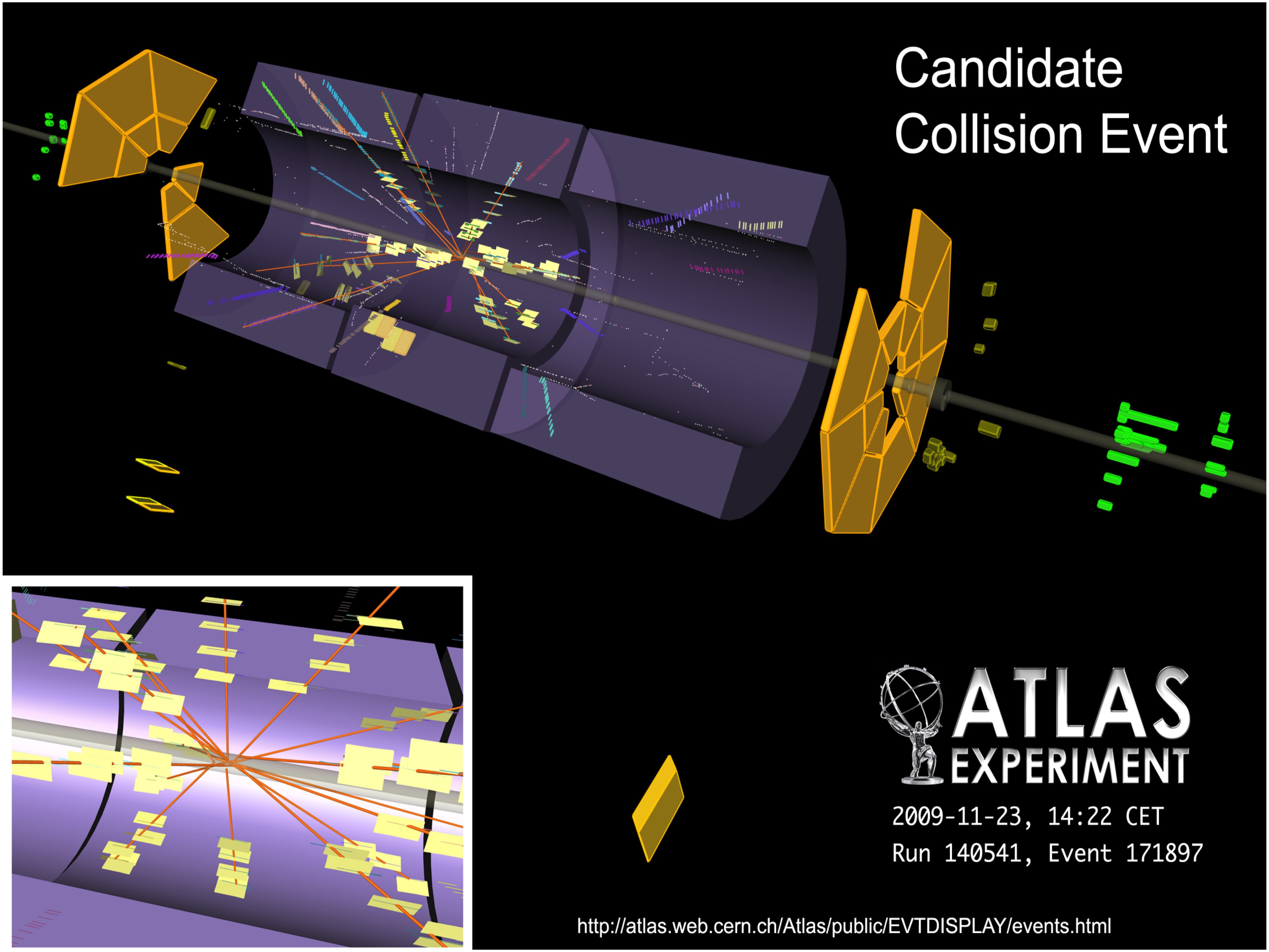
The LHC repairs in detail

1. 14 quadrupole magnets replaced
2. 39 dipole magnets replaced
3. 54 electrical interconnections fully repaired. 150 more needing only partial repairs
4. Over 4 km of vacuum beam tube cleaned

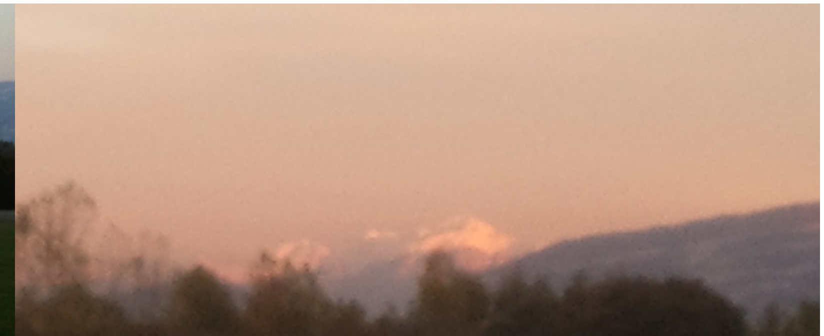


5. A new longitudinal restraining system is being fitted to 50 quadrupole magnets
6. Nearly 900 new helium pressure release ports are being installed around the machine
7. 6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid

+ 8 cryogenics!


Candidate
Collision Event
ATLAS
EXPERIMENT
2009-11-23, 14:22 CET
Run 140541, Event 171897
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html


Accelerating Science
Accélérateur de science
CERN




Accelerating Science
Accélérateur de science
vers de particules


ATLAS Control Room
13-7-10 11:24

Scenario 2010–2011 (OLD)

Following the technical discussions in Chamonix (January 2010) the CERN management and the LHC experiments decided

- Run at 3.5 TeV/beam up to a integrated luminosity of around $1 fb^{-1}$

- Then consolidate (fix) the whole machine for 7 TeV/beam (during a shutdown in 2012)

- From 2013 onwards LHC will be capable of maximum energies and luminosities

FERMILAB enters the race

In April 2010 D0 and CDF experiments at Tevatron presented a proposal to extend the current run by 3 years

In 4 years (by 2014) would increase the current integrated luminosity at 2 TeV from 8/fb to 16/fb per experiment and could compete with LHC with light Higgs searches (as LHC in the January scenario would only have ~ 1/fb at 7 TeV by 2013)

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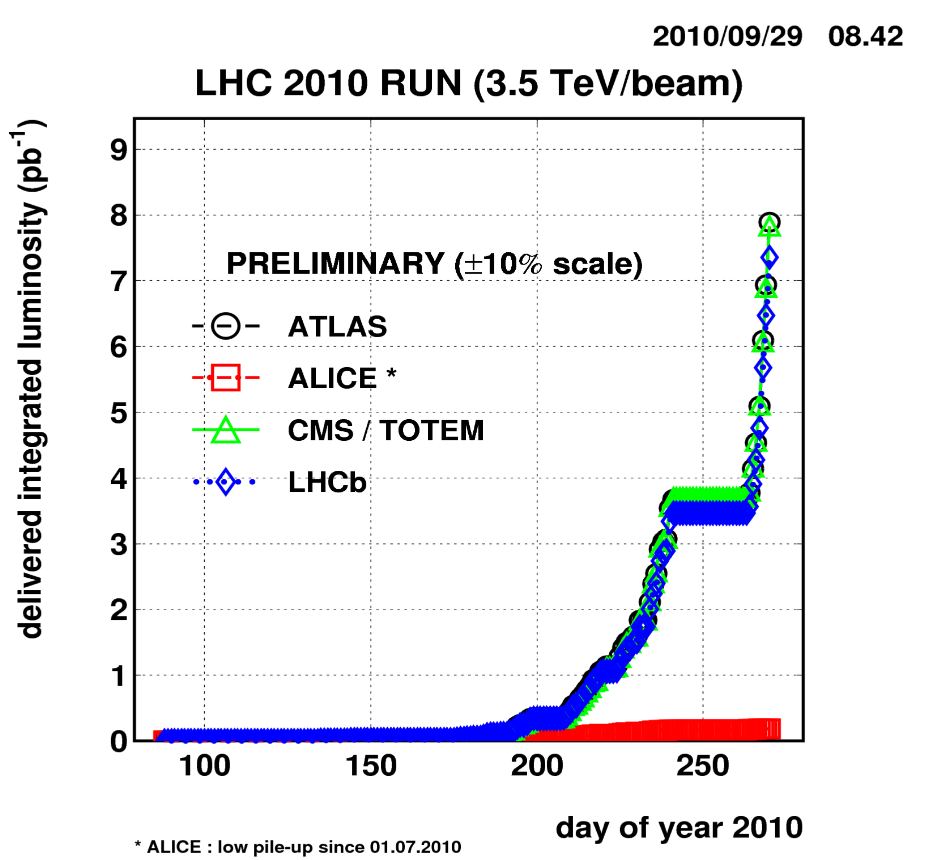
LHC performance in 2010

$L > 10^{32}\ cm^{-2}s^{-1}$ ($10\ nb^{-1}s^{-1}$)

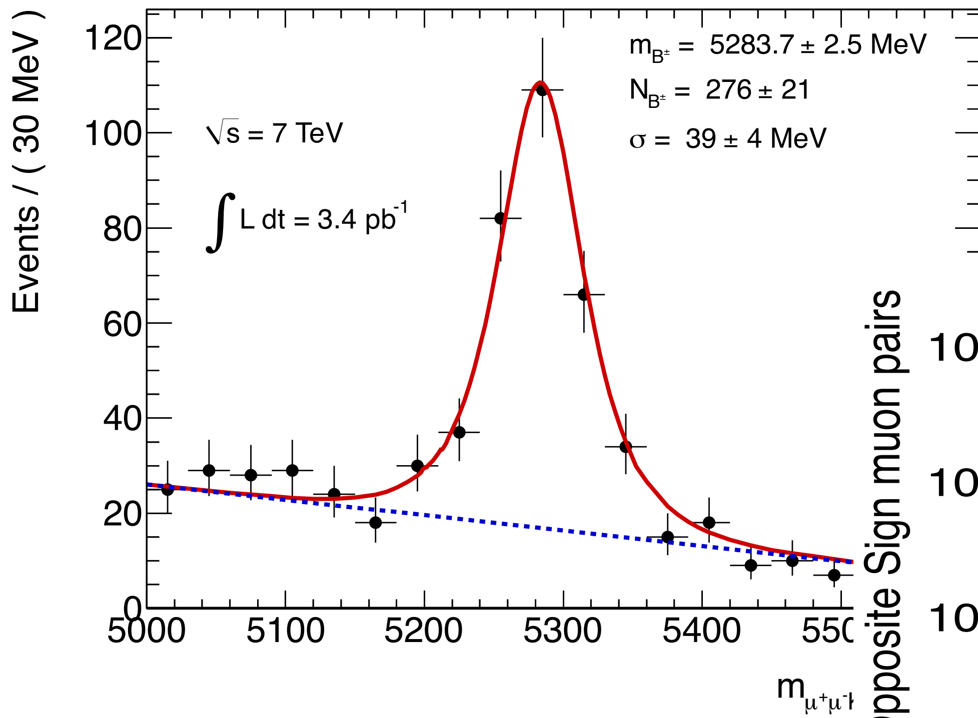
(this goal was exceeded yesterday!!)

~ 50/pb by end of 2010 !

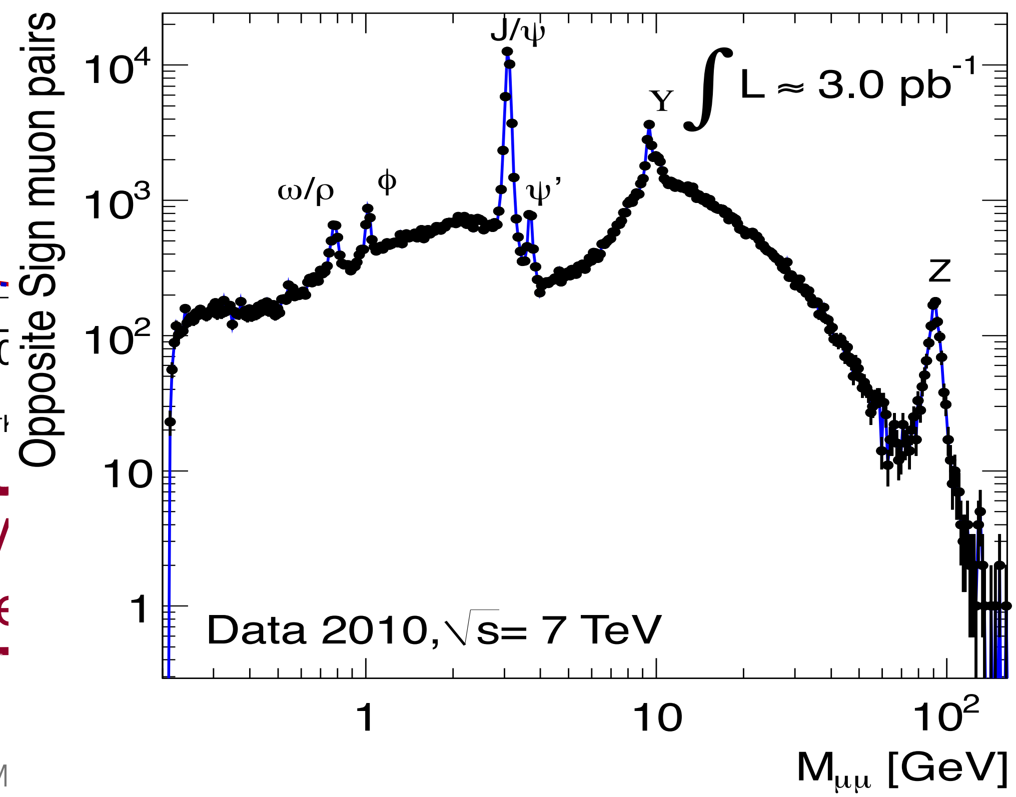


>3 fb^{-1} possible for 2011

$B^{+/-} \rightarrow J/\psi\ K^{+/-}$ Observation and Mass Fit



- Periods D to F used → total Luminosity 3.4 pb^{-1}
- 276 ± 21 signal events

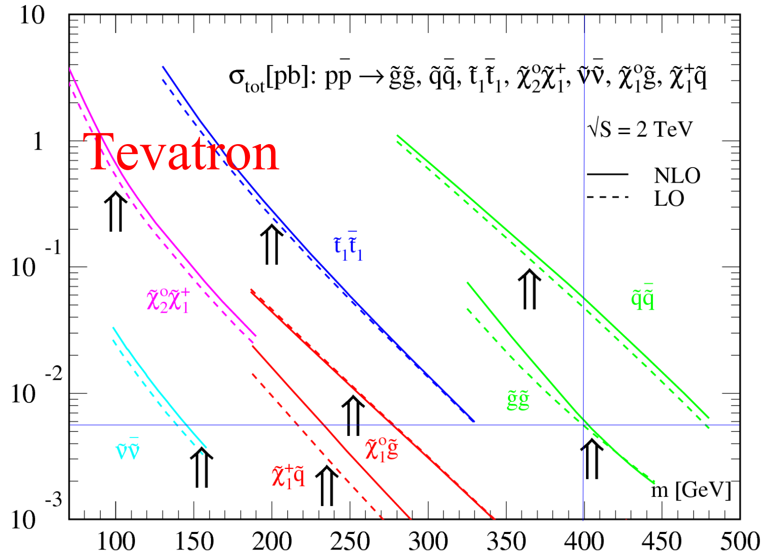


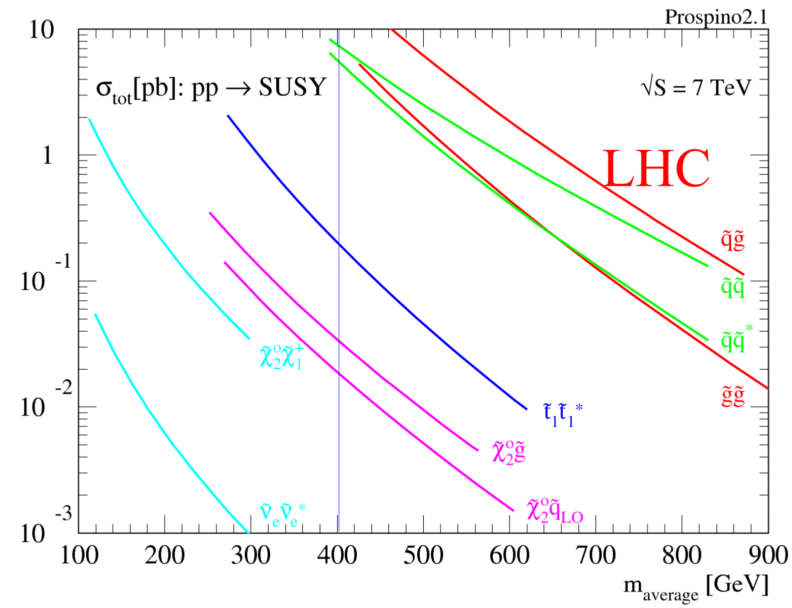
m_{inv} = 5283.7 ± 2.5 MeV

m_{PDG} = 5279.17 ± 0.29 Me

We already have produced more 400 GeV gluinos (if they exist) than the Tevatron

from Prospino





σ (400 GeV gluino) ~ 4 x 10^{-3} pb (Tevatron) → 32 gluinos in 8 fb^{-1}

~ 10 pb (LHC)

Exceed the Tevatron with ~ 3 pb^{-1}

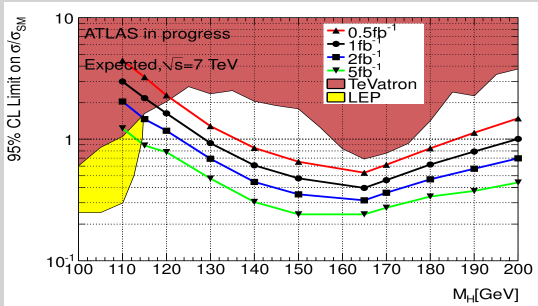
CERN NEW SCENARIO

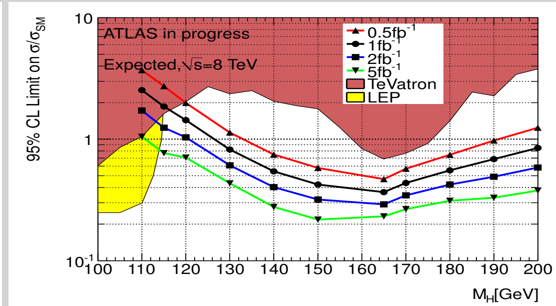
Run for 2 years and collect 5-10/fb at 7 TeV

if decision is taken soon (another Chamonix meeting in January 2011) then, in my mind, it does NOT make sense to run Tevatron Collider any longer, even for light Higgs it is not (and will not be) competitive with LHC and its superior ATLAS and CMS detectors

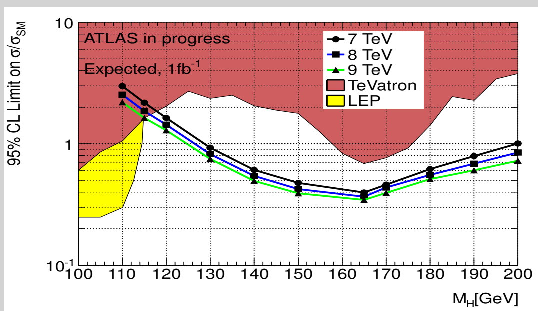
US DOE decision may become “political”, I am afraid

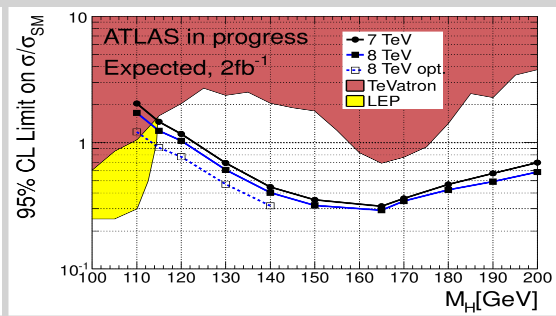
MSM Higgs discovery potential

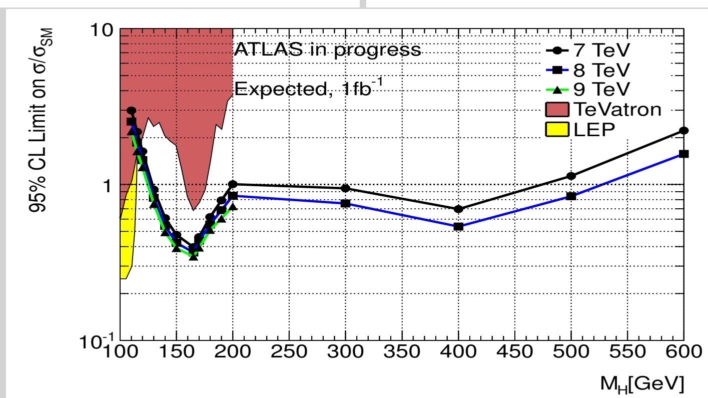




gure 14: Combined sensitivity for different integrated luminosity scenarios. Left is for 7 TeV and right r 8 TeV. See the text for details. Public results from LEP [28] and the Tevatron [27] are shown for mparison.







FUTURE OF PARTICLE PHYSICS ?

Not finding Higgs would be very interesting, but may not be good for the field, as too many unwise people have "promised" that it will be found…

Finding SUSY or something totally new would be fantastic and particle physics will be again as exciting as it was when I was a student

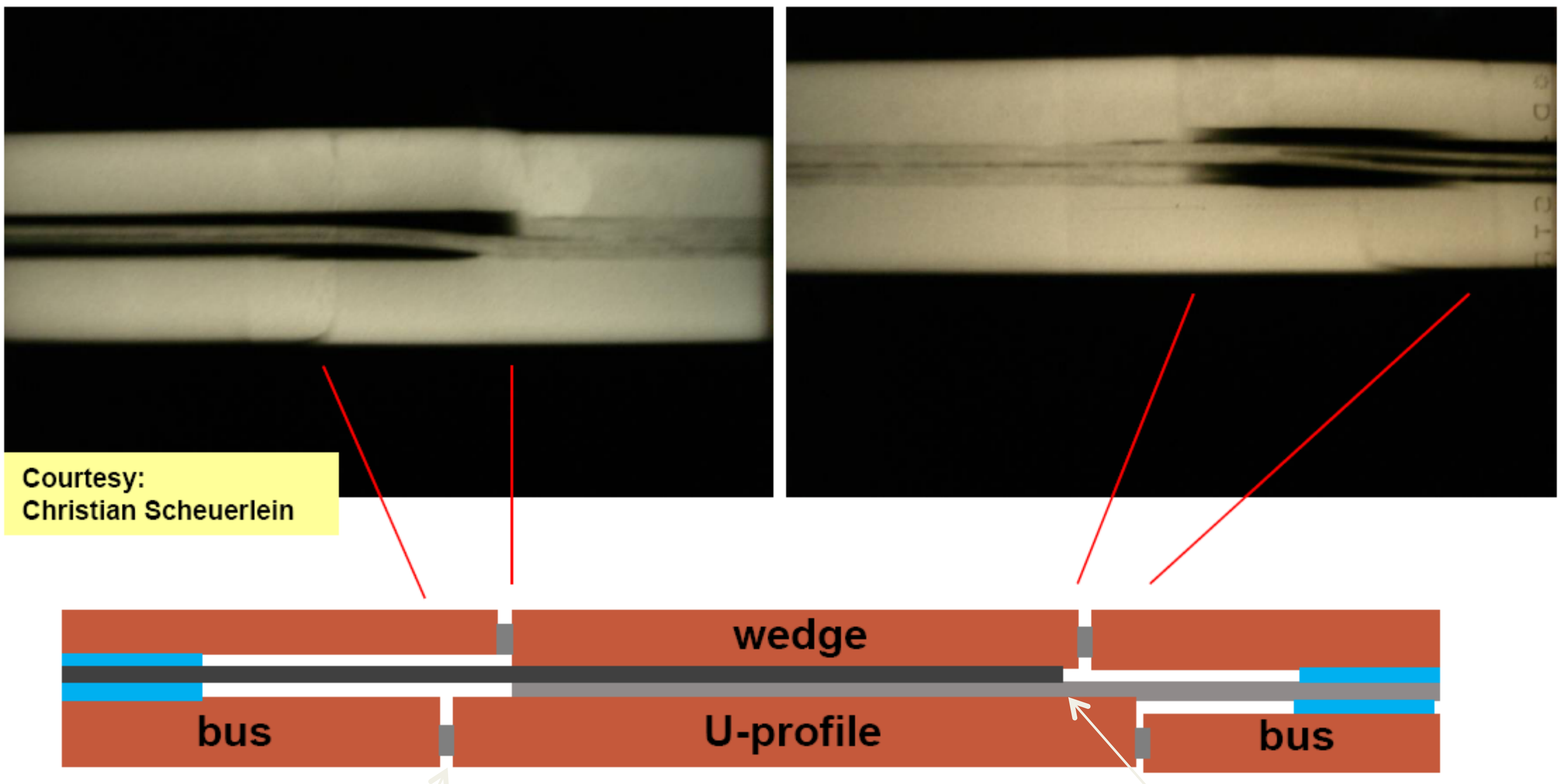
I am hopeful we'll learn something new and more about how the world works and about the laws of nature

If "new physics" is found, then the next step will be to build an electron-positron collider, a "clean" machine with which to study "new Physics", but one has to know what energy to build this machine for

Stabilizer problem

Bad surprise after gamma-ray imaging of the joints: Void is present in most of bus extremities because SnAg flew out during soldering of the joint

Gamma rays QBBI.B25R3-M3 before disconnection (QRL connection & QRL lyra sides)



Bad electrical contact between wedge and U-profile with the bus on at least 1 side of the joint

Bad contact at joint with the U-profile and the wedge

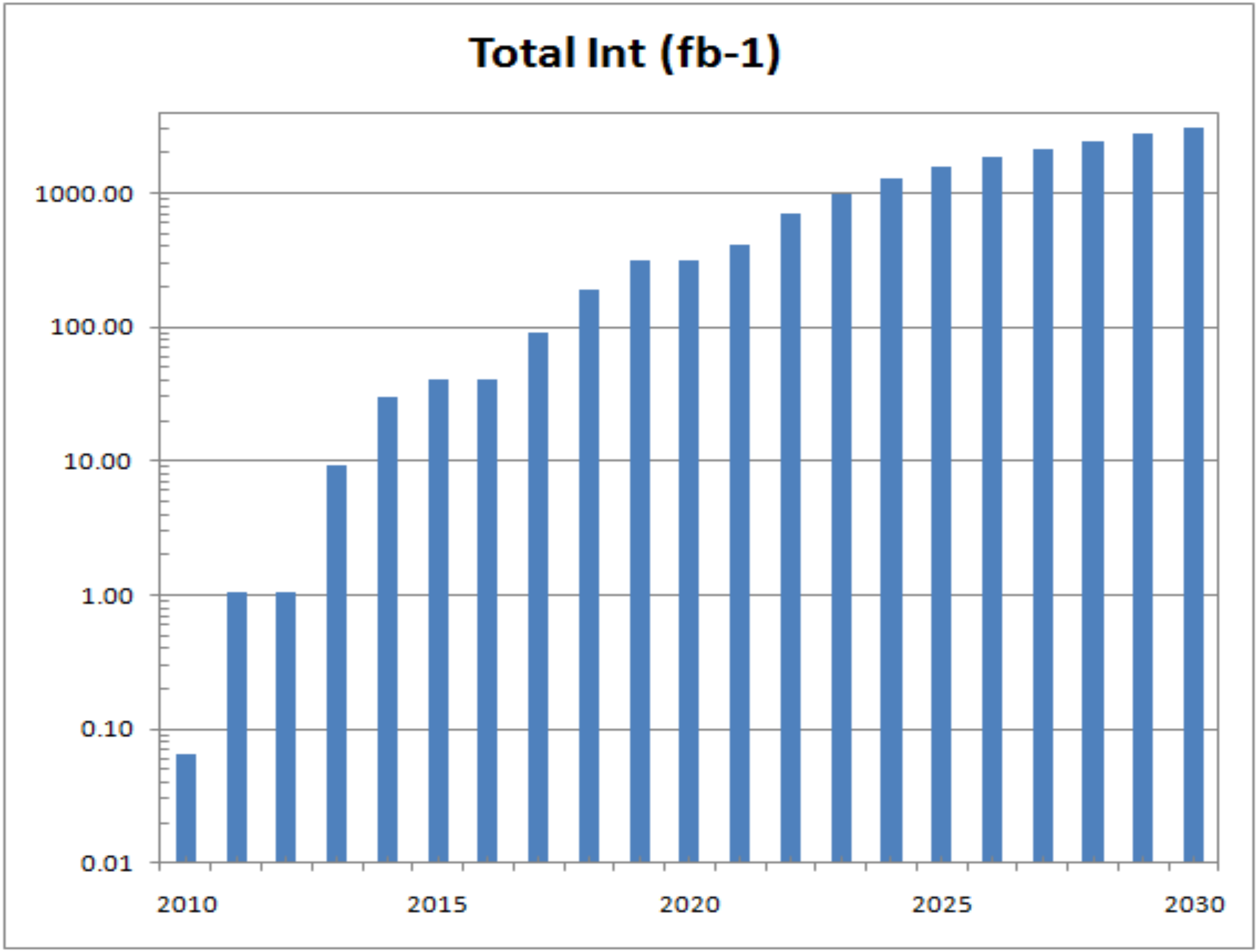
Longer Term Objectives

Integrated luminosity of $\geq 3000 fb^{-1}$ by the end of the LHC life

- requires a peak luminosity of $\geq 5 \times 10^{34} cm^{-2}s^{-1}$ during 2021-2030

- → integrated yearly luminosity of around 250-300fb^{-1}

LHC Preliminary Long Term Predictions



Outlook 2011

Possible gains in luminosity:

75/50 ns trains	x 2-3
β^* = 2 m	x 1.7
Lower emittance	x 1.3
Bunch charge to 1.3×10^{11} p	x 1.4
Total	x 6-9

! Total intensity may be limited by collimation or lifetime considerations – we may not gain the full factor !

SUSY: the “default new physics ??”

- SUSY is perhaps the most explored of “beyond the SM” physics scenarios
- As such, it will perhaps be “blamed” for any deviations from SM physics if observed at Tevatron or at LHC
- The problem will be to prove that, even if a statistically significant deviation from SM predictions is found, the observed events are really due to the supersymmetric particles and NOT to anything else. This will NOT be easy. As you should realize by now, there is an almost continuous spectrum of different SUSY models with different parameters
- Several times in the past (monojets at UA1- see Gary Taubes’s “Nobel Dreams”, CDF- the famous ee$\gamma\gamma$ event) the excitement ran quite wild about what later proved to be just very rare, but still normal SM, events ….

SUSY: the “golden” candidate for “new physics”

- CDF- the famous eeγγMET event: recorded April 28, 1995 in Run-I. Its “a posteriori” probability according to SM ~10^{-6}