Particles and People

Max Klein

Chair for Particle Physics

UNIVERSITY OF LIVERPOOL

Inaugural Lecture, 3. December 2007

Dedicated to
the memory of
Fritz Bernhard
1908-1986

Berlin
Humboldt
University
1973

Chair of Atomic Physics, HUB, Dean, Head of Math.Uni.Class, Colleague of Gustav Hertz

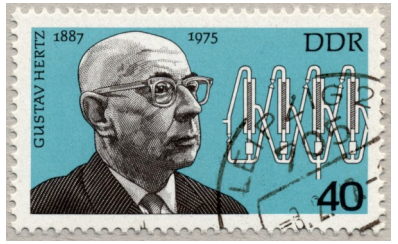
Particle Physics - a Sequence of Spectroscopies

- "Excitation of the 2536 Å Resonanc Line of Mercury"
  Franck /Hertz 1914
  Bohr $\rightarrow$ ATOMIC SPECTROSCOPY

- "Disintegration of Elements by High Velocity Protons"
  Cockcroft / Walton 1932
  pLi $\rightarrow \alpha\alpha$: NUCLEAR SPECTROSCOPY

- "Total Cross-Sections of Positive Pions in Hydrogen"
  Anderson/Fermi/Long/Nagle 1952
  $\Delta^{++} \rightarrow p\pi$: HADRON SPECTROSCOPY

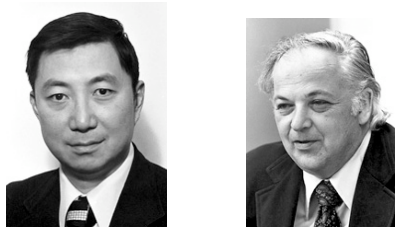
- The charming "November Revolution"
  Ting et al., Richter et al. 11.11.1974
  $\mathcal{J}/\Psi \rightarrow c\bar{c}$: QUARK SPECTROSCOPY



Gustav Hertz: Nobel 1925

John Cockroft and Ernest Walton: Nobel 1951

Enrico Fermi: Nobel 1935

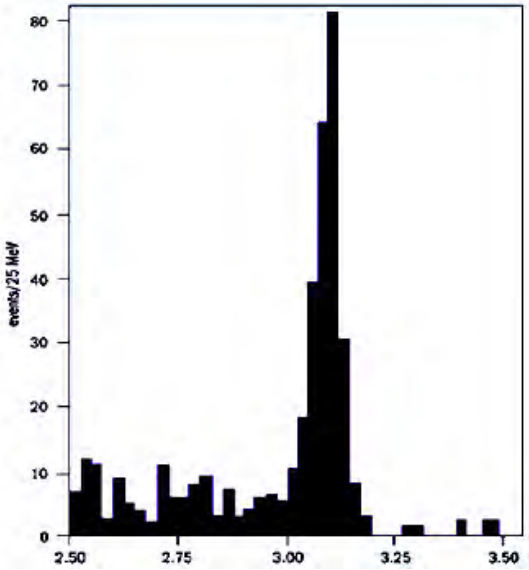


Sam Ting and Burt Richter: Nobel 1976

Particles or People?

$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$ $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$

leptons quarks



p Be → J X → e^+ e^- X

Visit in the fall of 1976 to Moscow
Vladimir Michailovitch Popow (Turok)

T : What are you doing?

M : I am investigating particles.

T : Are these of interest?

M : Yes very much, we just have restored lepton-quark symmetry.

T : May be you are right, but you know what, I find people much more interesting..

Particles and People

QED

Weak neutral currents

A few partons

Some thoughts on what follows

Quantum Electrodynamics [QED]

$$L_{QED} = \overline{\Psi} D \Psi + m \overline{\Psi} \Psi + (DA)^2 + eA \overline{\Psi} \Psi$$

e propagator e mass photon interaction

virtual particles: quantum theory

perturbative QED

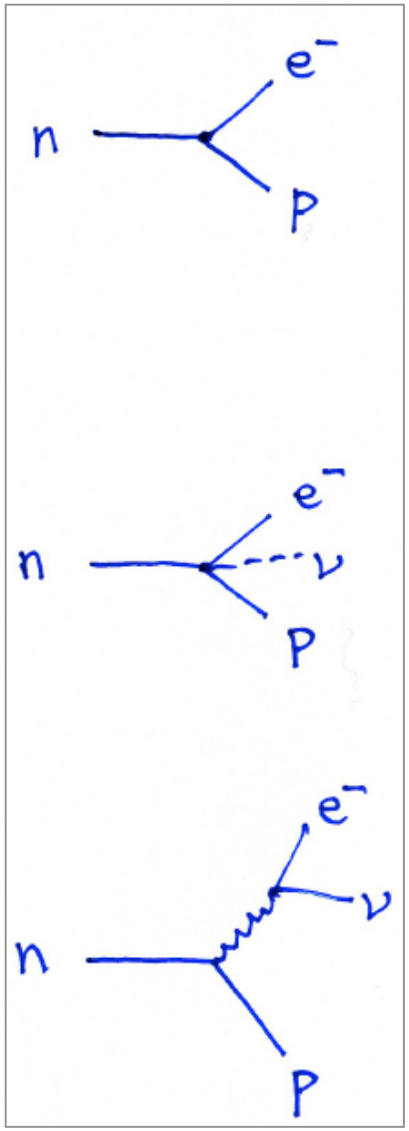
Diagrams
Rules
Integrals

Lamb shift: 1947

Renormalisation

Sin-Itiro Tomonaga, Julian Schwinger, Richard Feynman: Nobel 1965

β Decay and Weak Currents



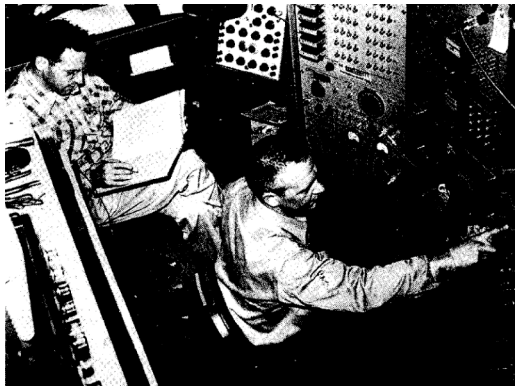
Bohr: E not conserved ?
Heisenberg: space-time not continuous ?
Pauli: a new particle - neutrino ?

"A Tentative Theory of ß Decay" : rejected for publication by "Nature"

4 fermion theory - Fermi
Short range of weak force.
Cross section of pointlike interaction divergent with rising energy.

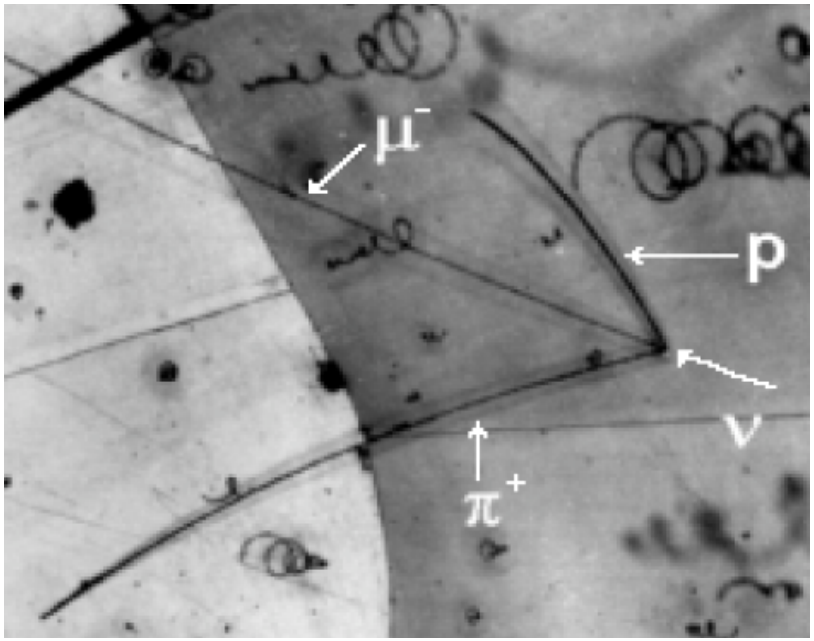
Charged virtual particle - intermediate vector boson damps cross section (W)
Oskar Klein: Electro-Photons (1938)

Discovery of the ν



Fred Reines, Clyde Cowan
Savannah River Reactor
$\nu p \rightarrow n e^+$ 1956

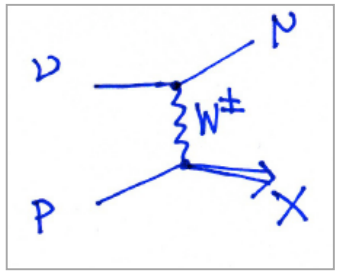
Neutral Currents?



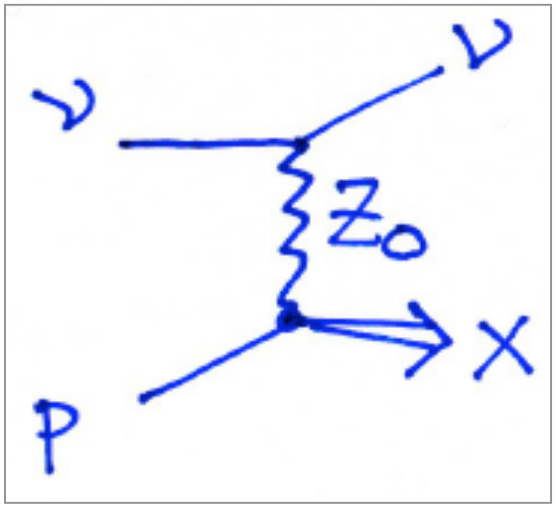
Carlo Rubbia
ICHEP Chicago 1972

"Neutral currents and other forbidden processes"

?

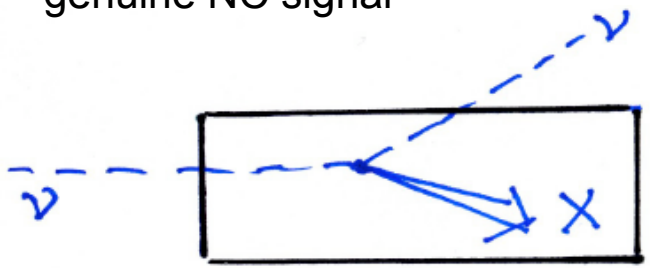


A charged current event in a bubble chamber

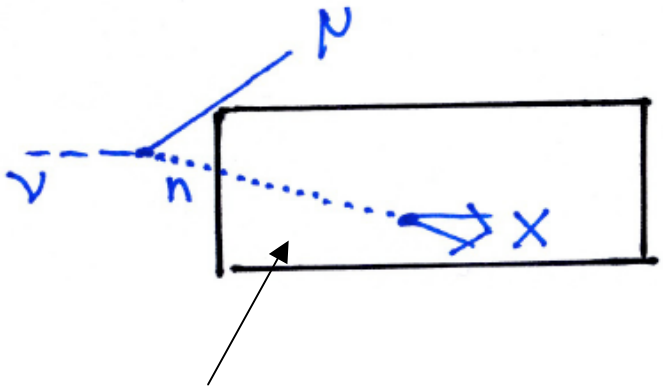


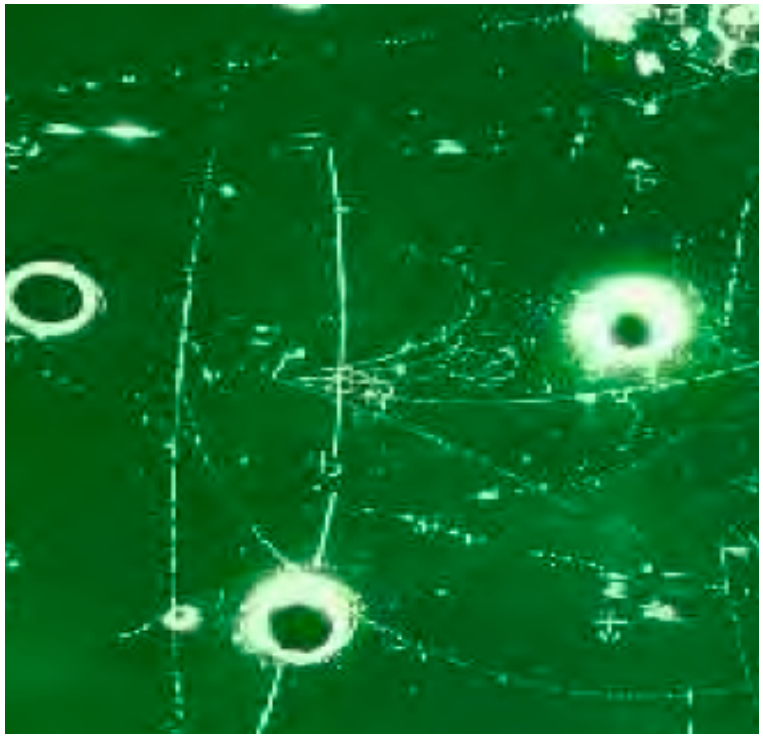
The Discovery of Neutral Currents

genuine NC signal



fake CC “neutron” background





NC: seen before Gargamelle, but misinterpreted

Measured in HPWF experiment but mis-simulated

Discovered in 1973 at CERN: 1st HEP seminar…

Electroweak Theory

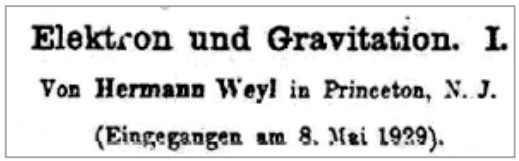

1919. № 10.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 59.

1. *Eine neue Erweiterung der Relativitätstheorie;* von H. Weyl.

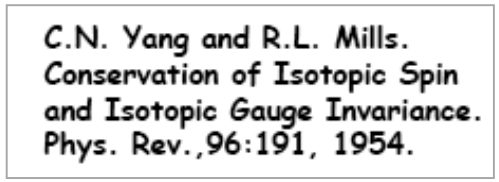
gauge invariance


Elektron und Gravitation. I.

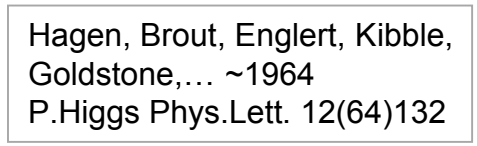
Von **Hermann Weyl** in Princeton, N. J.

(Eingegangen am 8. Mai 1929).

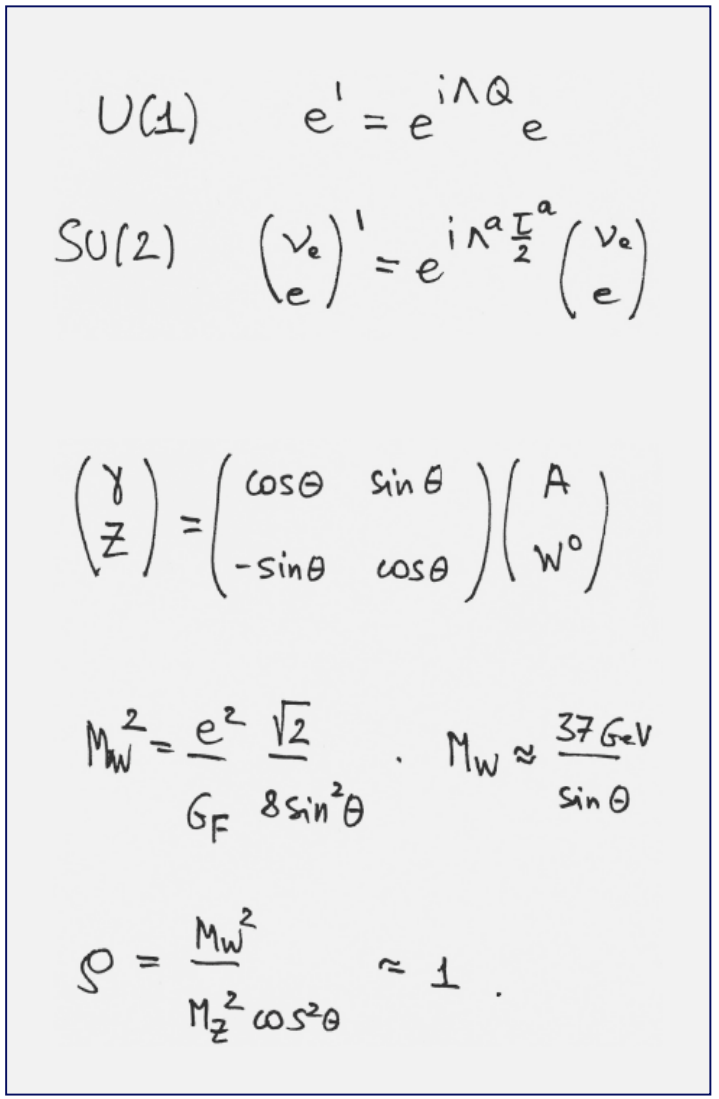
U(1) ; covariant derivative


C.N. Yang and R.L. Mills.
Conservation of Isotopic Spin
and Isotopic Gauge Invariance.
Phys. Rev.,96:191, 1954.

SU(2) doublets


Hagen, Brout, Englert, Kibble,
Goldstone,… ~1964
P.Higgs Phys.Lett. 12(64)132

Mass to the W,Z



one charge, A

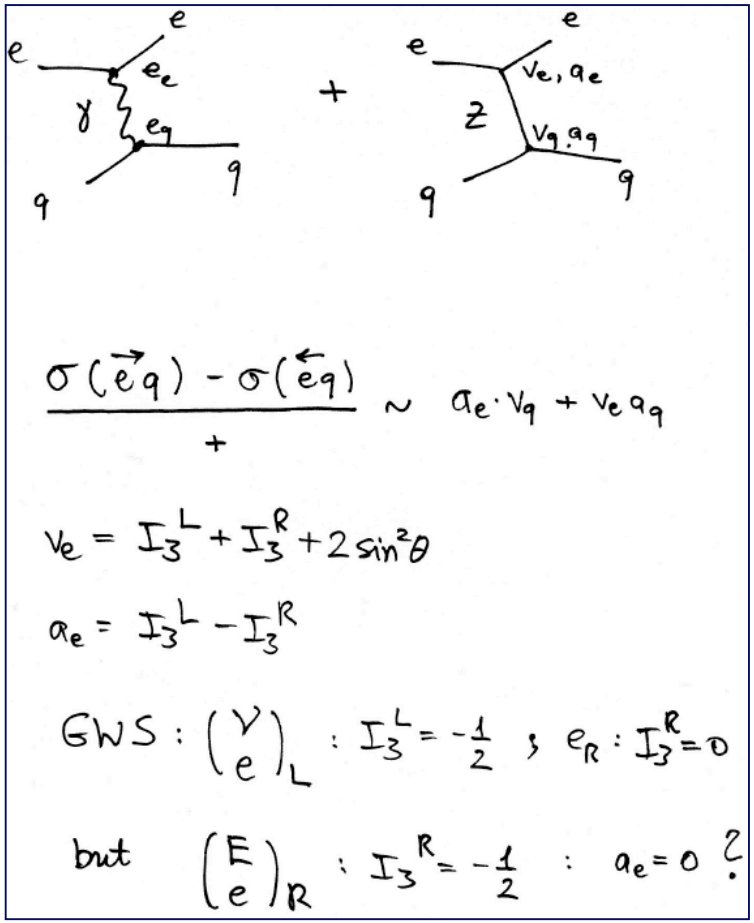
3 Pauli Matr. $W^{\pm,0}$

Mixing angle

W mass

Z mass

The triumph of the electroweak theory



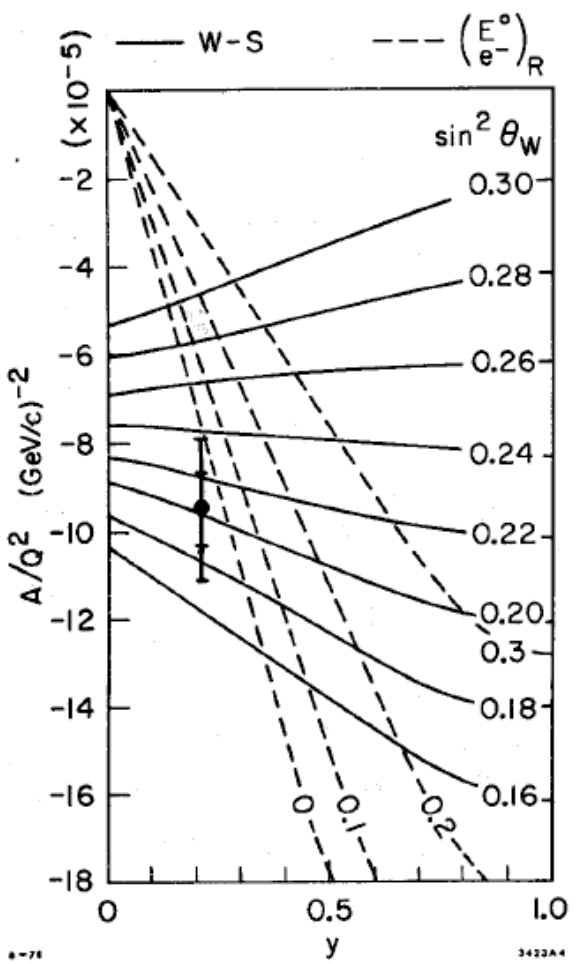
$$\frac{\sigma(\vec{e}q) - \sigma(\overleftarrow{e}q)}{+} \sim a_e \cdot v_q + v_e a_q$$

$$v_e = I_3^L + I_3^R + 2\sin^2\theta$$

$$a_e = I_3^L - I_3^R$$

GWS : $\begin{pmatrix} \nu \\ e \end{pmatrix}_L$: $I_3^L = -\frac{1}{2}$; e_R : $I_3^R = 0$

but $\begin{pmatrix} E \\ e \end{pmatrix}_R$: $I_3^R = -\frac{1}{2}$: $a_e = 0$?



SLAC-PUB-2148
July 1978
(T/E)

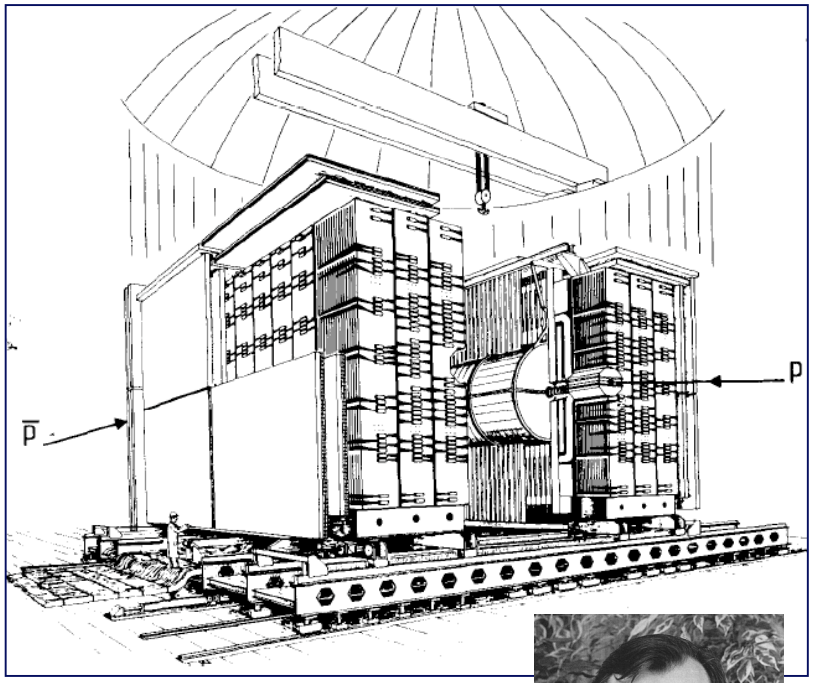
C. Y. Prescott.

Nobel 1979 to Glashow Weinberg Salam

Parity violation in Bi atom (Novosibirsk), γZ interference in muon scattering and $e^+ e^-$

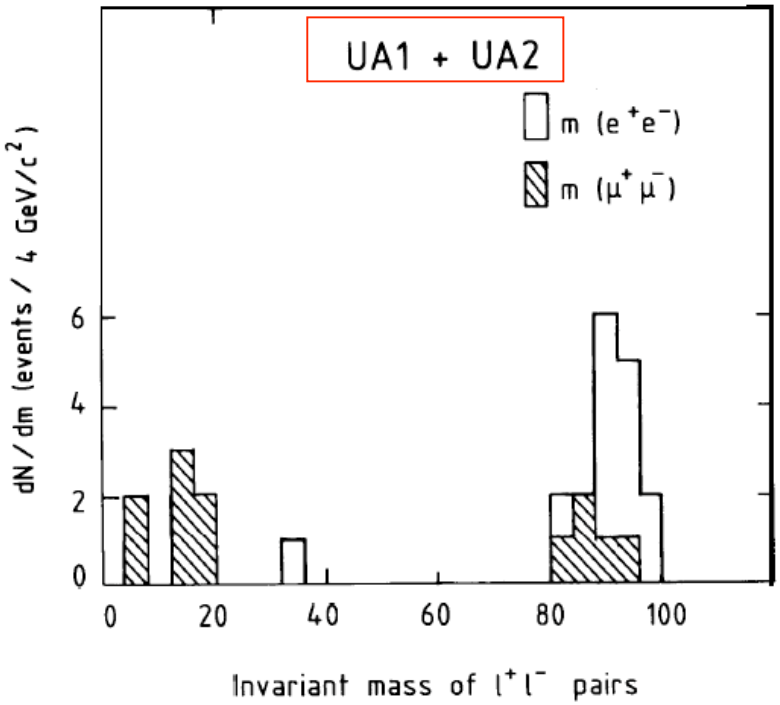
Habilitation 1984

The Discovery of the W and Z Bosons (1983)



" We have two tasks: kill Weinberg Salam, kill QCD"
Carlo Rubbia: 1978 BCDMS meeting at Dubna.
The failure to fulfill his task made Carlo famous…

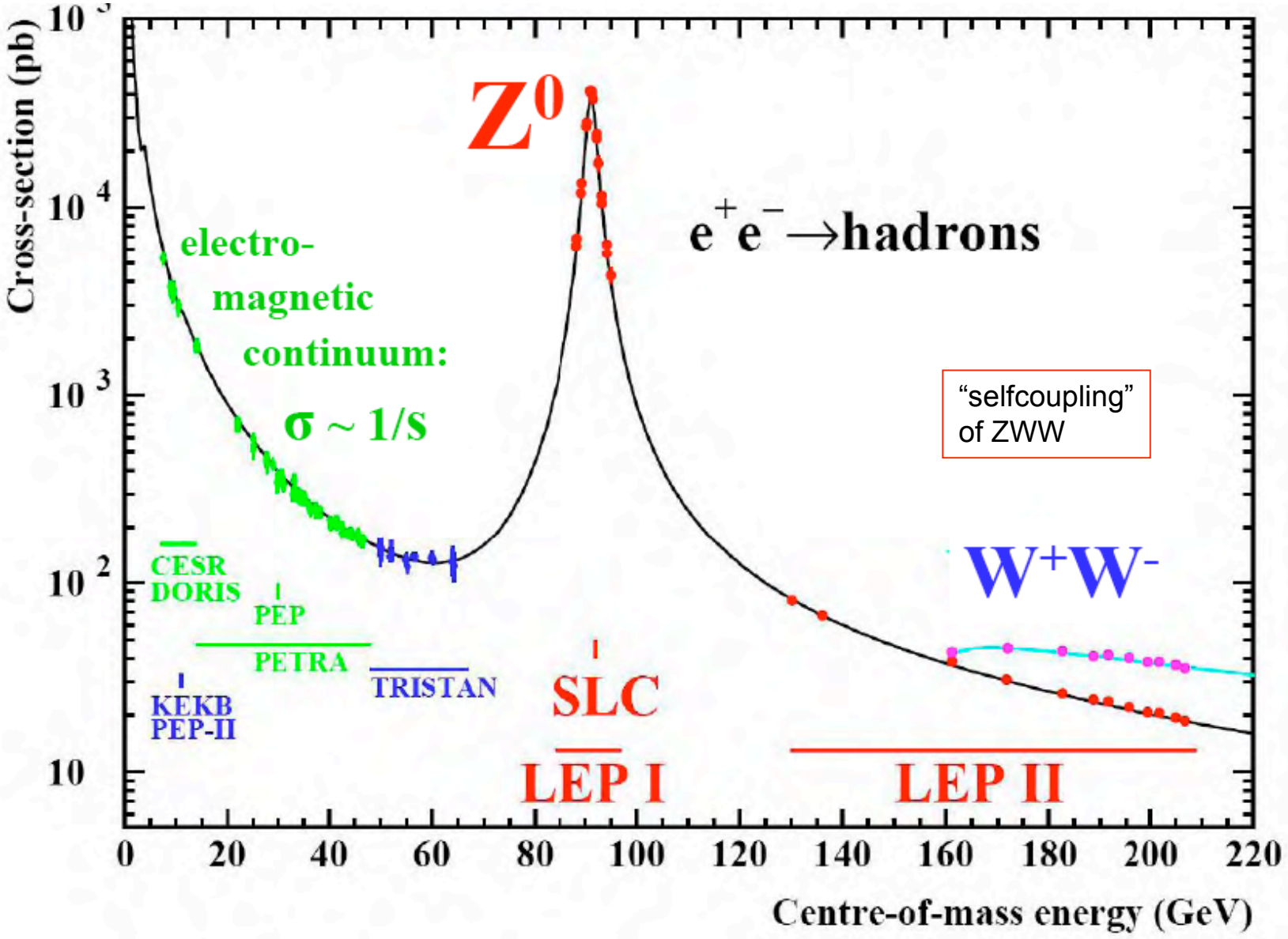
Carlo Rubbia: Nobel lecture 1984



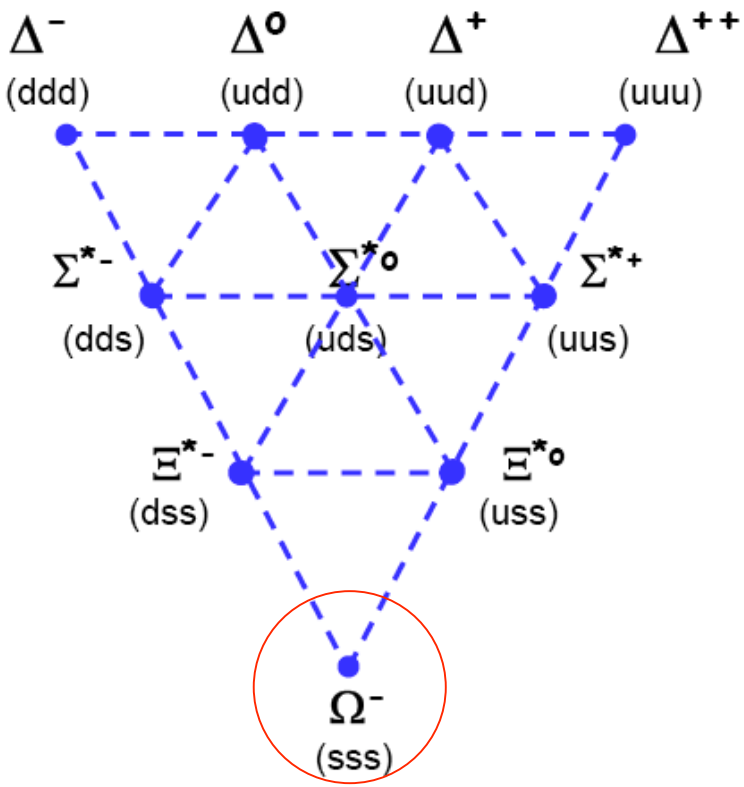
Simon van der Meer
Stochastic Cooling:
Ingenuitive method
to deliver luminosity

S.vd Meer: Nobel 1984

The Z Boson as measured at LEP (e^+e^-)



Constituent Quarks



Luiz Alvarez Nobel 1968

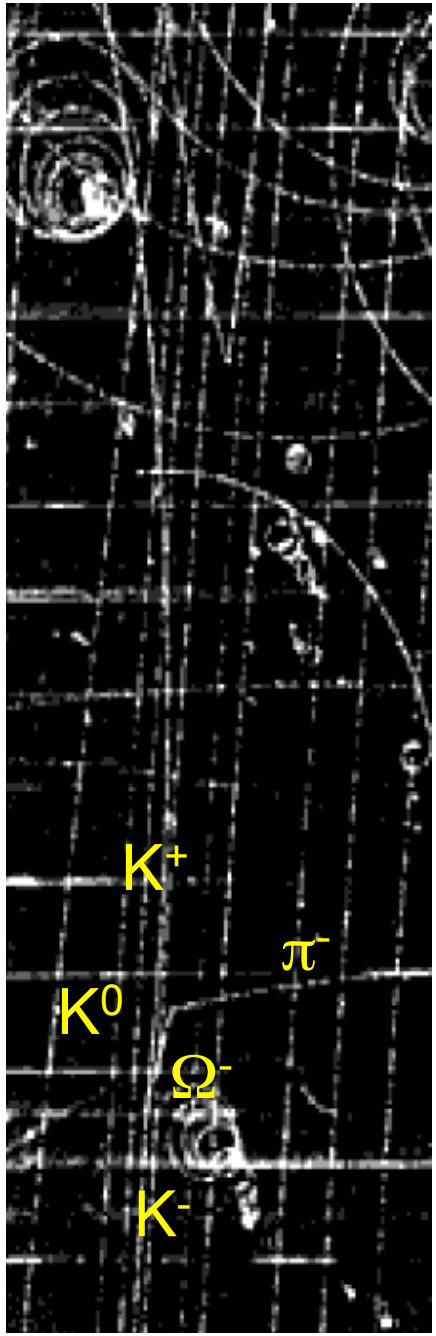
Murray Gell-Mann Nobel 1969

Predicted 1962 by Gell-Mann: M=1685 MeV

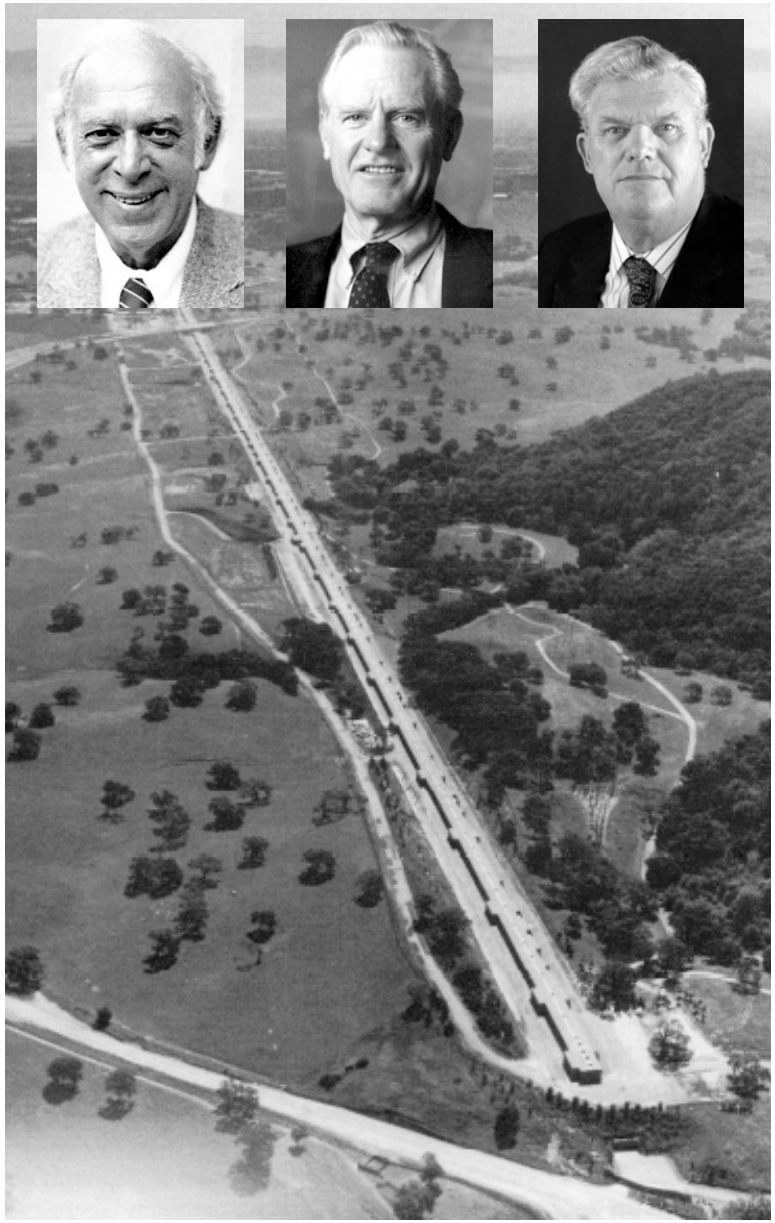
" The paper looks crazy, but if I accept it and it is nonsense, everyone will blame Gell-Mann and not Physics Letters. If I reject it and it turns out to be right, I will be ridiculed."

Observed 1964 at BNL: M=1686 ±12 MeV

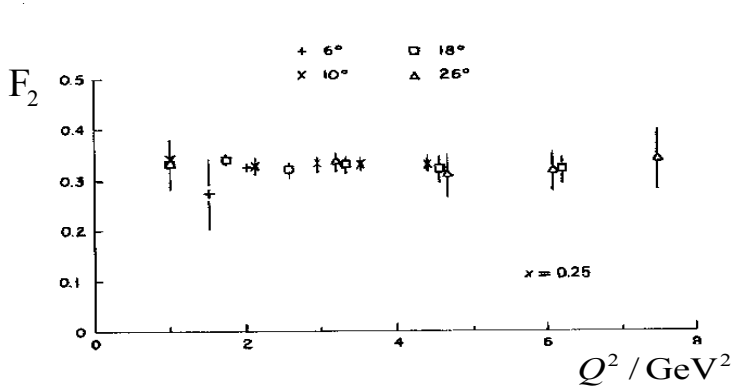
Georg Zweig too young?



2 mile e LINAC ~ 20 GeV at SLAC/Stanford



Partons



Quark density F_2 depends on parton momentum only

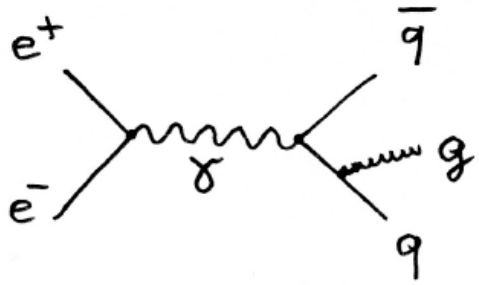
Proposal was for a:
"general survey of the basic cross-sections which will be useful for future proposals"!

Caltech group under B.Barish left, as the cross section was expected to be small, the radiative corr's large and the experiment to take long..

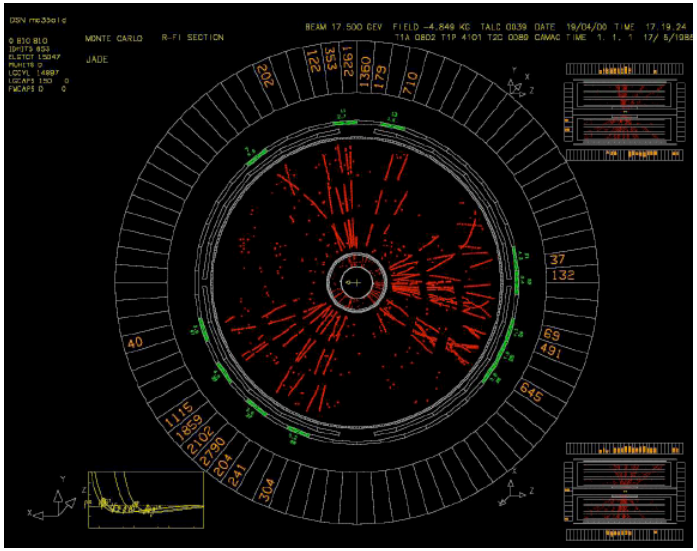
Feynman (partons), Bjorken (scaling) …

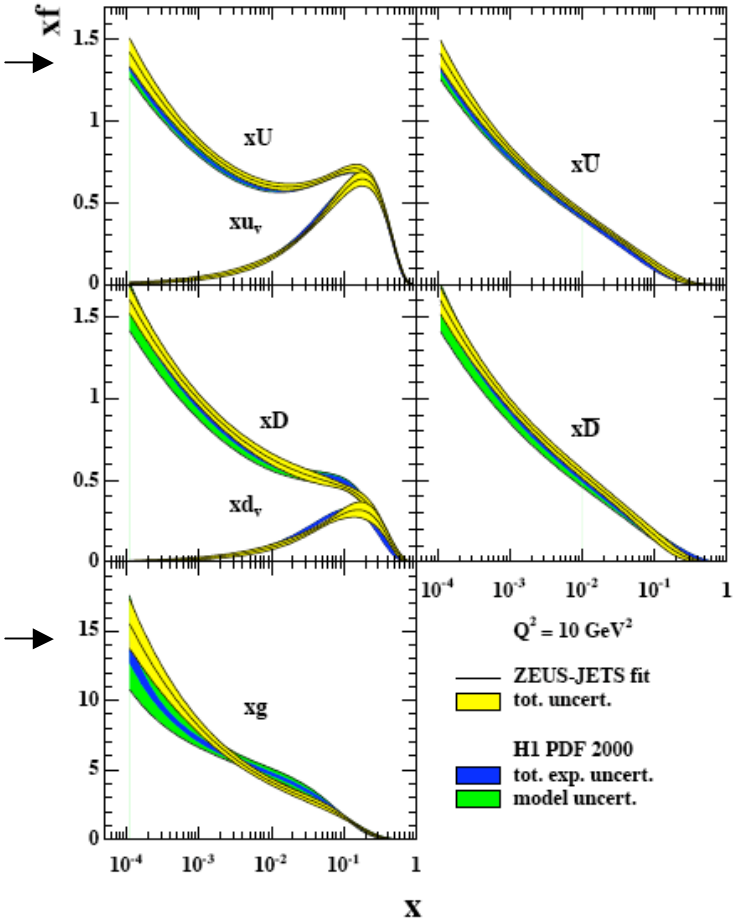
J.Friedman, H.Kendall and R.Taylor Nobel 90

Gluons - a triumph of Quantum Chromodynamics



3 jets discovered at PETRA/DESY





The gluon dominance as discovered at HERA/DESY

Top Quark

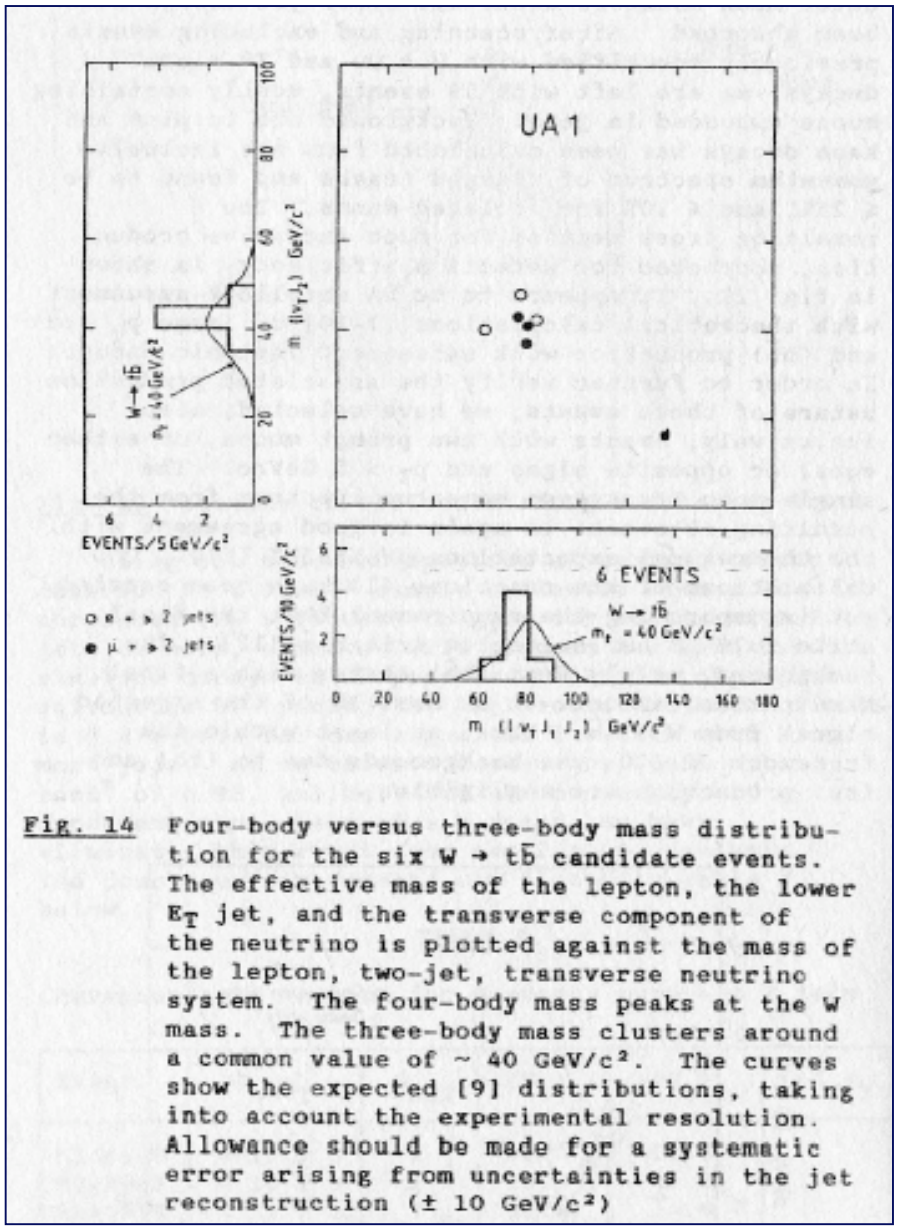
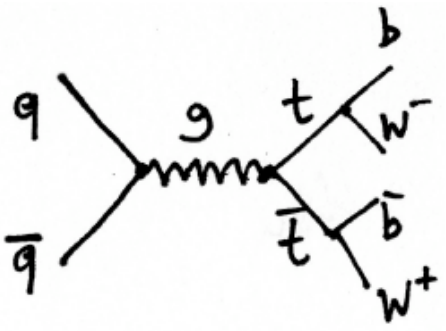
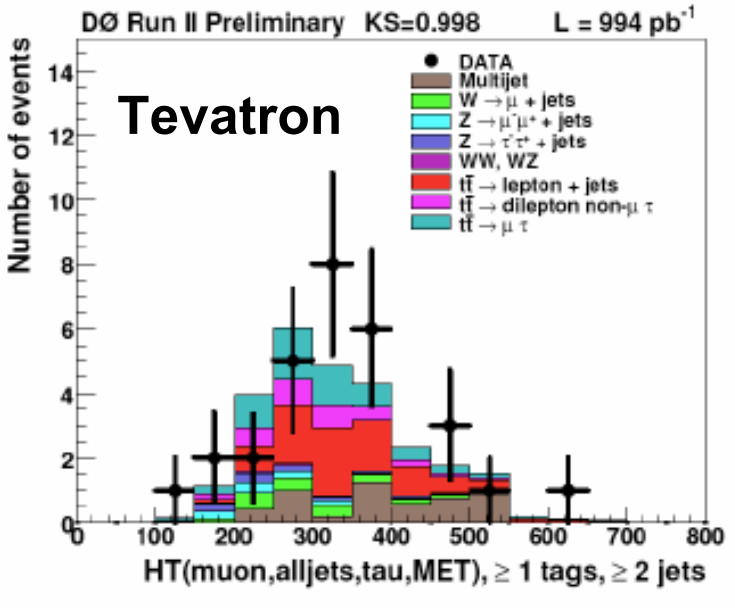


Fig. 14 Four-body versus three-body mass distribution for the six $W \to t\bar{b}$ candidate events. The effective mass of the lepton, the lower E_T jet, and the transverse component of the neutrino is plotted against the mass of the lepton, two-jet, transverse neutrino system. The four-body mass peaks at the W mass. The three-body mass clusters around a common value of ~ 40 GeV/c². The curves show the expected [9] distributions, taking into account the experimental resolution. Allowance should be made for a systematic error arising from uncertainties in the jet reconstruction (± 10 GeV/c²)





D0 & CDF: M_t =170.9 ±1.8 GeV

Prediction (h.o.+Z): 174 ± 4 GeV

ICHEP Leipzig 1984: Discovery of top (UA1)
Certain things went wrong in East Germany

who ordered t? elusive: 10^{-26} s

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

2007

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/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

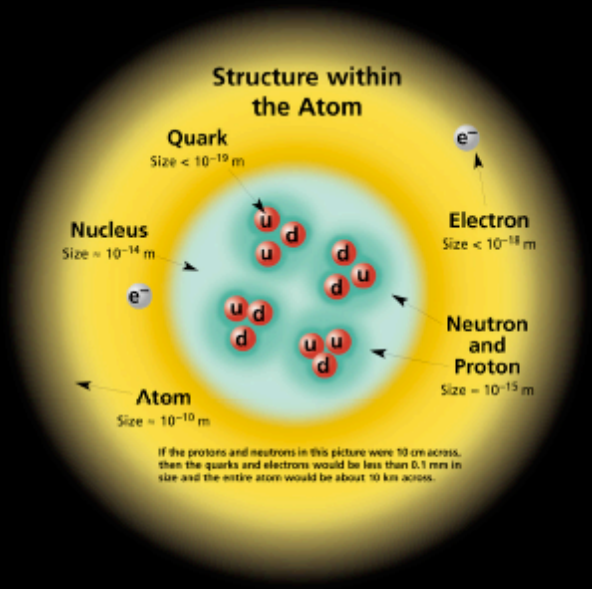
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	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

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

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

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



BOSONS

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

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	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 (Electroweak)	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^- Z^0	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
Strength relative to electromag for two u quarks at: 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/c^2	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

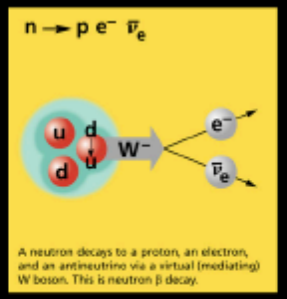
Mesons $q\bar{q}$

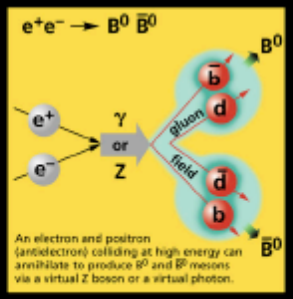
Mesons are bosonic hadrons.
There are about 140 types of mesons.

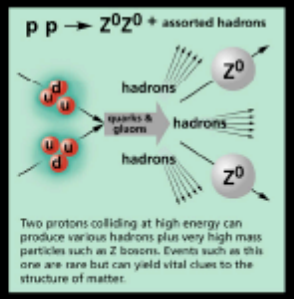
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

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

Figures
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.







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
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Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
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1967

Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS

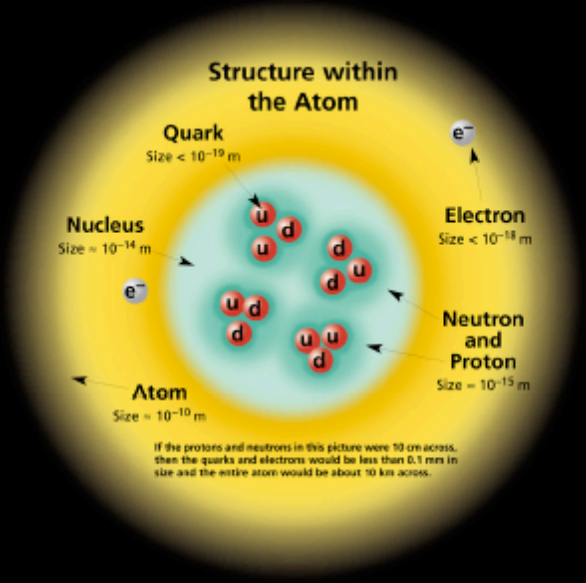
The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it 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/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1



Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where ħ = $h/2\pi$ = 6.58×10^{-25} GeV s = 1.05×10^{-34} J s.

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

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

BOSONS

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

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	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 (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy		Electric Charge		See Residual Strong Interaction Note
Particles experiencing:	All		Electrically charged		Hadrons
Particles mediating:	Graviton (not yet observed)		γ		Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}		1		Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}		1		
for two protons in nucleus	10^{-36}		1		20

Baryons qqq

Baryons are ... There are ...

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton				
$\bar{p}$	anti-proton				
n	neutron				
Λ	lambda				
Ω^-	omega				

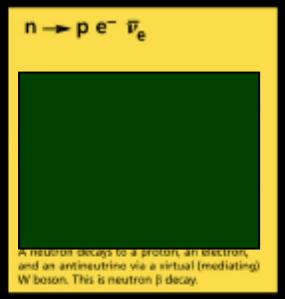
Mesons $q\bar{q}$

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

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+					
K^-					
ρ^+					
B^0					
η_c					

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

Figures
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the 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.

The Particle Adventure
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Sheldon Glashow, Steven Weinberg, Abdus Salam

8.December 1979@Stockholm and soon after at CERN

The SM cannot be right
Too many parameters
Artificial fine tuning

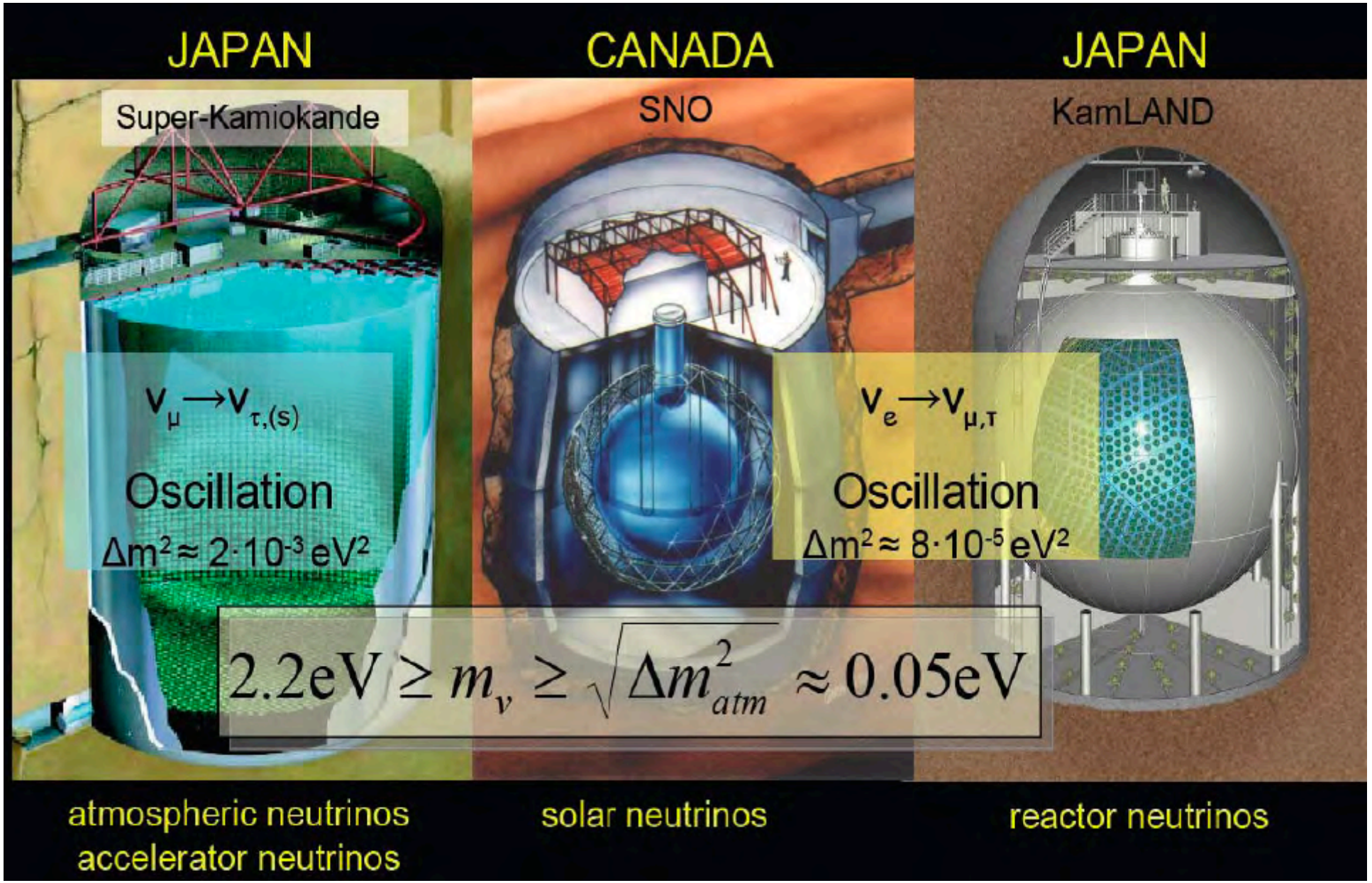
Making do w/o top

GUT - SU(5)
Proton decay
$\sin^2\Theta=0.2$
The prison of low T, E

Preons. SU(8)
q,l symmetry
Extra dimensions
$eg=2\pi n$
Magnetic monopoles

Beyond the soon Standard Model

How can one unify all interactions, are there more and do more/less particles exist?



JPARC, Japan: precision measurement of neutrino mixing parameters (+U.Liverpool)

Great Expectations

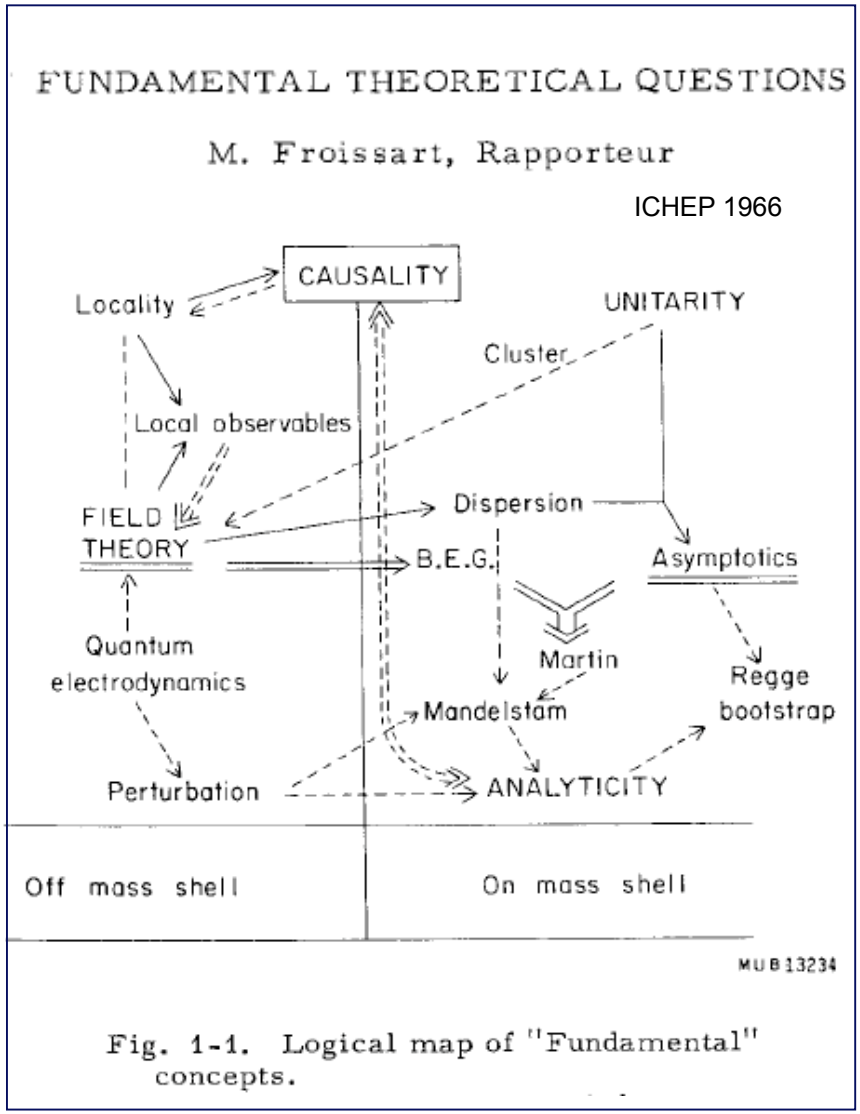


Fig. 1-1. Logical map of "Fundamental" concepts.

A few years before quarks and the November revolution

For the TeV scale:

'The Higgs' to determine mass of W,Z,..
but all we really know is that
the 4-IVB interaction diverges ~ E^2
and M_H > 114 GeV (LEP)

More Higgs particles, in SUSY
[avoids Higgs mass term divergence]

No Higgs particles, in Technicolour
[avoid unitarity limit violation]

Extra Dimensions and String Theory
[reminds on Heisenberg, Weyl, ..]

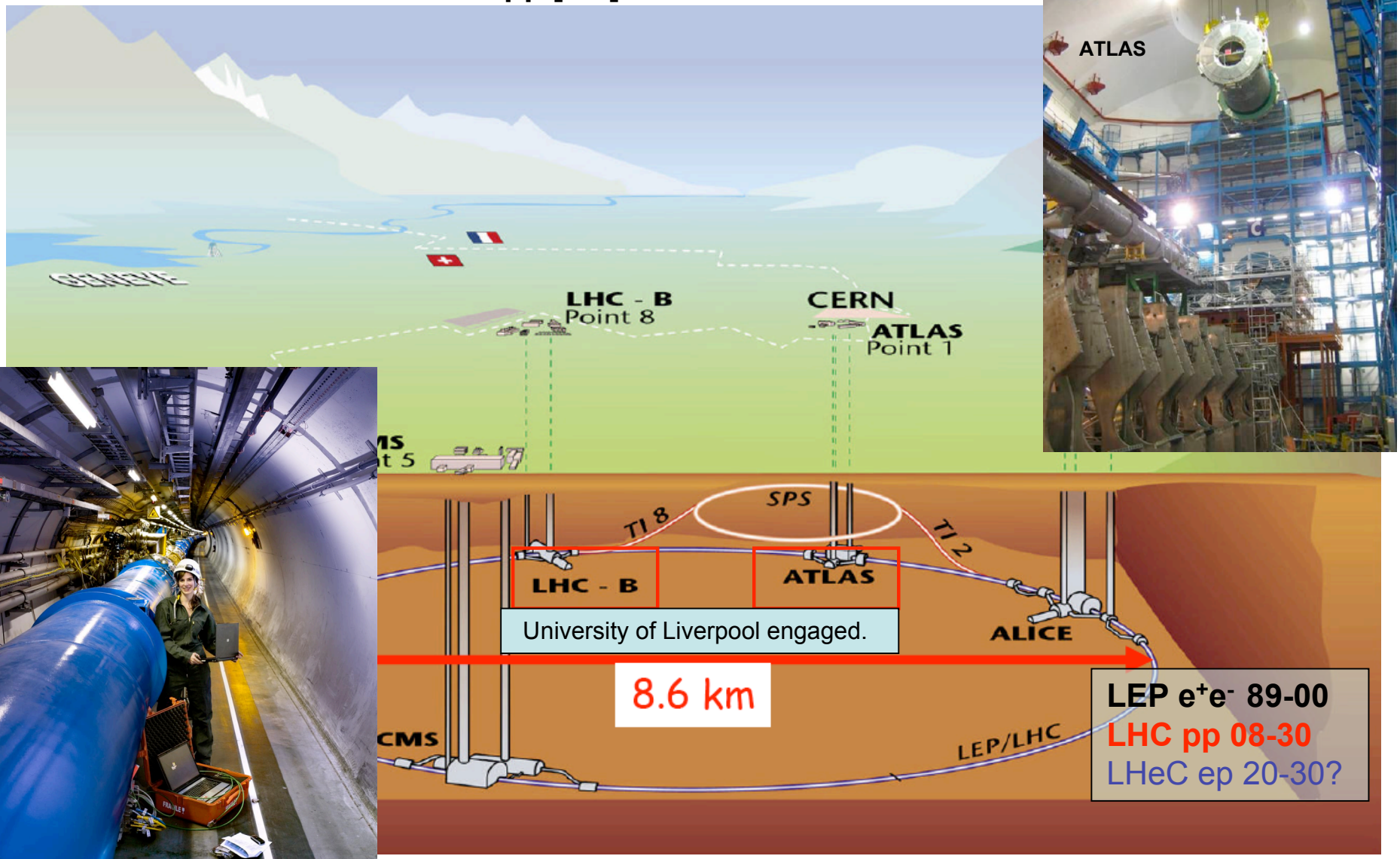
Unparticles
[reminds on Ether]

E8
[reminds on E6]
…

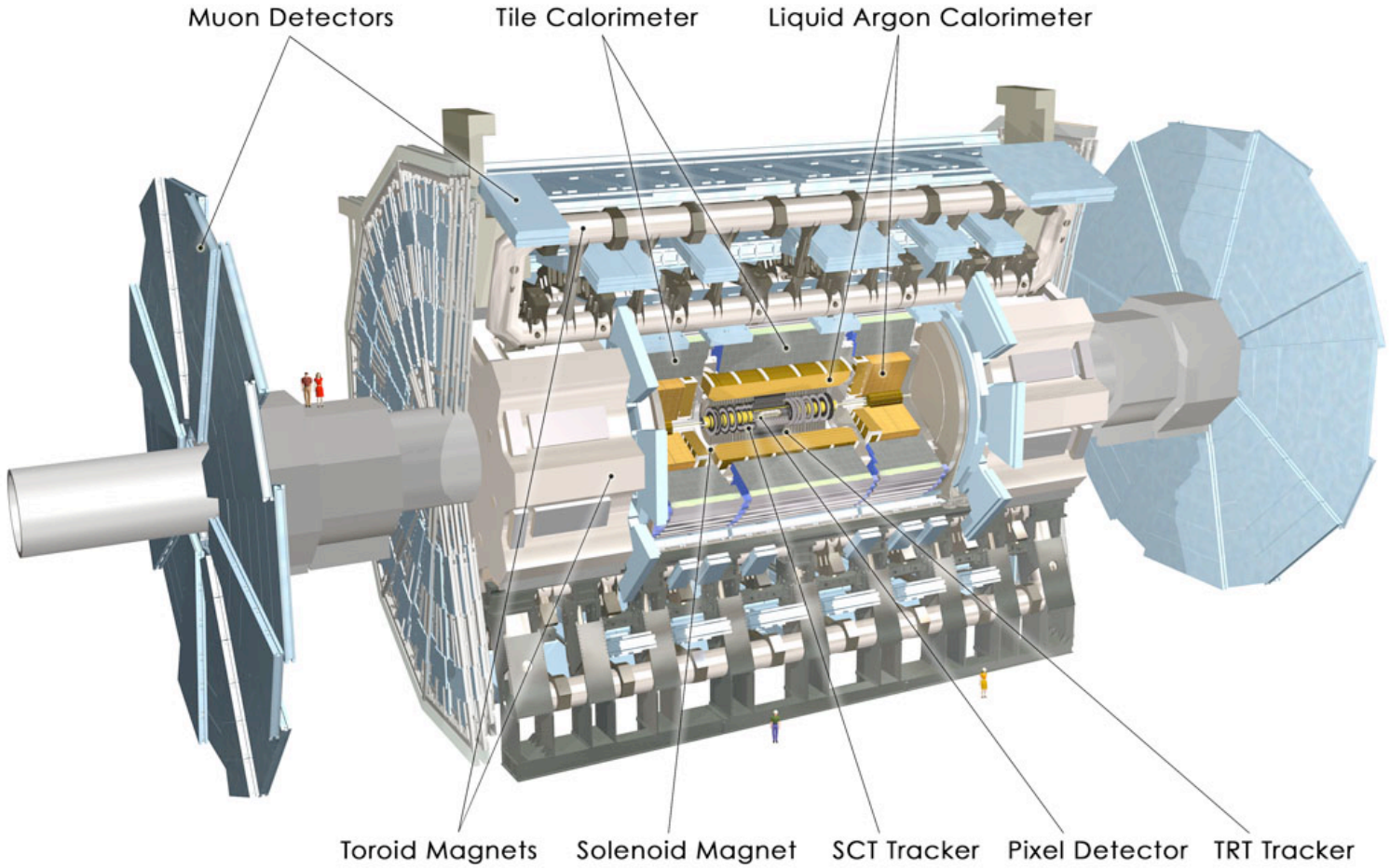
A few years before the LHC has explored the TeV scale

The Large Hadron Collider

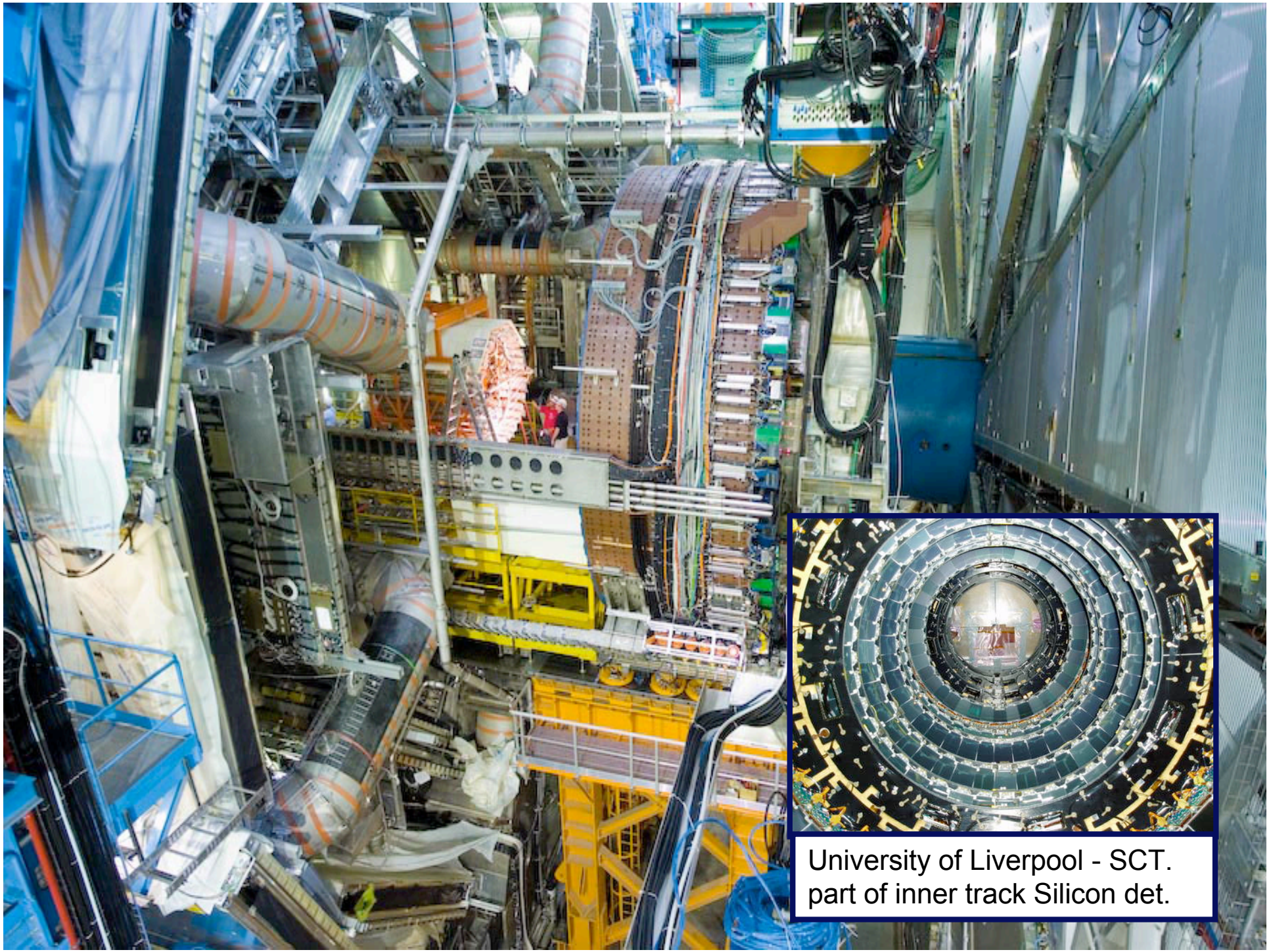
LHC: 7000 * 7000 GeV^2 pp [AA] from 2008 onwards



The ATLAS Experiment at the LHC



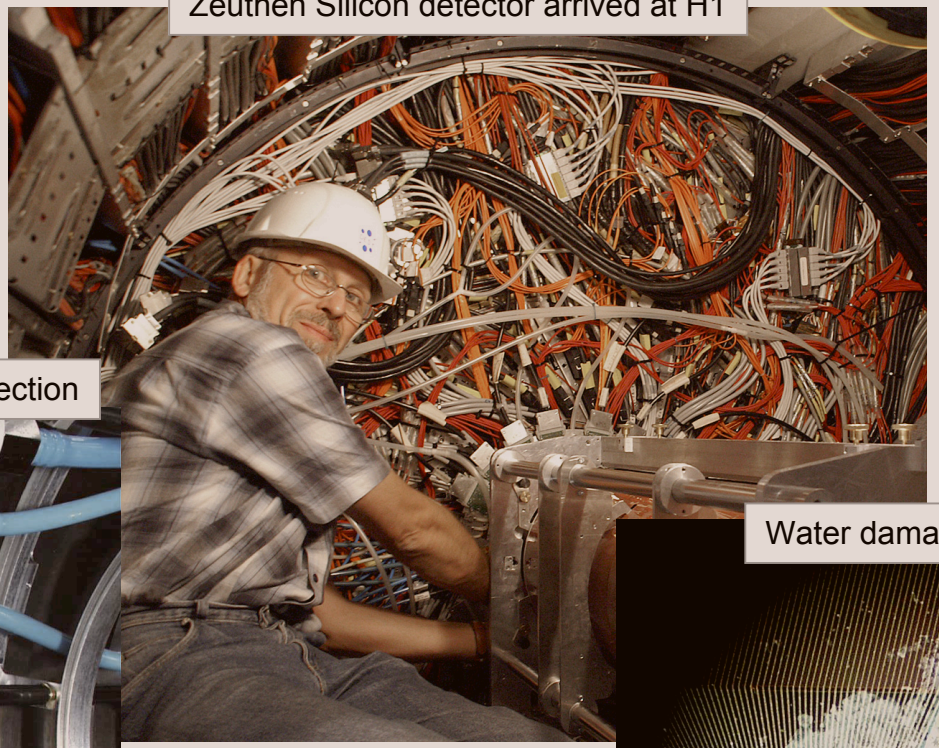
Worldwide collaboration of ~ 150 institutes and 1900 physicists and engineers to explore the physics at the accelerator energy frontier



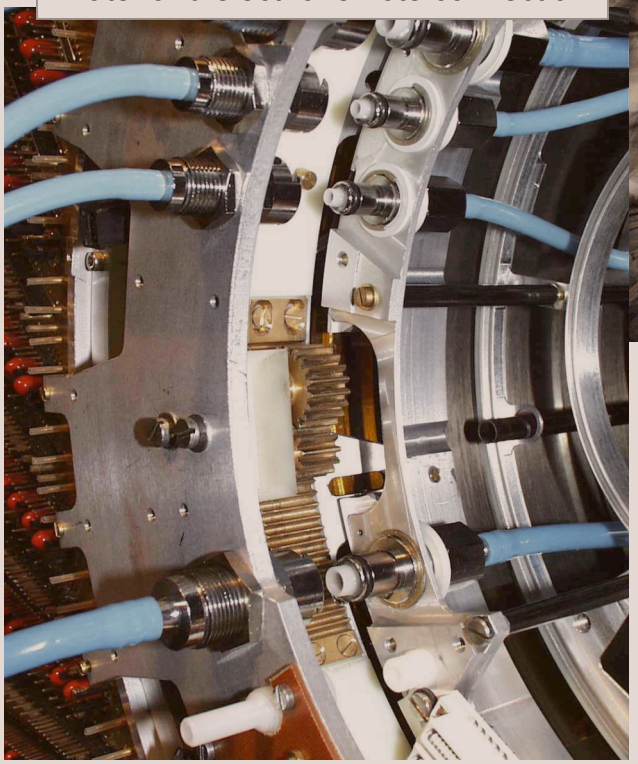
University of Liverpool - SCT.
part of inner track Silicon det.

Challenges Upgrade | **Engineers** Design&Installation | **Adventures** Operation

Zeuthen Silicon detector arrived at H1

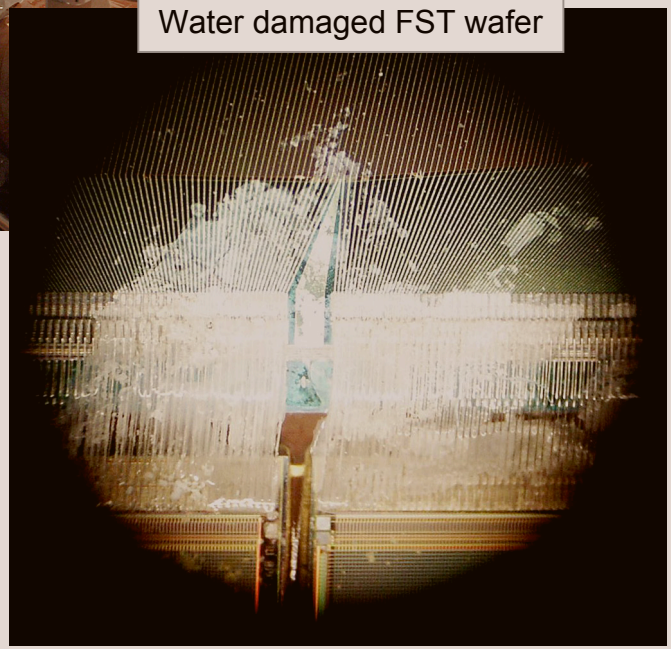


Water and electric remote connection

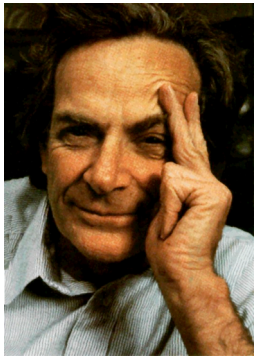


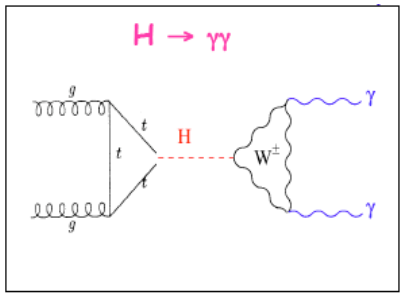
Joachim Meissner, noble, and the art of workshops.

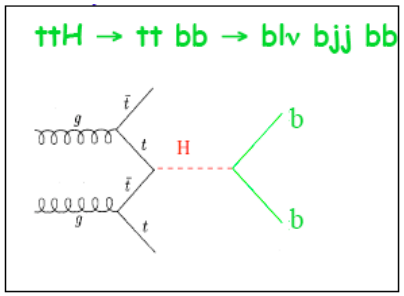
Water damaged FST wafer

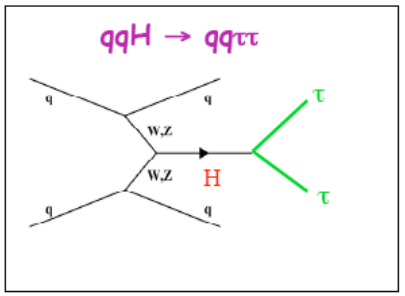


Feynman's Wisdom









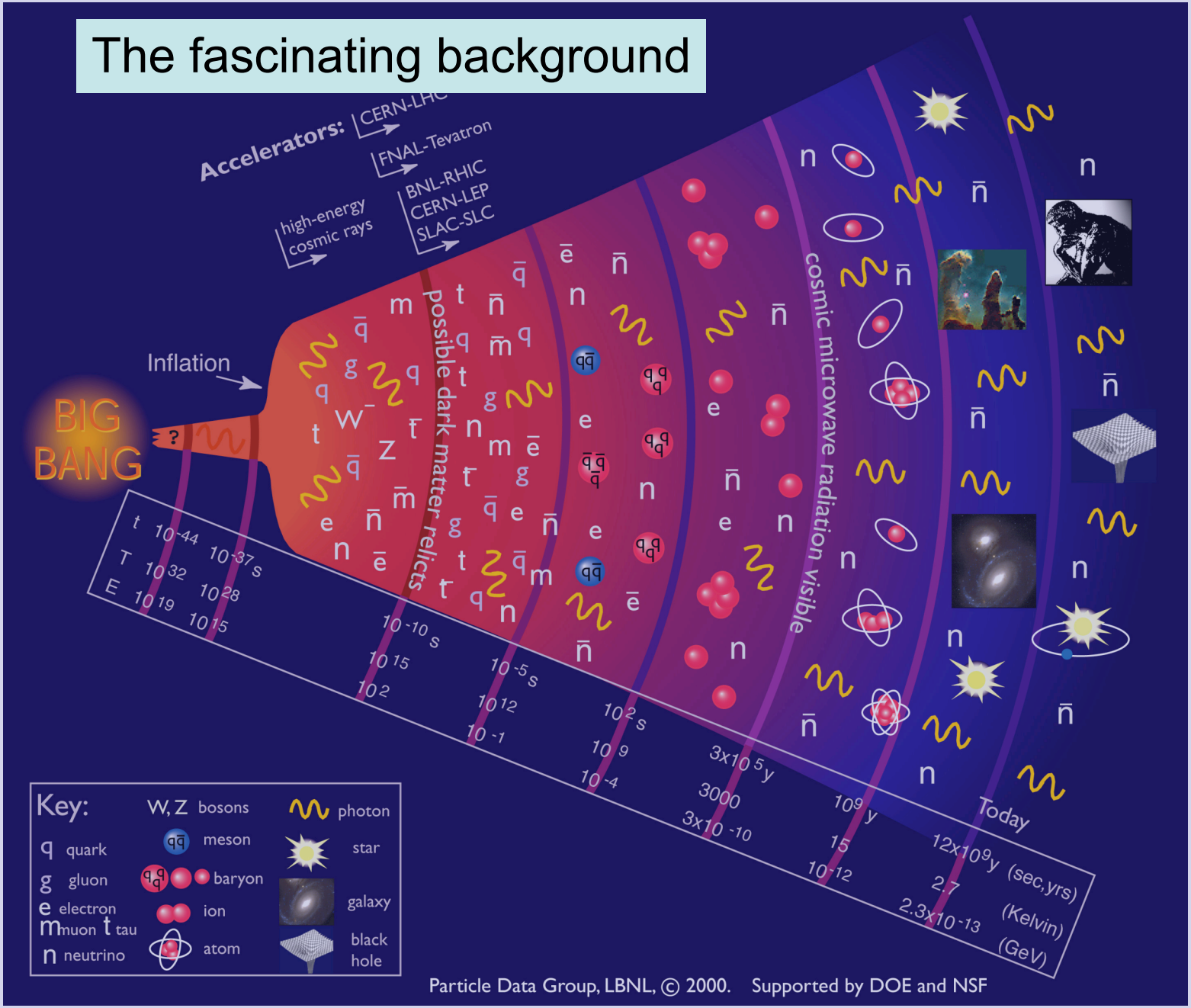
The 3rd family and the gluon may be there to uncover the Higgs mechanism **ILC - Linear Collider e^+e^-**

30km superconducting GDE 07

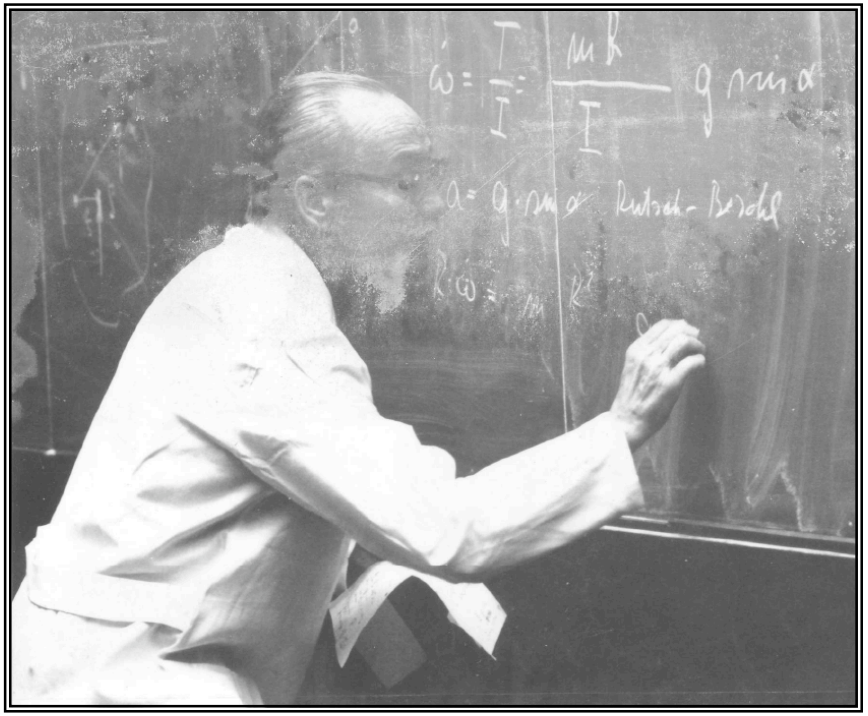
[9]I would like to quote Feynman in a recent interview to the "Omni" magazine: "As long as it looks like the way things are built with wheels within wheels, then you are looking for the innermost wheel - but it might not be that way. in which case you are looking for whatever the hell it is you find!". In the same interview he remarks "a few years ago I was very sceptical about the gauge theories... I was expecting mist. and now it looks like ridges and valleys after all."

Cited: Abdus Salam
Nobel Lecture 1979

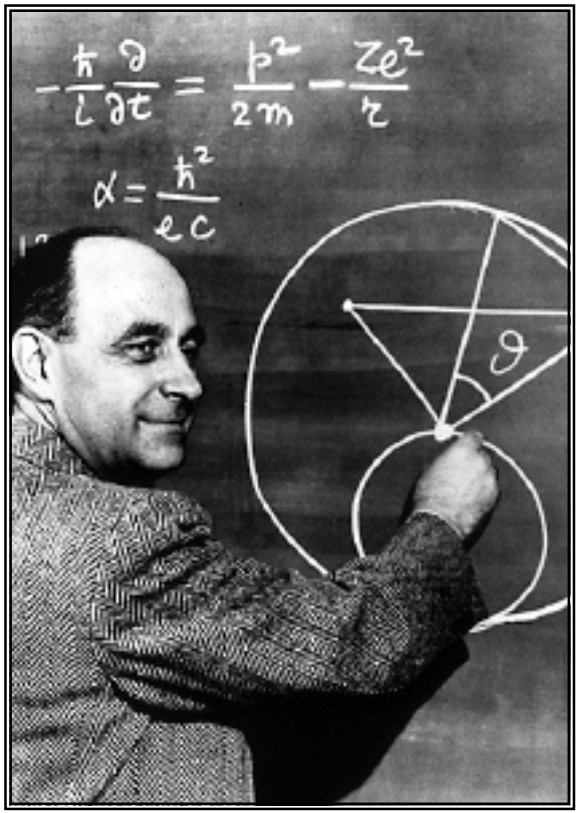
The fascinating background



The Need to Understand



Fritz Bernhard



Enrico Fermi

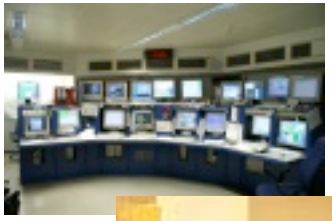
The Need to Think

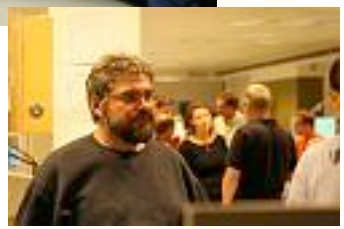
In particle physics you rarely walk alone

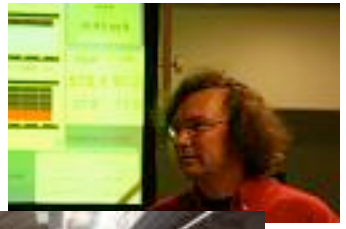
The last meeting at HERA/H1 1.7.2007

Thanks to my family **Anna-Dorothea, Fritz**, Uta, Anna, Felix, Mascha, Daniela, Sebastian, Wolfgang, Katharina
my teachers G.Sack, F.Bernhard, C.J. Biebl, K.Lanius, I.Savin, S.Bilenky, C.Rubbia, F.Eisele, E.Gabathuler
my colleagues Alberto, Jim, Joel, Martin, Peter, Rainer, Sasha, Ilja, Tim, John, Ferdi, Emmanuelle, Paul, Fabiola..
and many new and old friends around Phil and elsewhere

People - the last day of HERA

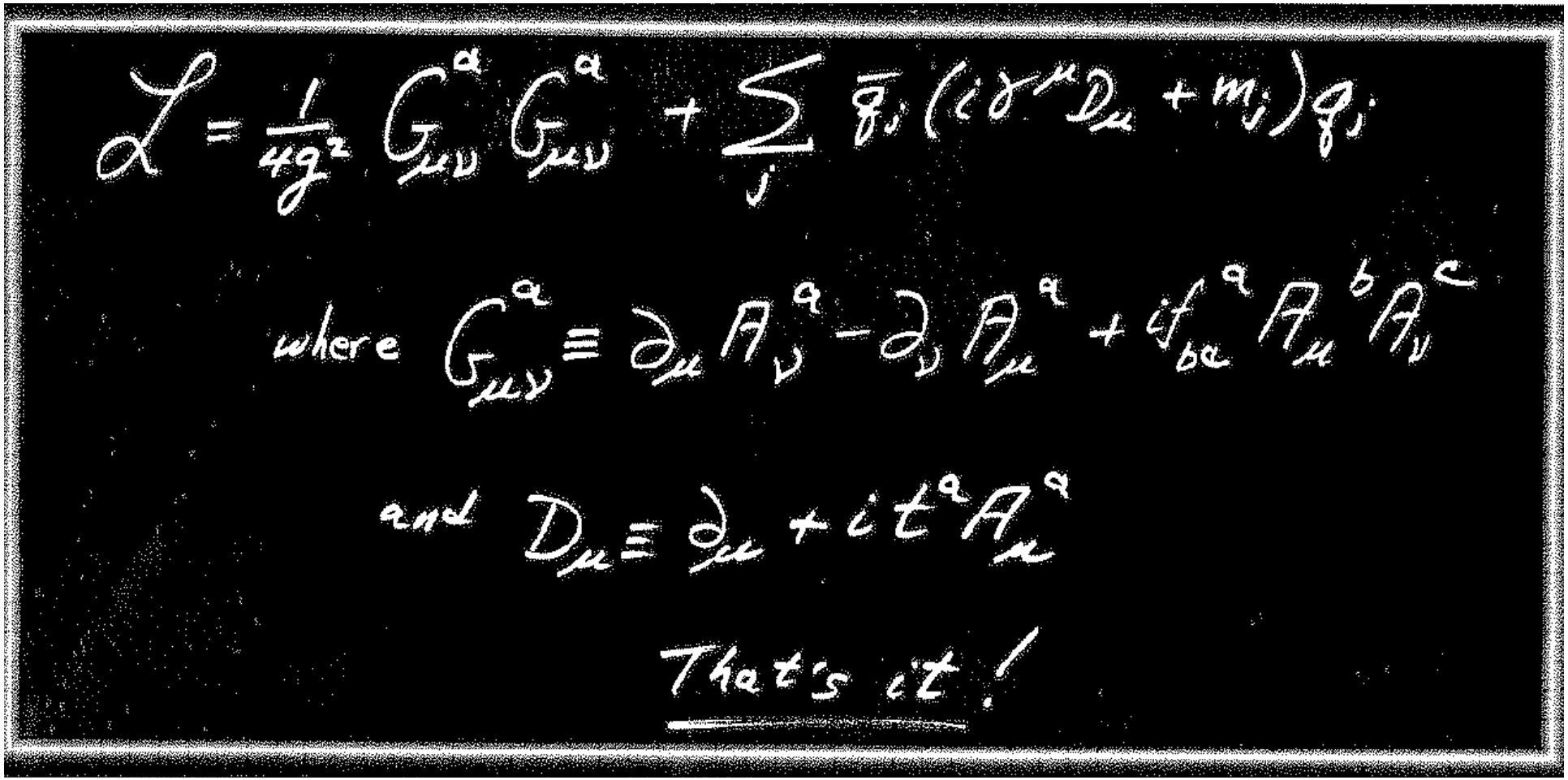






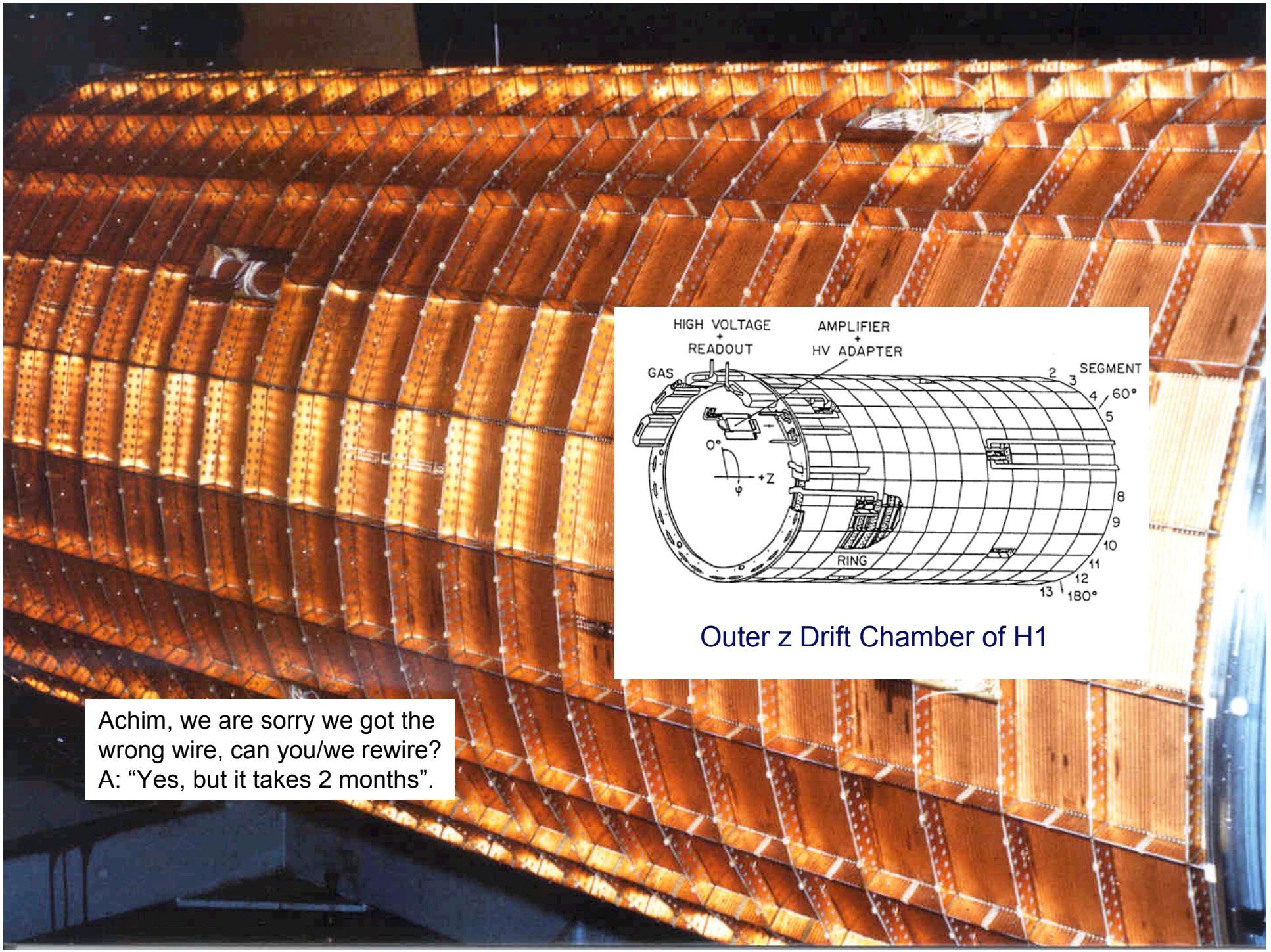
backup

The QCD Lagrangian



j … quark flavours a,b,c … 3 colours μ,ν … space-time

F.Wilczek, Physics Today, August 2000.



Outer z Drift Chamber of H1

Achim, we are sorry we got the wrong wire, can you/we rewire?
A: “Yes, but it takes 2 months”.