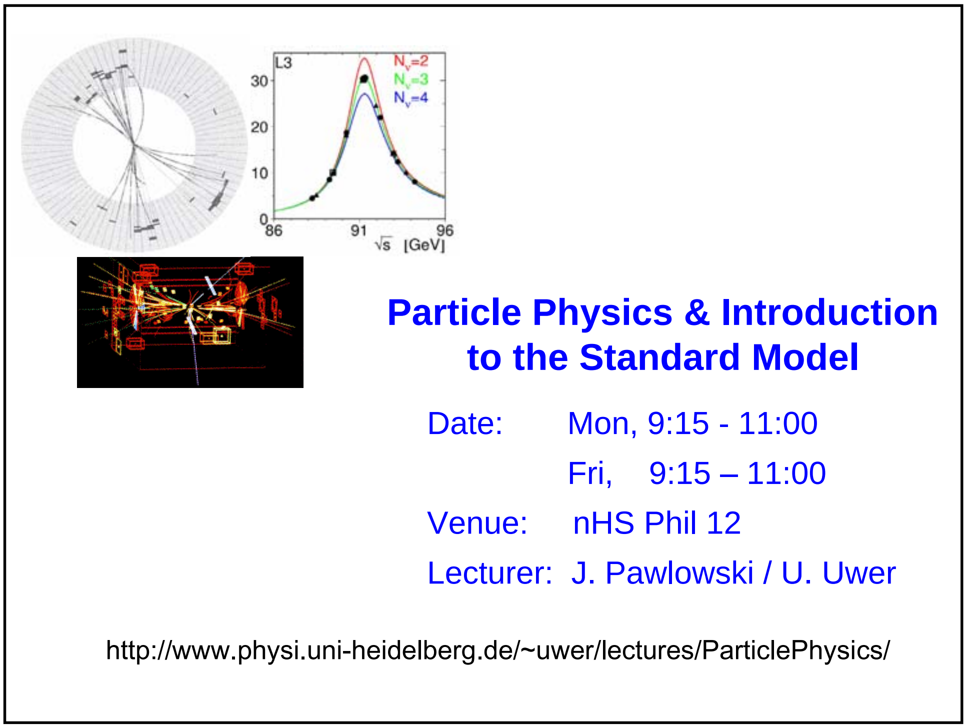


Particle Physics & Introduction to the Standard Model

Date: Mon, 9:15 - 11:00
Fri, 9:15 – 11:00
Venue: nHS Phil 12
Lecturer: J. Pawlowski / U. Uwer

http://www.physi.uni-heidelberg.de/~uwer/lectures/ParticlePhysics/

Particle Physics & Introduction to Standard Model

Outline

I. Introduction
II. Prerequisites
III. Introduction to QED
IV. e^+e^- annihilation experiments below the Z resonance
V. Weak interaction and phenomenological approach to the SM
VI. Standard Model
VII. Experimental tests of the Standard Model
VIII. Strong Interaction
IX. Flavor oscillations
X. Search for Physics beyond the Standard Model

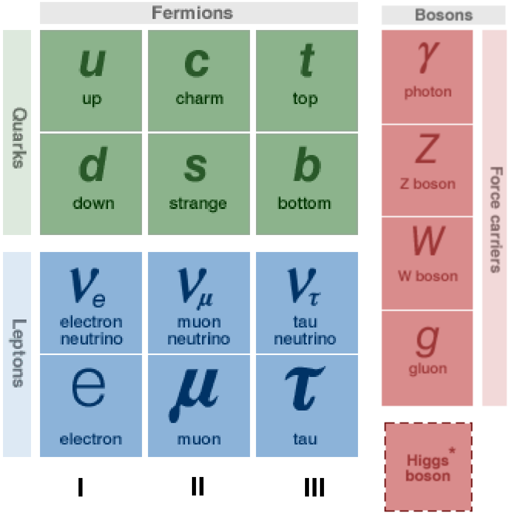
Literature

- O. Nachtmann: Elementarteilchenphysik, Vieweg
- F.Halzen, A.Martin: Quarks and Leptons, John Wiley.
- C.Berger: Elementarteilchenphysik, Springer.
- D.H.Perkins: Introduction to High Energy Physics, Cambridge University Press.
- Particle Data Group: Review of Particle Physics, 2008.
  http://pdg.lbl.gov/

I. Introduction
   1. Standard Model: Building blocks of matter and their interactions
   2. Experimental tools
   3. Natural units

What you already know from „Physik 5“

1. Standard Model *) of Particle Physics



Based on the principle of local gauge invariance

$SU_C(3)\times SU_L(2)\times U_Y(1)$

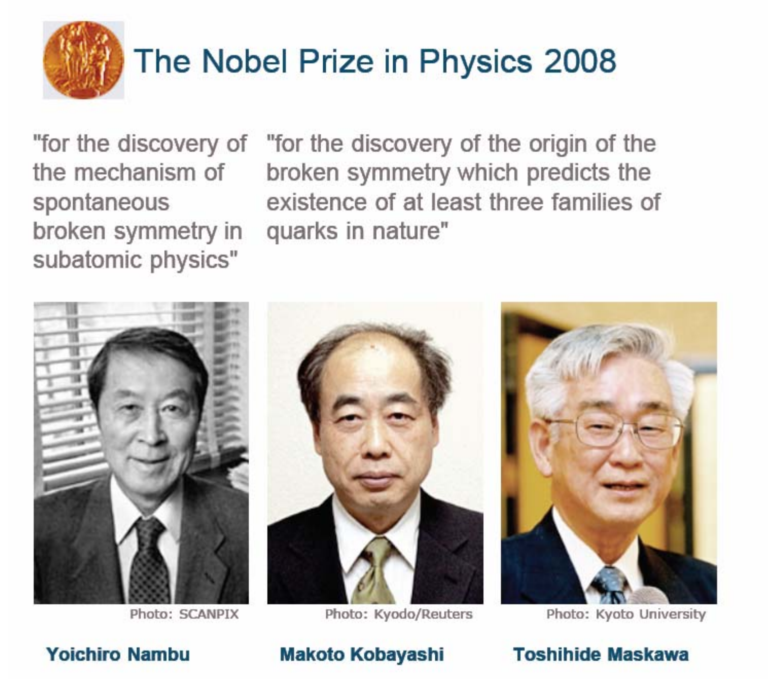
⇦ 12 gauge fields

⇦ Not yet directly observed

*) S. L. Glashow, A. Salam and S. Weinberg, 1967/8

History of Experimental Tests of Standard Model

1967/8	Standard Model, S. L. Glashow, A. Salam and S. Weinberg
1971	Renormalizability of non-abelian gauge theories, G. `t Hooft and M. Veltman
1973	Asymptotic freedom of QCD, D. Gross, D. Politzer and F. Wilzcek
1973	Discovery of Neutral Currents: „Z-Boson exchange“ (Gargamelle, CERN)
1974	Discovery of the 4th quark (SLAC / BNL)
1979	Discovery of the gluon (DESY)
1983	Observation of W and Z bosons (UA1/2, CERN)
1989	Start of LEP I: Z factory
	Z properties, measurement of radiative corrections, prediction of topmass
1995	Discovery of the Top-Quark at TEVATRON
1996	Start of LEP II: W Pair production and Higgs search (until Nov 2000)
2001	Start of TEVATRON Run II: Precision measurement of Top-Quark and W-Boson properties, B physics
2009	Start of LHC: Discovery of the Higgs boson ?



The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: SCANPIX

Photo: Kyodo/Reuters

Photo: Kyoto University

Yoichiro Nambu

Makoto Kobayashi

Toshihide Maskawa

1.1 Leptons and Quarks

Point-like, spin ½ , elementary building blocks of matter
$< 10^{-18}$ m

	Flavor-Generation	$Q\ [e]$
Leptons	$\begin{pmatrix}\nu_e\\ e\end{pmatrix}\ \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}\ \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}$	$\begin{pmatrix}0\\ -1\end{pmatrix}$
Quarks	$\begin{pmatrix}u\\ d\end{pmatrix}\ \begin{pmatrix}c\\ s\end{pmatrix}\ \begin{pmatrix}t\\ b\end{pmatrix}$	$\begin{pmatrix}+2/3\\ -1/3\end{pmatrix}$

Doublets reflect structure of weak interaction

Anti-particles with opposite charge to each lepton/quark

Lepton Properties

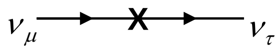
- All leptons exist as free particles
- Lepton number conservation

$$
\begin{array}{llll}
 & \pi^+ & \to \mu^+ & \nu_\mu \\
L_\mu = 0 & & \to -1 & 1
\end{array}
$$

		mass·c²	lifetime	Lepton number
	e⁻	511 keV	∞	L_e=1
	μ^-	106 MeV	2.2 μs	L_μ=1
1975	τ^-	1.78 GeV	0.3 ps	L_τ=1
	ν_e	< 2 eV	∞	L_e=1
	ν_μ	<190 keV	∞	L_μ=1
2000	ν_τ	<18.2 MeV	∞	L_τ=1

Direct measurements

Neutrino oscillations ⇔ Lepton flavor violation



In the **Standard Model** neutrinos are assumed to be massless. Recently clear evidence for **neutrino oscillations** have been observed: explained with **non-zero masses**. Mass difference are very small: $m_\nu < 3$ eV for all Neutrinos

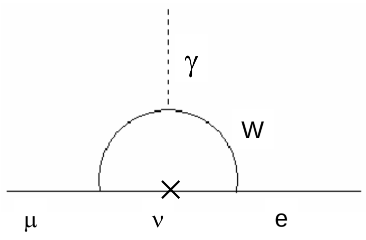
Impressive limits for lepton flavor violation of charged leptons:

$$BR_{\mu\to e\gamma} = \frac{\Gamma(\mu\to e\gamma)}{\Gamma(\mu\to e\bar{\nu}_e\nu_\mu)} < 1.2\cdot 10^{-11}$$

$$BR_{\mu\to e} = \frac{\Gamma(\mu^- + (Z,A) \to e + (Z,A))}{\Gamma(\mu^-(Z,A)\to \nu_\mu + (Z-1,Z))} < 8\cdot 10^{-13}$$ Muon capture

proposed: MEG $BR_{\mu\to e\gamma} < 5\cdot 10^{-14}$ proposed: MECO $BR_{\mu\to e} < 8\cdot 10^{-17}$ (Al)

Standard model process:



Effect of neutrino mass is "GIM suppressed" by a factor of $(\Delta m_\nu^2/M_W^2)^2 \sim 10^{-50}$ and hence unobservable

SUSY-GUT scenarios predict larger BR for LFV decays.

Quark Properties

- Quarks are confined in hadrons: mesons ($q\bar{q}$) or baryons (qqq)
- Quark masses cannot be measured directly: mass is well defined only for free particles
- Heavy quarks: <u>Constituent quark masses.</u> Determination from observed hadron mass spectra + assumed binding potential

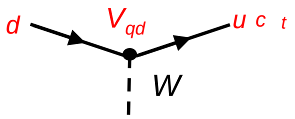
  For the light quarks (u,d,s,) the masses are estimates of the "<u>current masses</u>" which appear in the QCD Lagrangian
- Quarks carry color charge

Interesting question: do we need massive quarks to build massive hadrons ?

	quark mass$\cdot c^2$	Flavor number
u, d	~5 and ~8 MeV	I=±1/2
s	80 - 130 MeV	S=-1
c	1.15 - 1.35 GeV	C=+1
b	4.6 – 4.9 GeV	B=-1
t	~175 GeV	T=+1

1995

Flavor changing weak currents



There are no flavor changing neutral currents (no FCNCs).

Questions:

- Why are there three generations ?
- Mass hierarchy ?
- Charges = 0, 1/3e, 2/3e or e ?
- Is there a symmetry which explains the flavor sector ?

If we are honest, we don't really understand the flavor sector of the SM

1.2 Fundamental interactions

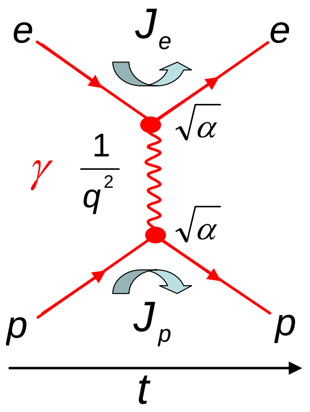
IA	Mediator boson	strength
Strong	Gluon g / massless	1
Elektro-magnetic	Photon / massless	~10^{-2}
weak	$W^{\pm}$ Z^0 / massive	~10^{-6}
Gravitation	Graviton / massless	~10^{-39}

M_W~83 GeV

M_Z~91 GeV

- Forces are mediated by virtual field quanta (bosons)
- Virtual bosons transfer energy and momentum for which in general $m^2_{Boson} \neq E^2 - p^2$ (off mass-shell)

a.) Electro-magnetic interaction



ep scattering:

$$M_{fi} \sim J_e \cdot \sqrt{\alpha} \cdot \frac{1}{q^2} \cdot \sqrt{\alpha} \cdot J_p \sim \frac{\alpha}{q^2}$$

Diff. cross section:

$$d\sigma = |M_{fi}|^2 \times \mathrm{PS} \sim \frac{\alpha^2}{q^4} \times \mathrm{PS}$$

Phase space

(Rutherford formula)

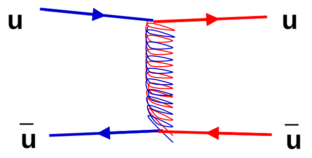
$$\alpha = \alpha_{QED} = \frac{e^2}{4\pi\varepsilon_0\hbar c} \underset{\substack{\uparrow \\ \hbar = c = 1}}{=} \frac{e^2}{4\pi}$$

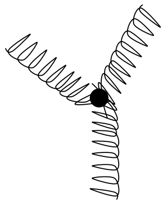
b.) Strong interaction

Color charges and gluons.

- Quarks and anti-quarks carry 3 different (anti) color charges
- Interaction is mediated by 8 massless colored gluons (spin 1)
- Color symmetry is exact: strong interaction only depends on color and is independent of quark flavor
- Color charge of gluons ⇒ gluon-gluon coupling: triple gluon vertex

q: r g b **$\bar{q}$: $\bar{r}$ $\bar{g}$ $\bar{b}$**





How strong is “strong” ?

Use decay times of the following kinematically similar Σ decays:

Σ decays	Q-value	Decay time	IA
$\Sigma^0(1192, \lvert uds\rangle) \to \Lambda\gamma$	74 MeV	10^{-19} s	e.m.
$\Sigma^+(1189, \lvert uus\rangle) \to p\pi^0$	189 MeV	10^{-10} s	weak
$\Sigma^0(1385, \lvert uds\rangle) \to \Lambda\pi^0$	208 MeV	10^{-23} s	strong

Q value is a measure of phase space

For the decay times one finds

$$\tau = \frac{\hbar}{\Gamma} \sim \frac{1}{\lvert M_{fi}\rvert^2} \sim \frac{1}{\alpha_{IA}^2}$$

α_{IA} = effective coupling of decay process

Neglecting kinematics:

$$\frac{\tau(\Sigma \to \Lambda\gamma)}{\tau(\Sigma \to \Lambda\pi^0)} \approx \frac{\alpha_s^2}{\alpha_{em}^2} \approx 10^4$$

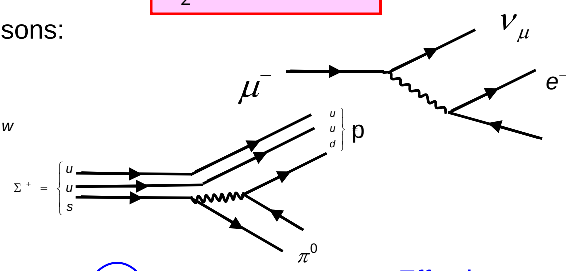
with $\alpha_{em} = \frac{1}{137} \Rightarrow \alpha_s \approx 1$

c.) Weak interaction

$$M_W \approx 80\,GeV/c^2$$
$$M_Z \approx 91\,GeV/c^2$$

Mediated by massive bosons:

$$M_{fi} \sim g_w \cdot \frac{1}{q^2 - M_W^2} \cdot g_w$$



for Σ decay: $q^2 << M_W^2$: $M_{fi} \sim \frac{g_w^2}{M_W^2} \sim G_F \approx 10^{-5}\,\text{GeV}^{-2}$

Effective weak coupling α_w is small

(massive propagator leads to suppression)

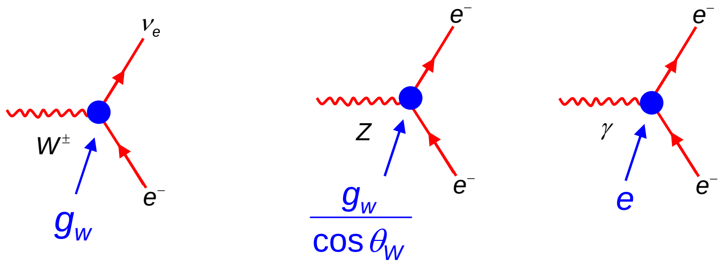
Estimate the strength from $\Sigma \to$ **p** π^0 decay

$$\frac{\tau(\Sigma \to \Lambda\gamma)}{\tau(\Sigma \to p\pi^0)} \approx \frac{\alpha_w^2}{\alpha_{em}^2}$$

$$\Rightarrow \frac{\alpha_w}{\alpha_{em}} \approx 10^{-5} \ldots 10^{-4}$$

"effective weak coupling"

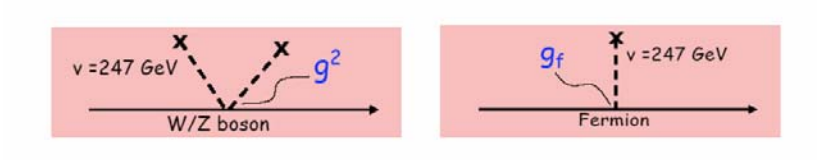
Electroweak unification



$$g_w = \frac{e}{\sin\theta_W}$$

1.3 Higgs Boson = additional scalar Field

Scalar Higgs field couples to the boson fields and fermion fields and generates through the coupling masses:



$$\frac{g^2 v^2}{4} W_\mu W^\mu + \frac{(g^2+g'^2)v^2}{8} Z_\mu Z^\mu - g_f \frac{v}{\sqrt{2}} \bar{\Psi}\Psi$$

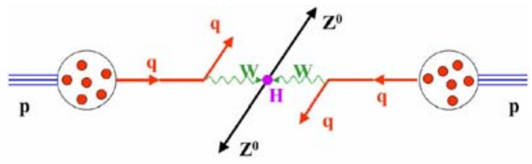
boson mass terms

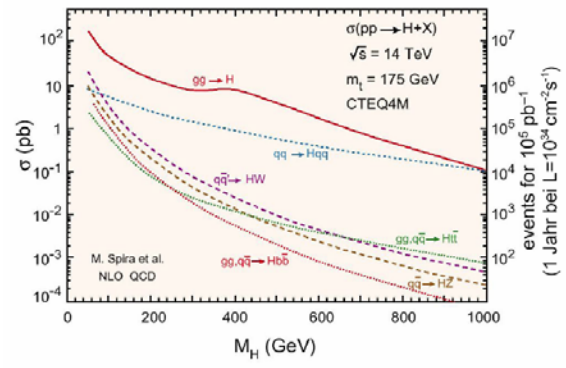
fermion mass terms

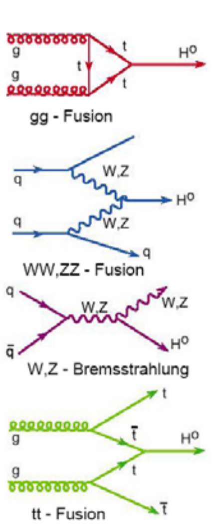
$$M_W = \frac{1}{2}\upsilon g \qquad \frac{M_W}{M_Z} = \frac{g}{\sqrt{g^2+g'^2}} = \cos\theta_w$$

$$M_Z = \frac{1}{2}\upsilon\sqrt{g^2+g'^2} \qquad \uparrow \; g\sin\theta_w = g'\cos\theta_w$$

Higgs production in Proton-Proton Collisions

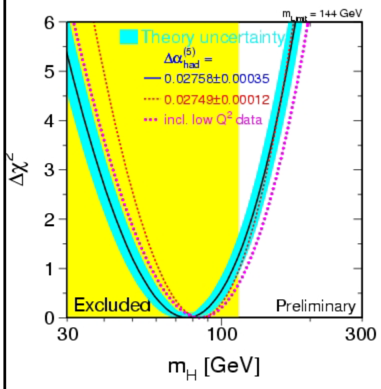


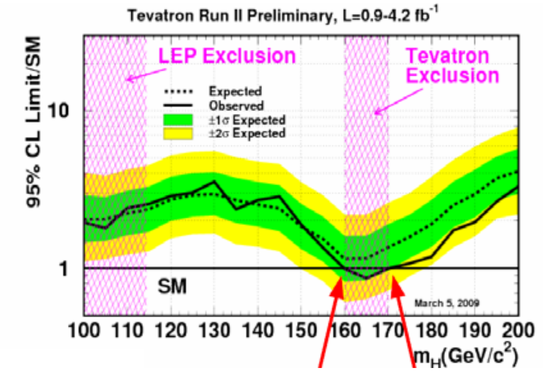




Current Higgs Limits:

Moriond 2009

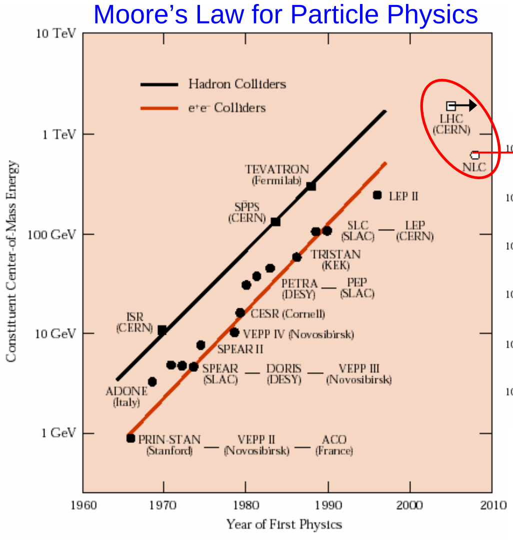




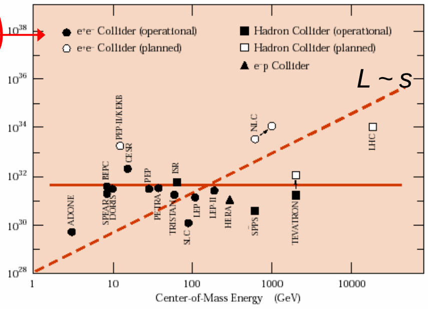
2. Experimental tools

2.1 Particle accelerators

Moore's Law for Particle Physics



Cross sections $\sigma \sim \frac{1}{s}$



From W.K.H.Panofsky: The evolution of particle accelerators and colliders

Large Hadron Collider

Momentum at collision	**7 TeV/c**
Momentum at injection	450 GeV/c
Dipole field at 7 TeV	8.33 Tesla
Circumference	26658 m

High beam energy in LEP tunnel
superconducting NbTi magnets at 1.9 K

Luminosity	**10^{34}**	**$cm^{-2}s^{-1}$**
Number of bunches	2808	
Particles per bunch	$1.1 \cdot 10^{11}$	
DC beam current	0.56	A
Stored energy per beam	**350**	**MJ**

Normalised emittance	**3.75**	**µm**
Beam size at IP / 7 TeV	15.9	µm
Beam size in arcs (rms)	300	µm

High luminosity at 7 TeV
very high energy stored in the beam

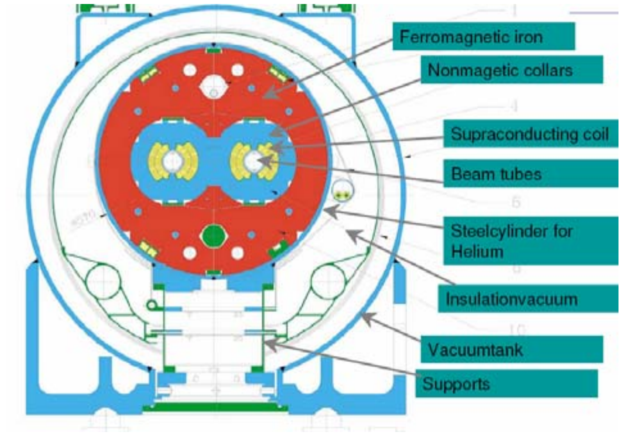
beam power concentrated in small area

Arcs: Counter-rotating proton beams in two-in-one magnets

Magnet coil inner diameter	**56**	**mm**
Distance between beams	194	mm

Limited investment
small aperture for beams

LHC Dipole Magnet



Dipole current: 12 KA (super-conducting, T=1.9 k), B = 8.3 T

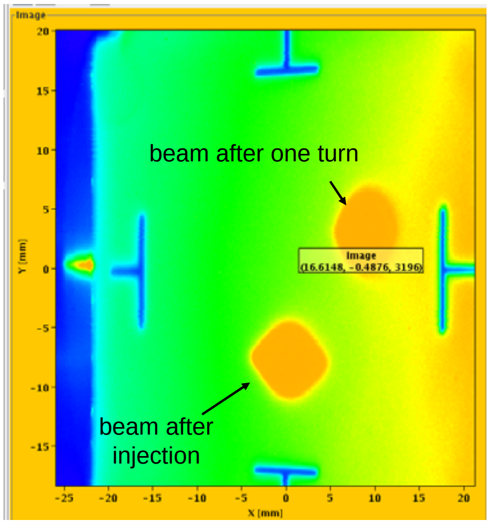
Energy stored in 1 dipole: 7.6 MJ in all 1232 dipoles: 9.4 GJ

First circulating beams on September 10th 2008

10:30
Beam1 around the ring (~1h).
~3 turns.

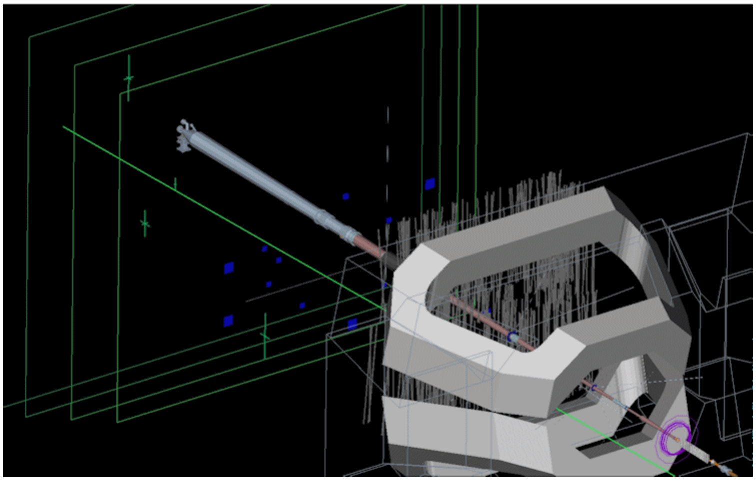
15:00
Beam2 around the ring.
3…4 turns.

Beam Position Monitor



First Beam Induced Particles (here in LHCb)

10.9. 2008 11:32:26 +50ns



Track reconstruction algorithm: *M. Schiller (HD)*

LHC Accident

- During ramping of one sector (S34, 8.7kA) : development of resistive zone (200 nΩ) in the super-conductive bus bar between quadrupole and neighboring dipole → loss of superconductivity

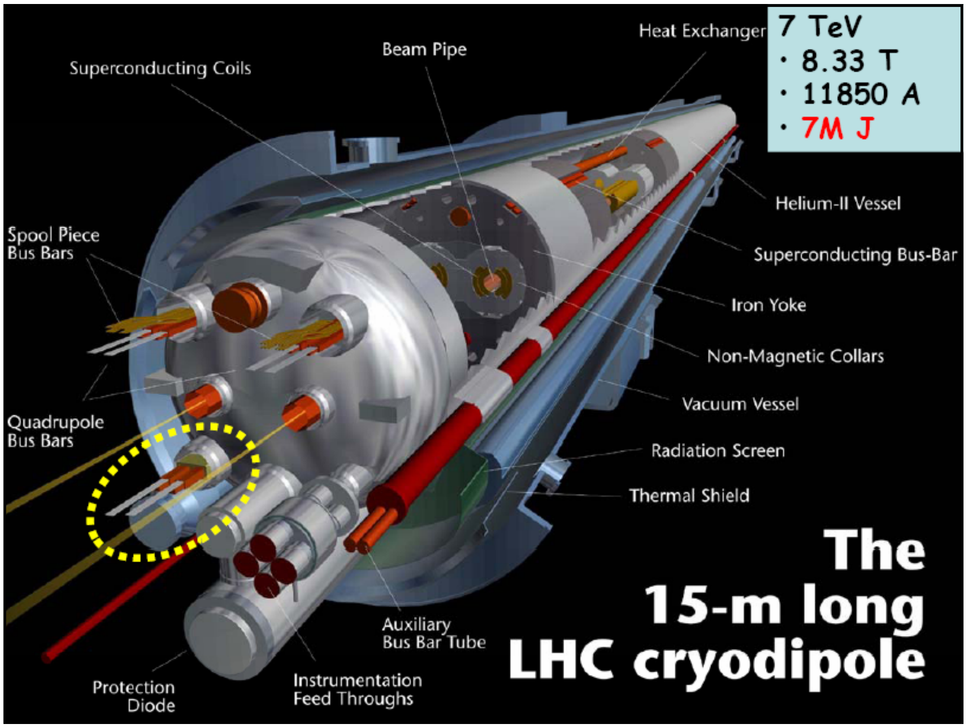
➡ Electrical arc developed, evaporated the power bar and punctured the He enclosure.

~2 t of LHe released into the insulating vacuum.

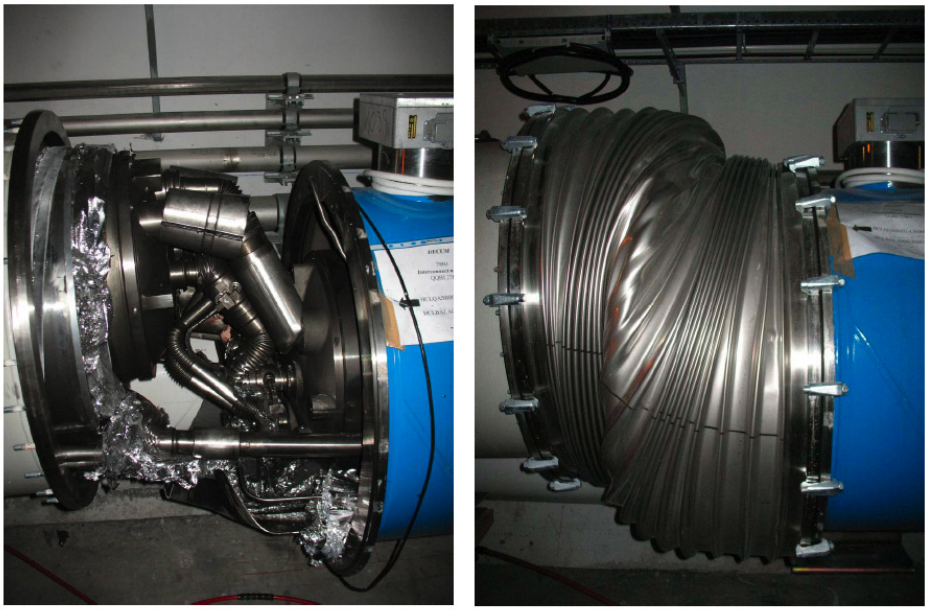
Of the 340 MJ stored in S34 only 2/3 went into dump resistors.

➡ Rapid pressure rise inside magnets.
Relief valves opened but could not handle the overpressure.
Pressure wave (estimated 4 - 5 bars) propagated until it reached vacuum barriers. Several tons of load on the barriers: displaced magnets, breaking anchors.

➡ 6 of 15t of LHe of S34 released into the tunnel (30000 m^3 He)

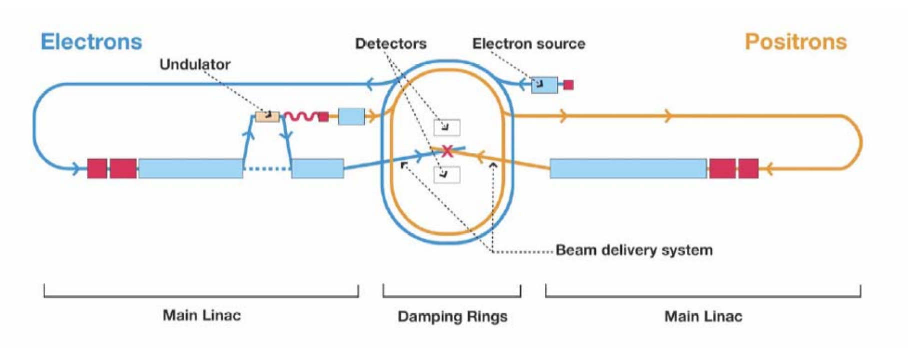


7 TeV
- 8.33 T
- 11850 A
- 7M J



Repair is progressing very well - expect beam in October!

International Linear Collider



30 km

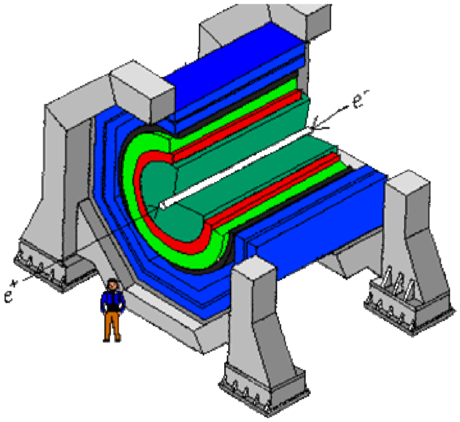
Center of mass energy: √s=500 … 1 TeV   Field gradients: ~35 MV/m

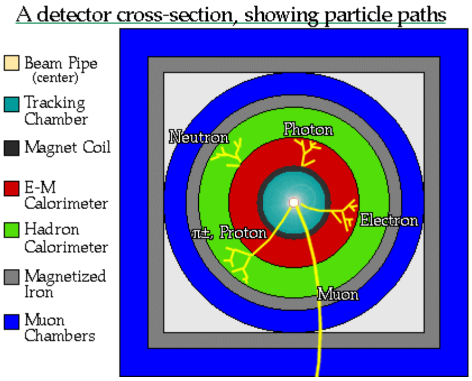
Remember: synchrotron radiation for circular machines

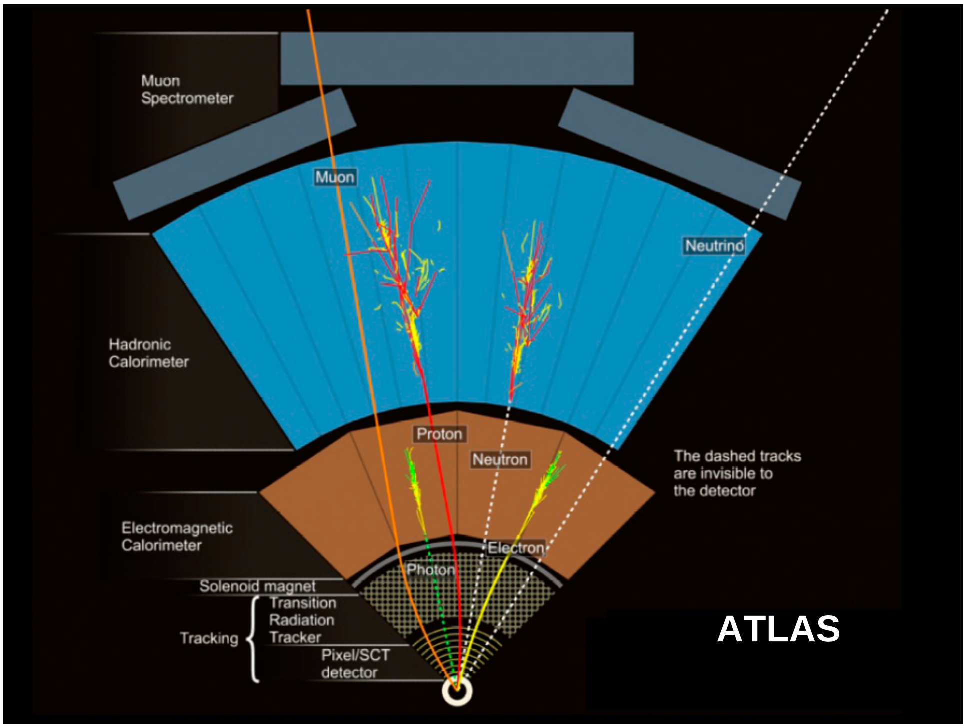
$$P = \frac{2\alpha}{3R^2}\beta^4\gamma^4 \xrightarrow{\beta\approx 1} = \frac{2\alpha}{3R^2}\left(\frac{E}{m}\right)^4$$

2.2 Particle detectors

Prototype of a modern compact particle detector







3. Natural units

$$\boxed{\hbar = c = 1}$$

With this choice one has the freedom to choose the unit of one other physical quantity. Typically: **[E] = GeV**

⇒ Units of all other quantities are defined

Quantity	HEP unit	⟶	SI unit
Energy	GeV		$1.6\cdot 10^{-10}\,J$
Mass	GeV	$\times 1/c^2$	$1.78\cdot 10^{-27}\,kg$
Time	GeV^{-1}	$\times \hbar$	$6.58\cdot 10^{-25}\,s$
Length	GeV^{-1}	$\times \hbar c$	$0.197\,fm$
Area	GeV^{-2}	$\times (\hbar c)^2$	$0.389\,mb$
Charge e	$\sqrt{4\pi\alpha}$	$\times (\hbar c \varepsilon_0)^{1/2}$	$1.6\cdot 10^{-19}\,C$
Temp Tk	GeV	$\times 1/k$	$1.16\cdot 10^{16}\,K$

Heaviside Lorentz Units: $\varepsilon_0 = \mu_0 = 1$

$$\alpha = \frac{e^2}{4\pi}$$

useful const.: $\hbar c = 197\ \mathrm{MeV}\cdot\mathrm{fm}$

$(\hbar c)^2 = 0.389\ \mathrm{GeV}^2\mathrm{mb}$