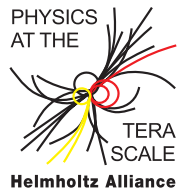


Physics at the Terascale



Daniel Wicke
(Johannes Gutenberg-Universität, Mainz)



What is the Terascale?

“Research in particle physics is motivated by the goal of attaining a fundamental description of the laws of physics.”

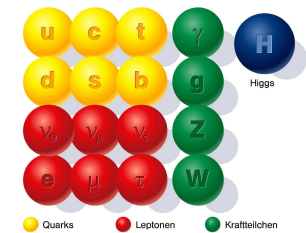
- Looking at fundamental description requires to probe elementary particles
- Probing the shortest possible distances requires to use the highest possible energies in the reactions (c.f. de Broglie wavelength)
- Technologically we can reach $\mathcal{O}(\text{TeV})$ (Energy reached by an electron in an electric field difference of $10^{12}V$)
 - Linear Collider: $0.5 \dots 1 \text{ TeV}$
 - Large Hadron Collider: up to 14 TeV (but protons aren't fundamental)

This lecture will discuss the basics of particle physics,
try to explain why the Terascale is believed to yield new insight,
and how we experimentally seek to find this new insight.

Outline

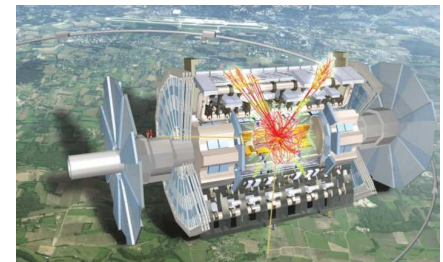
Part I: The Standard Model of Particle Physics

- Basic components of the SM
- Fundamental interactions (Feynman diagrams)
- Symmetry breaking and the Higgs boson



Part II: Challenging the Standard Model

- Successes of the Standard Model (LEP, HERA, Tevatron)
- Problems/Limits of the Standard Model
- The International Linear Collider
- The LHC and its experiments



Conclusion

The Standard Model of Particle Physics

The Particle Content

Matter (Fermions, Spin $\frac{1}{2}$)

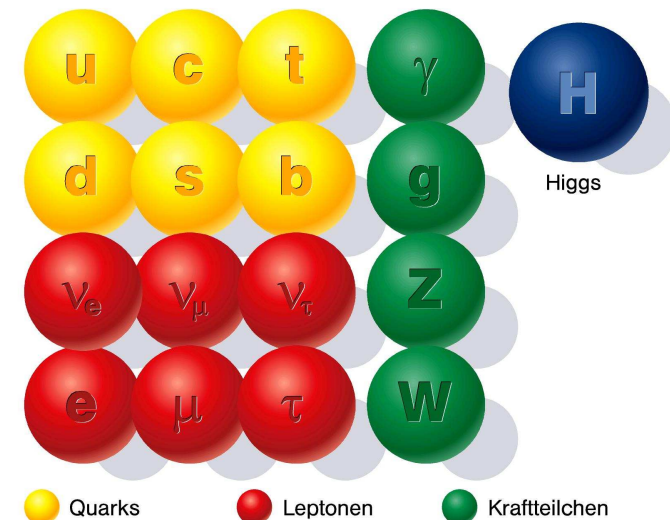
- **Ordinary Matter** Additional Generations Charge

up-Quarks	charm-Quarks	top-Quarks	$+2/3e$
down-Quarks	strange-Quarks	bottom-Quarks	$-1/3e$
Neutrinos	μ -Neutrinos	τ -Neutrinos	0
Electrons	Muons	Taus	$-1e$
- Each Fermion has its anti-particle

Interactions (Gauge Boson, Spin 1)

- Electromagnetism \Leftrightarrow Photon
- Strong nuclear force \Leftrightarrow Gluons
- Weak nuclear force $\Leftrightarrow W^{\pm}$ - and Z -bosons

Higgs (Scalar, Spin 0)

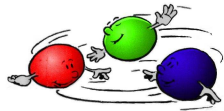


From Quarks to Hadrons

- Quarks do not occur as free particles, they always form hadrons.
- Each quark may have one of three different charges “colours” (anti-quarks have anti-colours)
- To form Hadrons one has to build colour neutral objects:

Baryons:

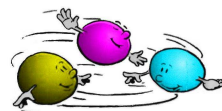
3 Quarks



Proton (uud), Neutron (udd)

Anti-baryons:

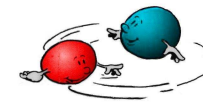
3 Anti-quarks



Antiproton ($\bar{u}\bar{u}\bar{d}$),
Antineutron ($\bar{u}\bar{d}\bar{d}$)

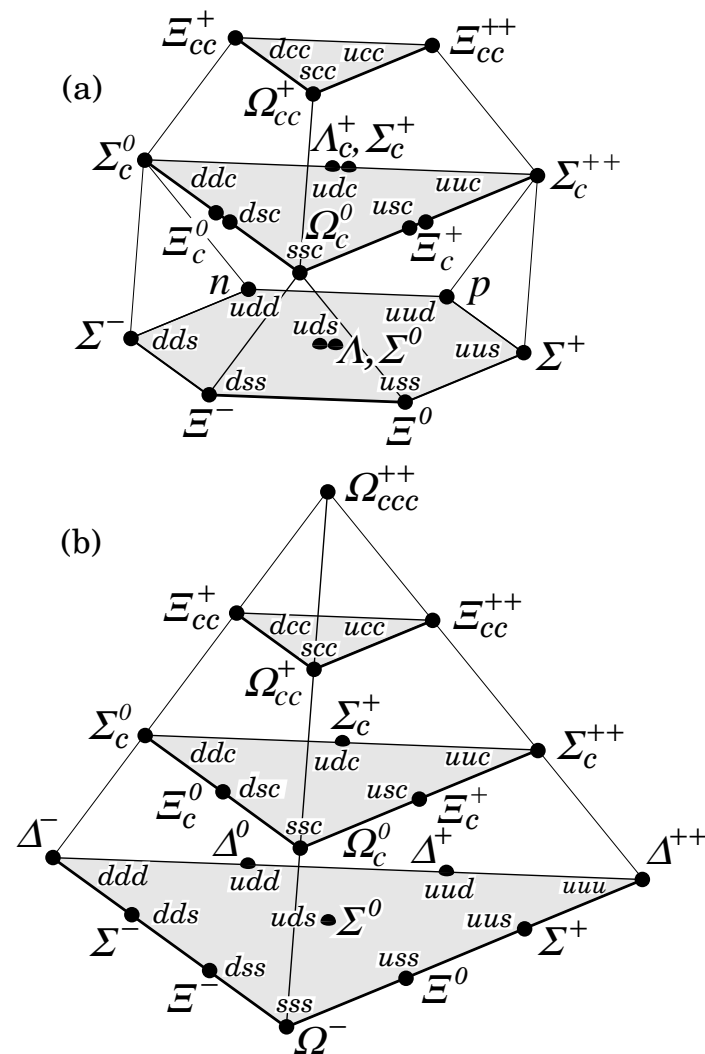
Mesons:

1 Quark and 1 Anti-quark



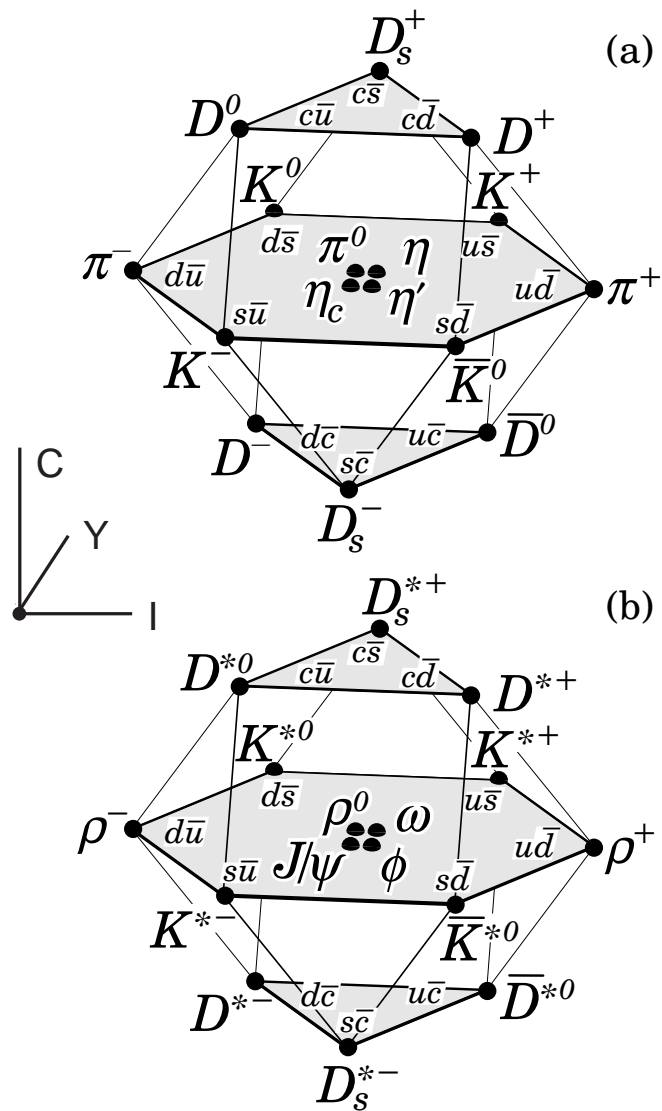
Pionen ($u\bar{u}, u\bar{d}, \dots$)

Baryon Multiplets



- Three quarks of spin $\frac{1}{2}$ can be combined to form spin $\frac{1}{2}$ or $\frac{3}{2}$
 - Two multiplets of baryons which have the same spin but varying quark content
 - Special role of the spin $\frac{3}{2}$ -baryons Λ^- , Λ^{++} and Ω^- .
 - Three quarks seem to be in the same quantum state
 - Forbidden by Pauli's exclusion principle: "No two identical Fermions may occupy the same quantum state"
- ⇒ We really need 3 colours

Meson Multiplets



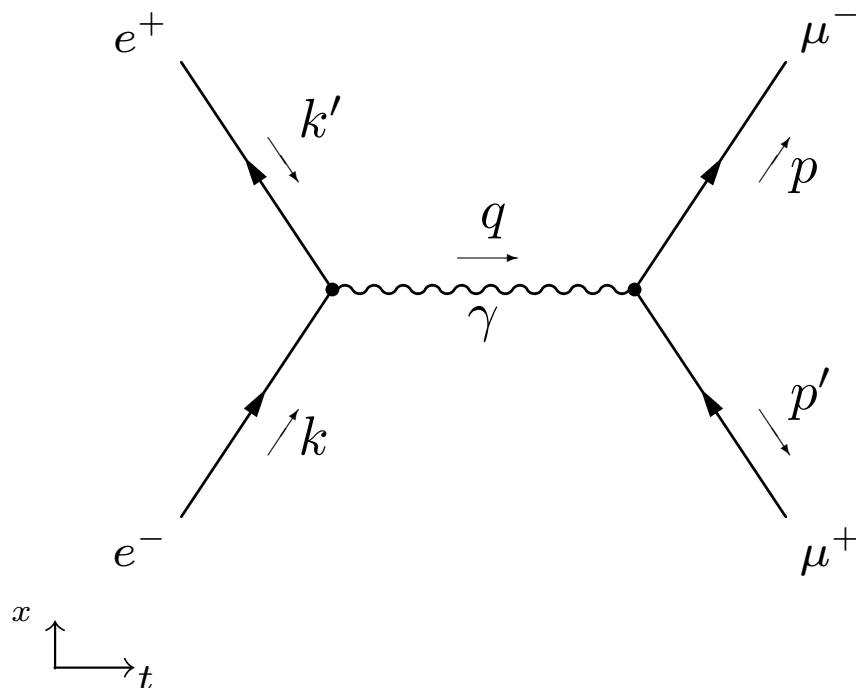
- Quark and Anti-quark can be combined to form spin 0 or 1 mesons.
- Two multiplets of mesons which have the same spin but varying quark content

Interactions

Feynman Diagrams

... as a graphical representation of processes of elementary particles:

Example: Electron and positron of momenta k and k' annihilate to form a photon which creates a muon pair of momenta p and p' .



- (Anti)Fermions as directed line
 - Fermions go along the line's direction
 - Antifermions go against the direction
- Bosons as wiggled lines
- Interaction as vertex of lines

Energy-momentum conservation at each vertex imposes $k + k' = q = p + p'$

Feynman Diagrams

... as a prescription to compute processes of elementary particles:

The cross-section for a reaction $A + B \rightarrow C + D$ is given by

$$d\sigma = \frac{|\mathcal{M}|^2}{j_e} d\Phi \quad (\text{Fermi's golden rule})$$

with

j_e	=	flux density of incoming particles	} process independent
$d\Phi$	=	phase space element	
\mathcal{M}	=	matrix element	} process dependent

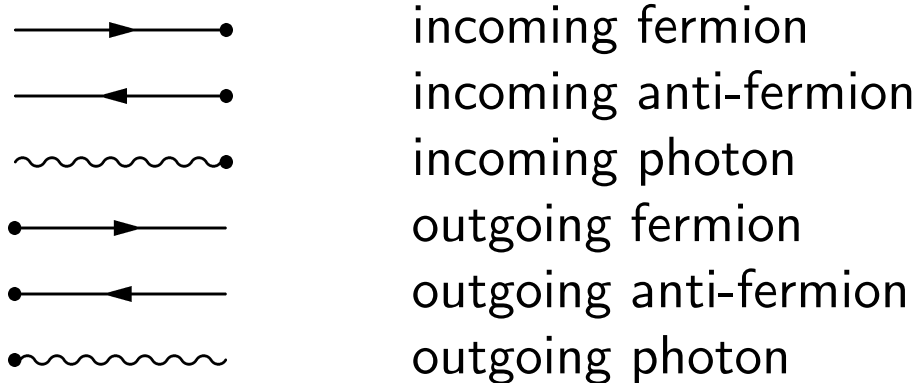
\mathcal{M} is computed from Feynman diagrams

- each diagram represents a mathematical term
- \mathcal{M} is the sum all possible diagrams which depict $A + B \rightarrow C + D$.

Which diagrams are allowed? What are their mathematical terms?

Building blocks of Feynman diagrams

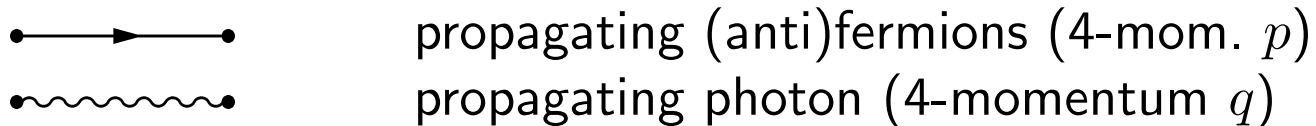
External lines



Mathematical term

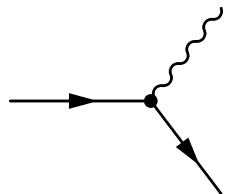
plane waves

Internal lines



“ $\frac{m + p}{p^2 - m^2 + i\delta}$ ”
 “ $\frac{1}{q^2 - M^2 + i\Gamma}$ ”

Vertices



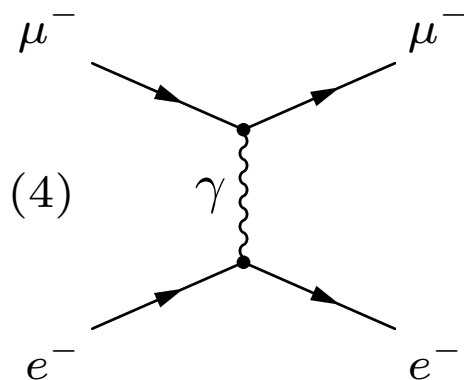
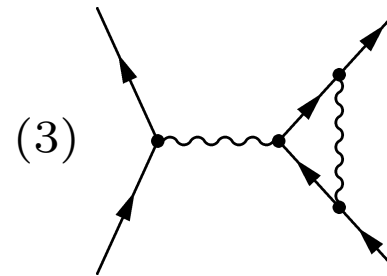
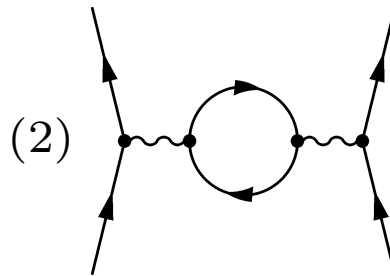
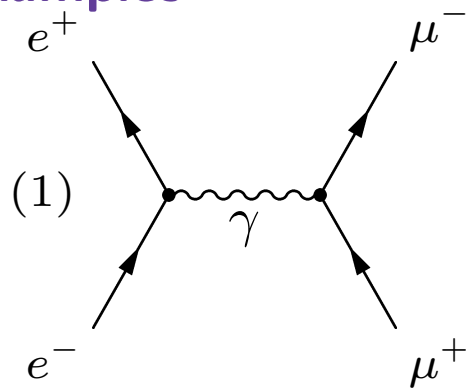
interaction of photon with (anti)fermion (charge e) $\sim e$

Drawing Feynman diagrams

These building blocks can be combined (almost) arbitrarily:

- Vertices need to be connected to the indicated number and type of lines
- Fermion lines need to keep their direction

Examples



(1) Muon pair production from e^+e^- annihilation

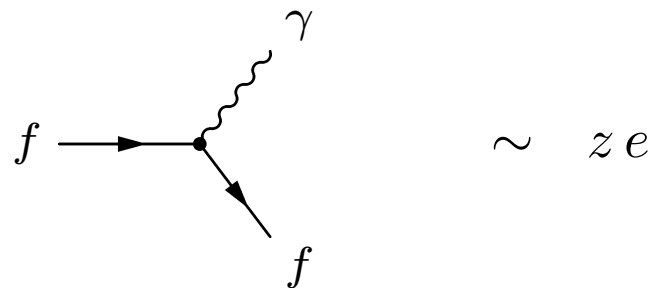
(2) Quantum correction (loop) in propagator

(3) Quantum correction (loop) at vertex

(4) Electron-Muon scattering


The Electromagnetic Interaction

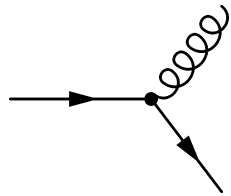
In terms of Feynman diagrams the electromagnetism is described by



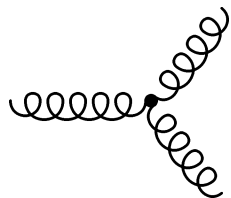
- For brevity one line per particle type.
- Implicitly included: the variation of incoming, outgoing and internal
- Fermions
- Photons
- and their interaction vertex
 - Fermion (charge ze) radiating a photon
 - Photon splitting to two fermions
 - To fermions annihilating to a photon(depending on the time direction in the diagram)

The Strong Nuclear Force

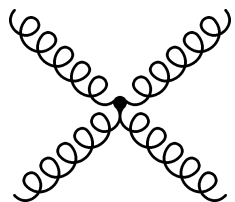
g  g



$\sim g_s$



$\sim g_s$



$\sim g_s^2$

- Only Quarks (=Fermions as before)
 - Note: Each quark actually is 3 Fermions corresponding, to the three colours
- Gluons (eight of them)
- Fermion gluon-vertex (similar to electromagnetic)
- Gluon self-coupling
 - Triple gluon vertex
 - Four gluon vertex

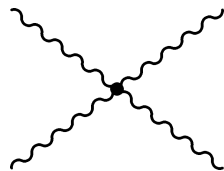
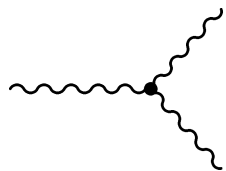
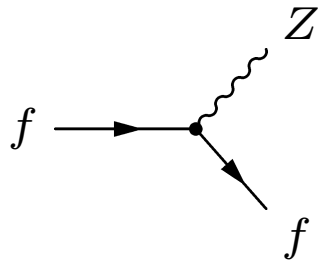
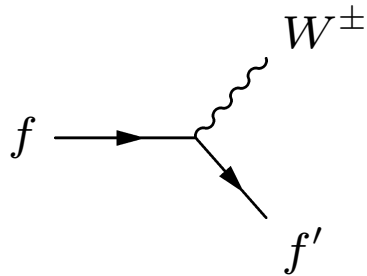
g_s is strong coupling

Note:

Summing the 3 colours or 8 gluons will give extra “colour factors” to the vertices

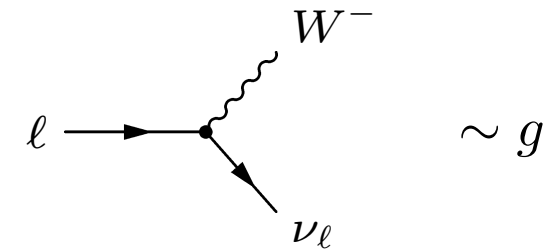
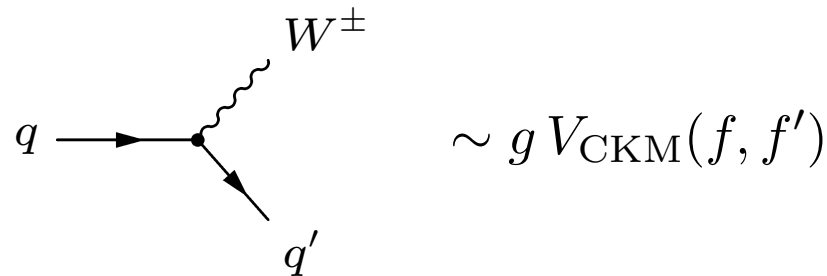
The Weak Nuclear Force

$$W^\pm, Z \sim \text{wavy line} \sim W^\pm, Z$$



- Three gauge bosons: W^+ , W^- , Z
- Fermion- W^\pm -vertex
 - Only for left-handed fermions
 - May change generation for quarks (flavour changing)
- Fermion- Z -vertex
 - At different strength for left- and right-handed fermions
 - No flavour change (FCNC) possible
- Triple boson coupling (ZW^+W^- or γW^+W^-)
- Four boson coupling

The Cabbibo-Kobayashi-Maskawa Matrix



- The flavour change at radiation of W^\pm is described by the CKM matrix

- $$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 0.97 & 0.23 & 0.0036 \\ 0.23 & 0.97 & 0.042 \\ 0.0087 & 0.041 & 0.999 \end{pmatrix}$$

(complex phases suppressed)

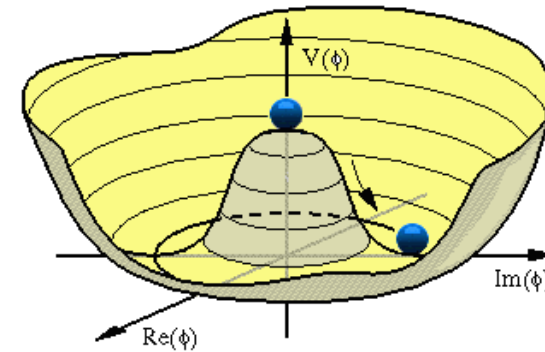
- In the SM the corresponding matrix for leptons is a unit matrix
i.e. Charged leptons change into their corresponding neutrino, only
But since 2000 we know that such neutrino mixing exists and is strong

The Higgs Mechanism

Problem: Experimentally, W^\pm and Z are massive, but the theory cannot be consistently written for massive vector bosons.

Solution: The Higgs Mechanism.

Add a scalar (Higgs) doublet Φ
with a weird potential: $-\mu^2\Phi\Phi^* + \lambda(\Phi\Phi^*)^2$



Giving mass to gauge bosons

- Lowest potential energy at $\Phi = \begin{pmatrix} 0 \\ v \end{pmatrix}$ ($v =$ vacuum expectation value)

Rewrite Φ as $\Phi = \begin{pmatrix} 0 \\ v \end{pmatrix} + \begin{pmatrix} \phi_1 + i\phi_2 \\ h + i\phi_3 \end{pmatrix}$

- $\phi_{1,2,3}$ behave like the missing longitudinal components of gauge bosons. They “give mass” to the three weak gauge bosons: W^+, W^-, Z .
- h is the physical Higgs boson

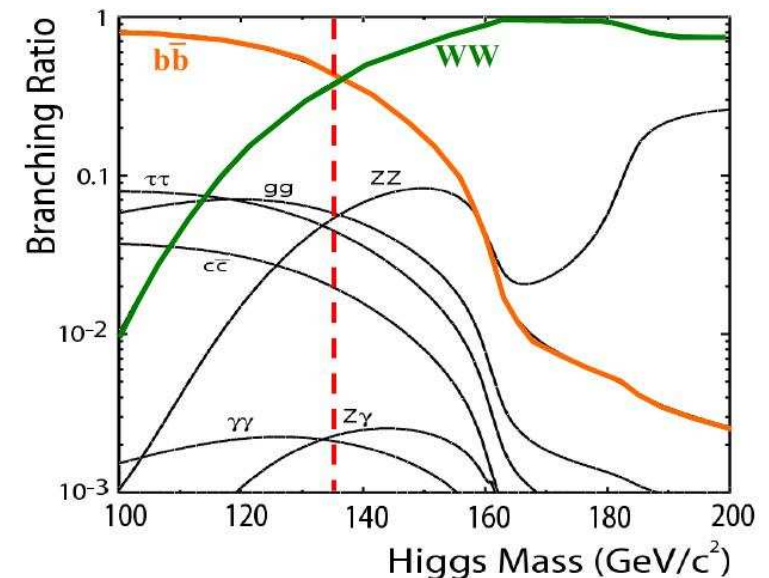
Giving mass to fermions

- Apply rewriting of Φ to Higgs-Fermion coupling:

$$\begin{array}{c} \Phi \\ | \\ \bullet \rightarrow \bullet \rightarrow \bullet \\ | \\ y \end{array} = \begin{array}{c} \bullet \rightarrow \bullet \rightarrow \bullet \\ | \\ vy \end{array} + \begin{array}{c} H \\ | \\ \bullet \rightarrow \bullet \rightarrow \bullet \\ | \\ y \end{array}$$

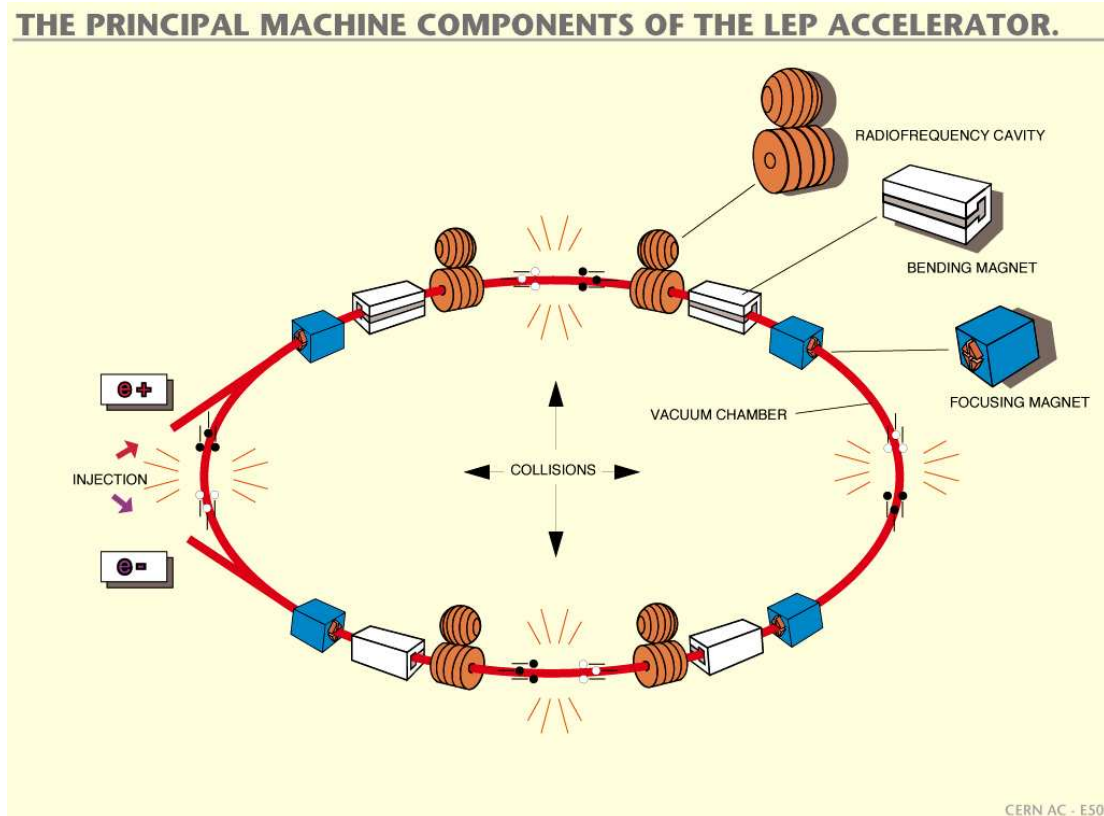
- Coupling of the physical Higgs to a Fermion is proportional to the Fermion mass
- Coupling to gauge bosons is “stronger”

Thus Higgs decays dominantly to $b\bar{b}$ if light or dominantly to W^+W^- if heavy (even above $t\bar{t}$ threshold, i.e. $M_H > 2m_t$)



Status of Experimental Verification of the Standard Model

The Concept of a Collider



- Acceleration
 - High frequency clystrons produce electrical fields that accelerate the particles
 - Particles lose energy through synchrotron radiation
- Bending
 - Dipol Magnets required to bend the beams

- Colliding
 - Straight sections with focussing elements to steer to collision

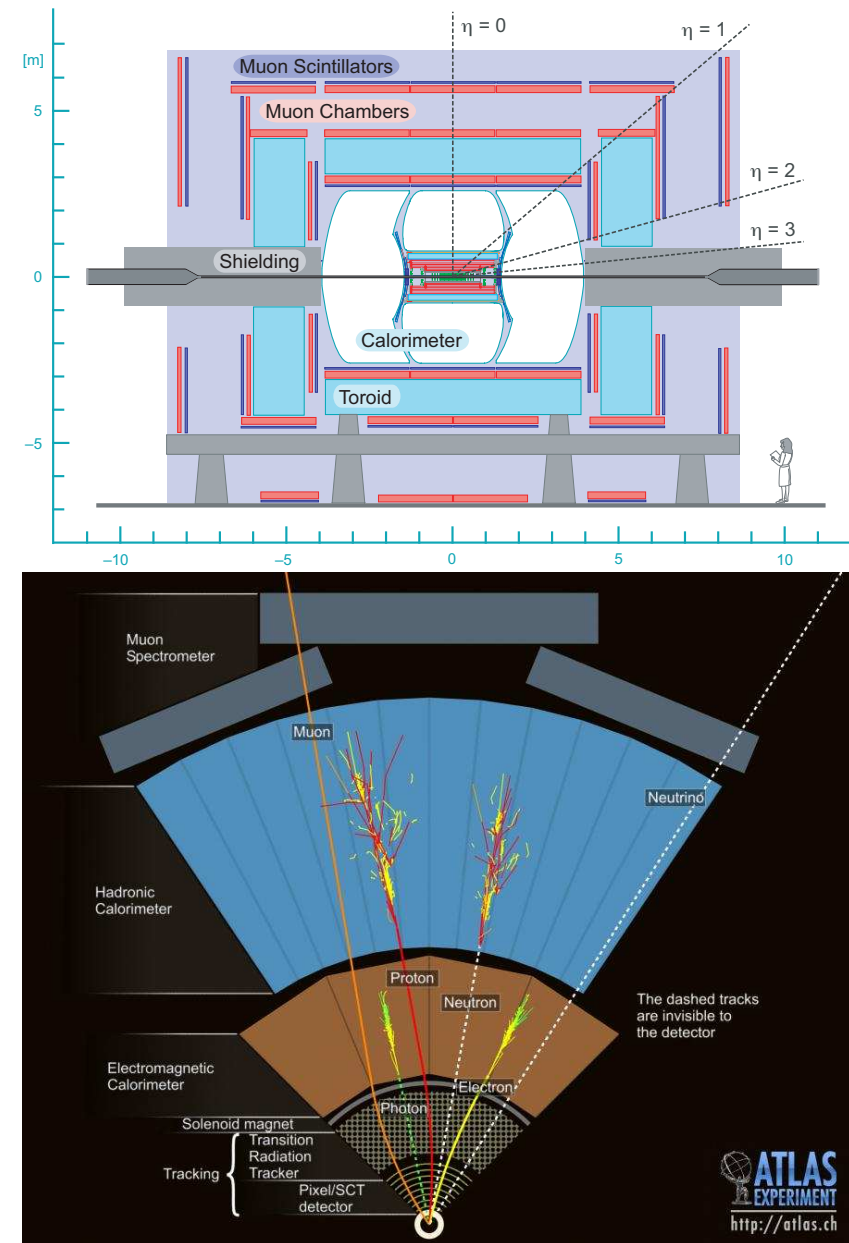
Particle Physics Detectors

E.g DØ: 4π general purpose detector:

- Tracking in 2T solenoid
 - Silicon microstrip
 - Scintillating fiber tracker
- Calorimetry
 - Uranium/liquid argon
- Muon spectrometer
 - 3 layers of drift tubes
 - Toroidal magnetic field

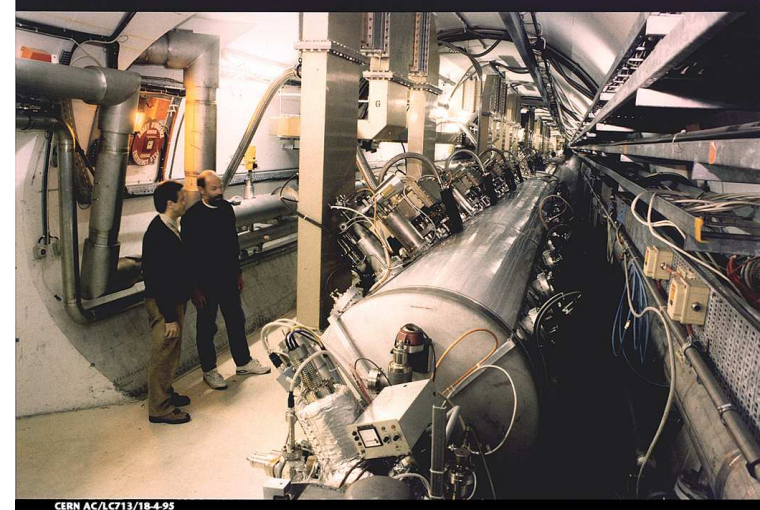
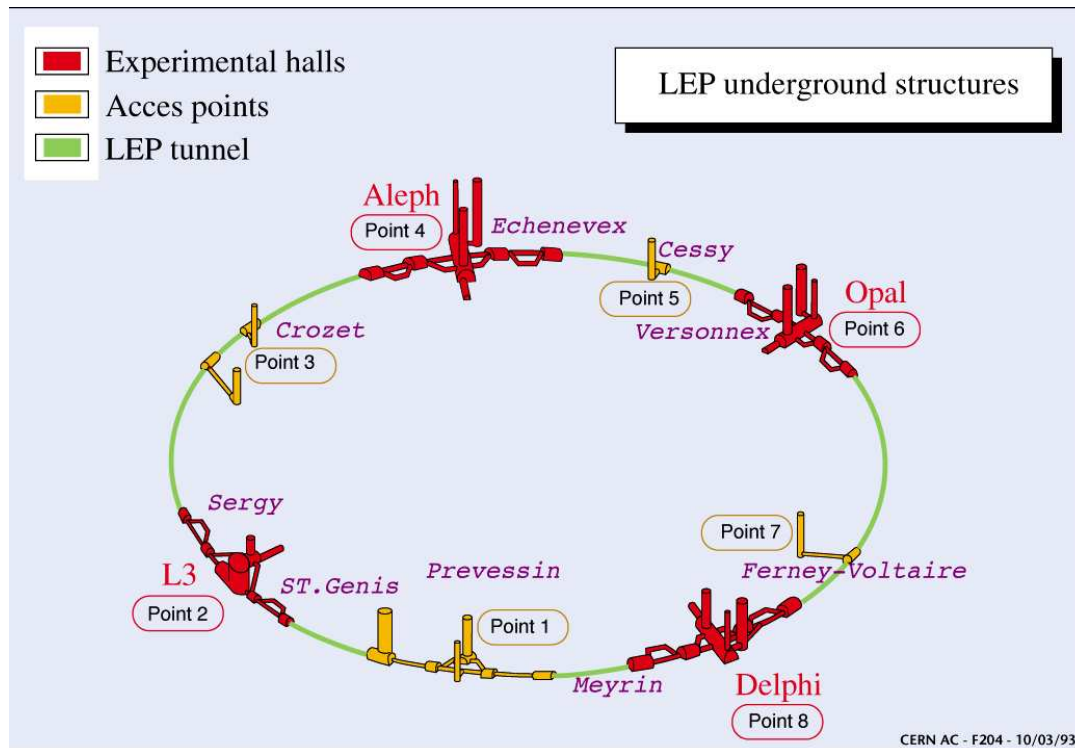
ATLAS: Same conceptual components

- different realisation



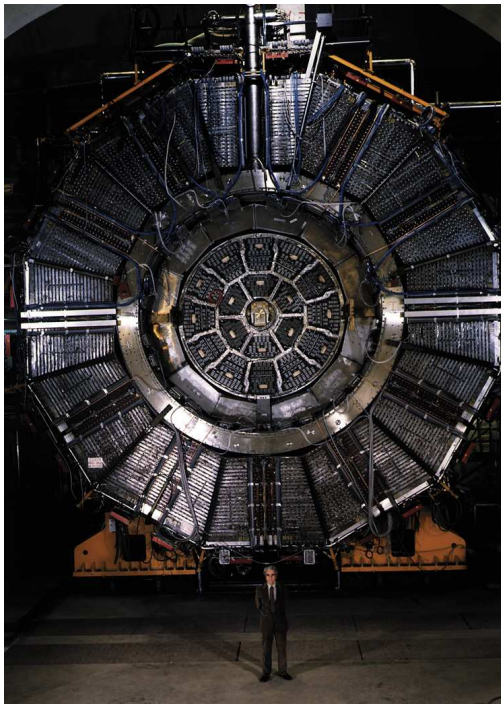
Large Electron Positron Collider (LEP)

- Circumference 27 km
- LEP1 1989 – 1995: $\sqrt{s} \simeq 91$ GeV
- LEP2 1996 – 2001: $\sqrt{s} \simeq 130 \dots 210$ GeV

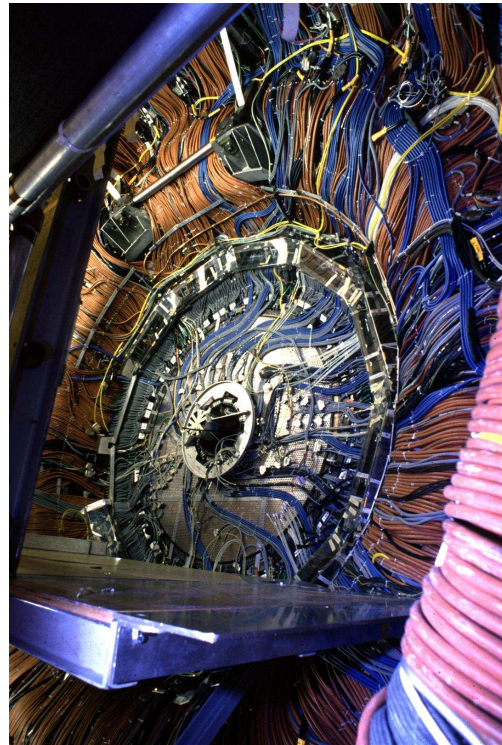


The LEP Experiments

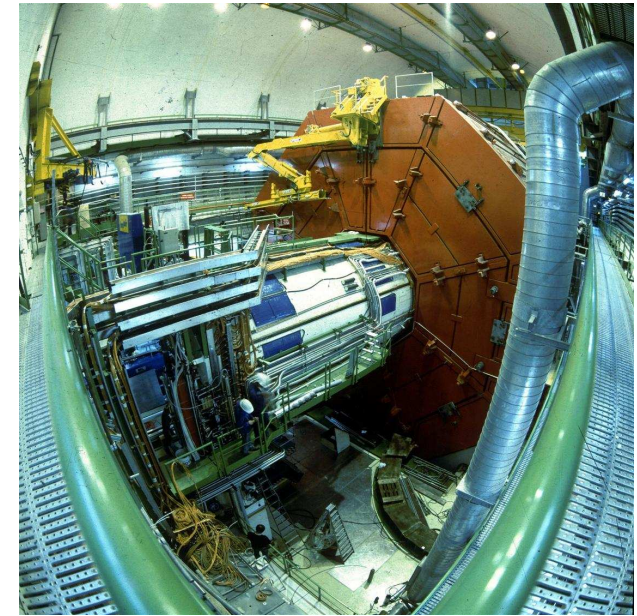
- Four omni-purpose 4π detectors
- Different strengths and weaknesses



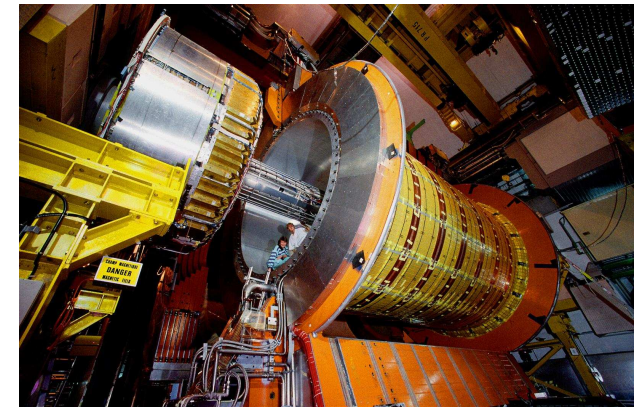
ALEPH



DELPHI



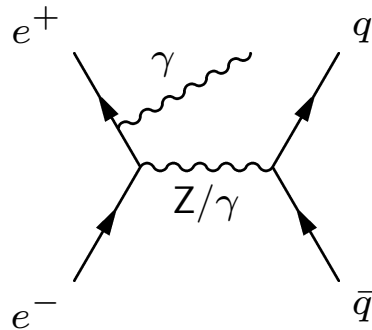
L3



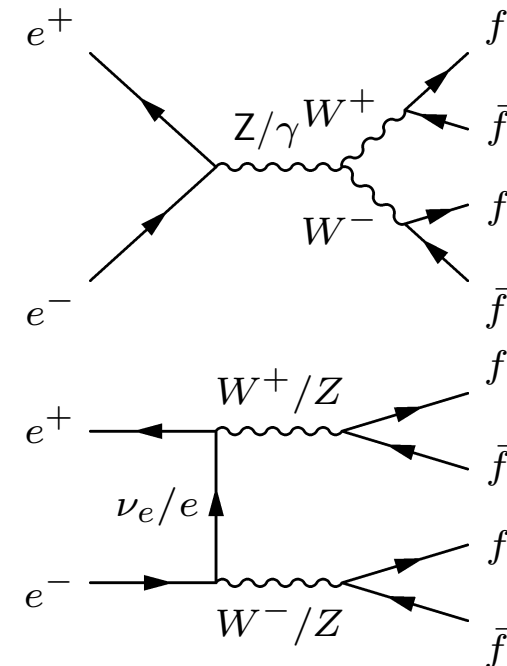
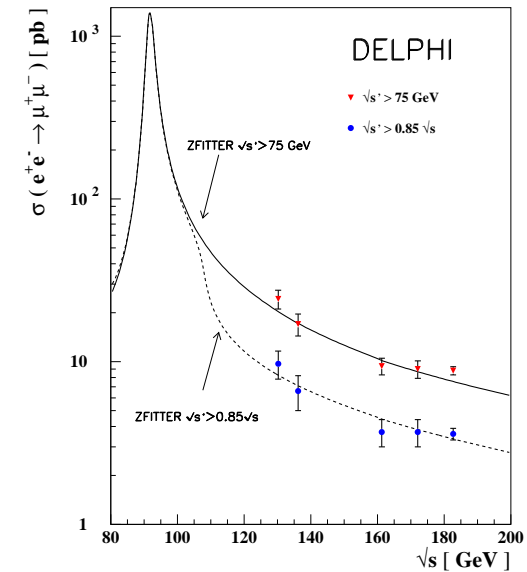
OPAL

Basic Processes at LEP

- LEP1 $\sqrt{s} \simeq 91$ GeV is dominated by Z production:

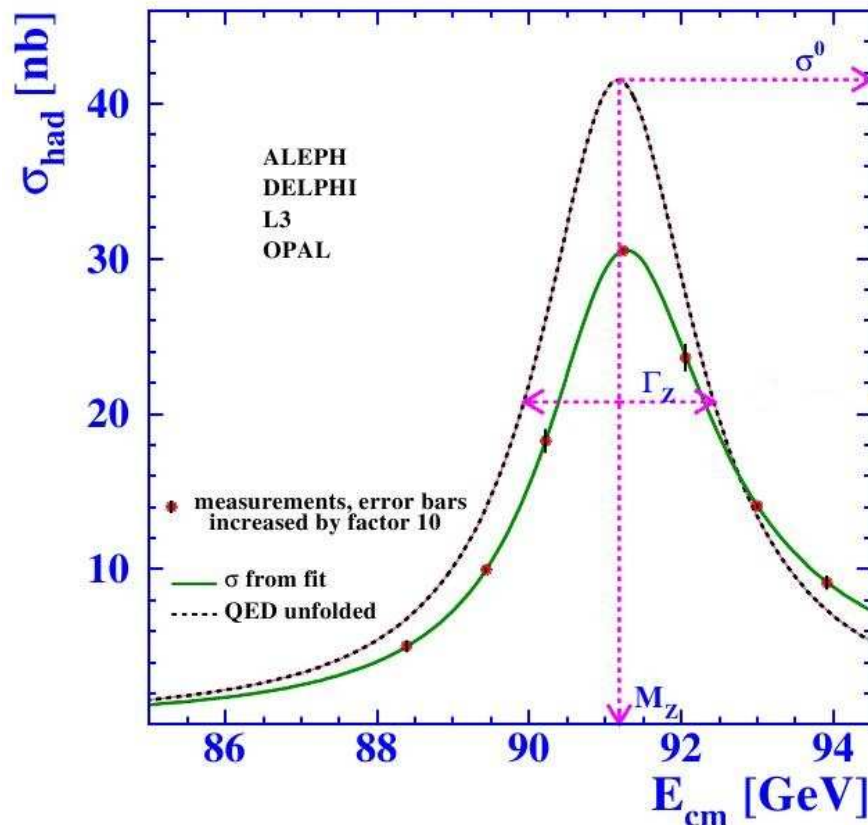


- LEP2 runs with increased beam energies three processes become more and more important:
 - Initial state photon radiation more important “Z-returns”
 - Above $\sqrt{s} \simeq 160$ GeV W -pair production
 - Above $\sqrt{s} \simeq 180$ GeV Z -pair production



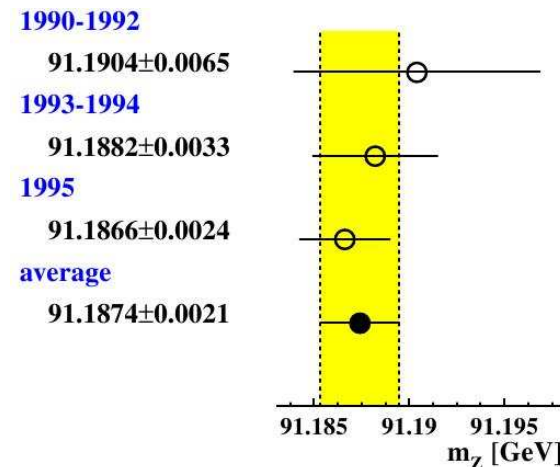
Z-Boson Mass and Width

Resonance peak of Z -production yields information about the mass and the width



$$\Gamma = 2.4953 \pm 0.0023 \text{ GeV}$$

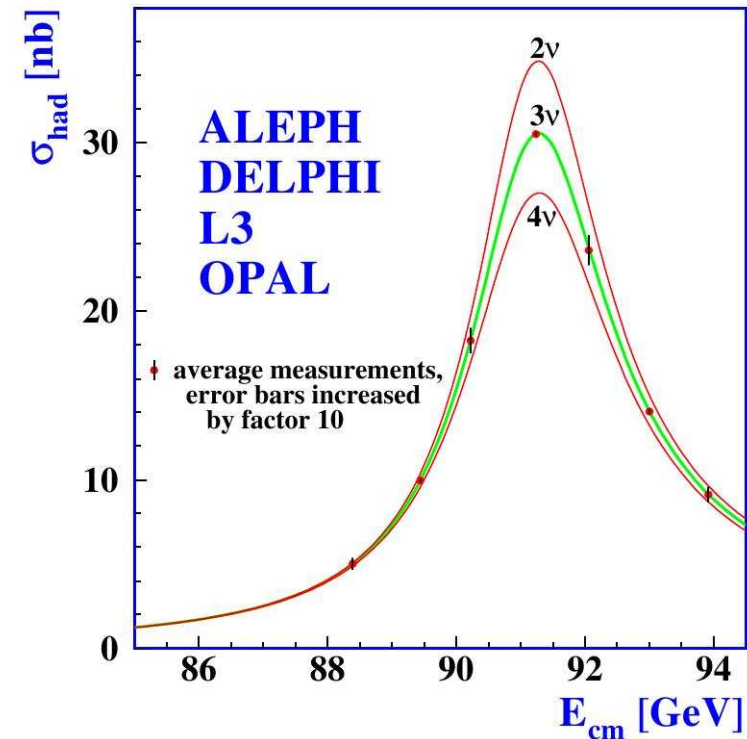
- LEP was run at ~ 7 energies near M_Z
 - Exact knowledge of \sqrt{s} required
- The data are shown with error-bars that are increased by a factor of 10.
- Radiative correction modify the shape



$$M_Z = 91.187 \pm 0.0021 \text{ GeV}$$

Number of Neutrino Flavours

- Decay width depends all possible decays
- Including neutrinos
- The more decays the wider



The number of neutrinos that occur in $Z \rightarrow \nu\bar{\nu}$ is $N_\nu = 2.9840 \pm 0.0082$.

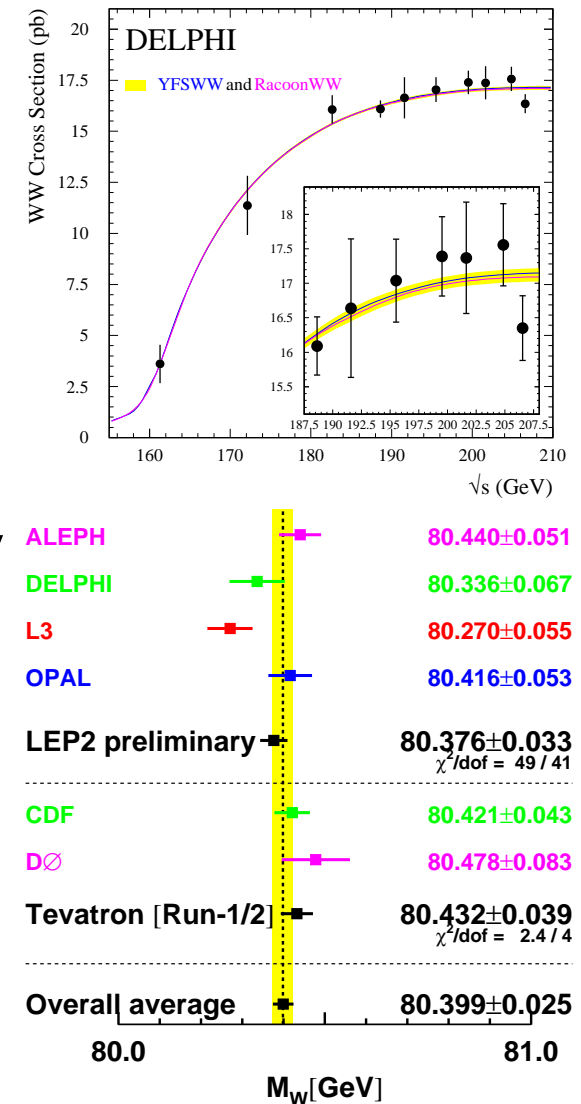
W Boson Mass (at LEP)

At centre-of-mass energies above 160 GeV
 W -boson pairs can be produced LEP

At LEP W -mass determined in two ways

- Cross-section of W production at $\sqrt{s} = 161$ GeV
 - At $\sqrt{s} = 161$ GeV cross-section is most sensitive
 - Invariant mass of decay products $\sqrt{s} = 161 \dots 208$ GeV ($e/\mu/\tau + \text{jets}$ and 4jets)
 - apply energy momentum conservation
 - apply equality of W^{+-} and W^{-} -mass
- \Rightarrow Build invariant mass from fitted objects

Combination of all LEP experiments and Tevatron
 $M_W = 80.399 \pm 0.025$ GeV



Forward Backward Asymmetry

- M_W and M_Z are related the ratio of left- and right-handed couplings, determined by the Weinberg angle θ_W

$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2} = 0.2226 \pm 0.00025$$

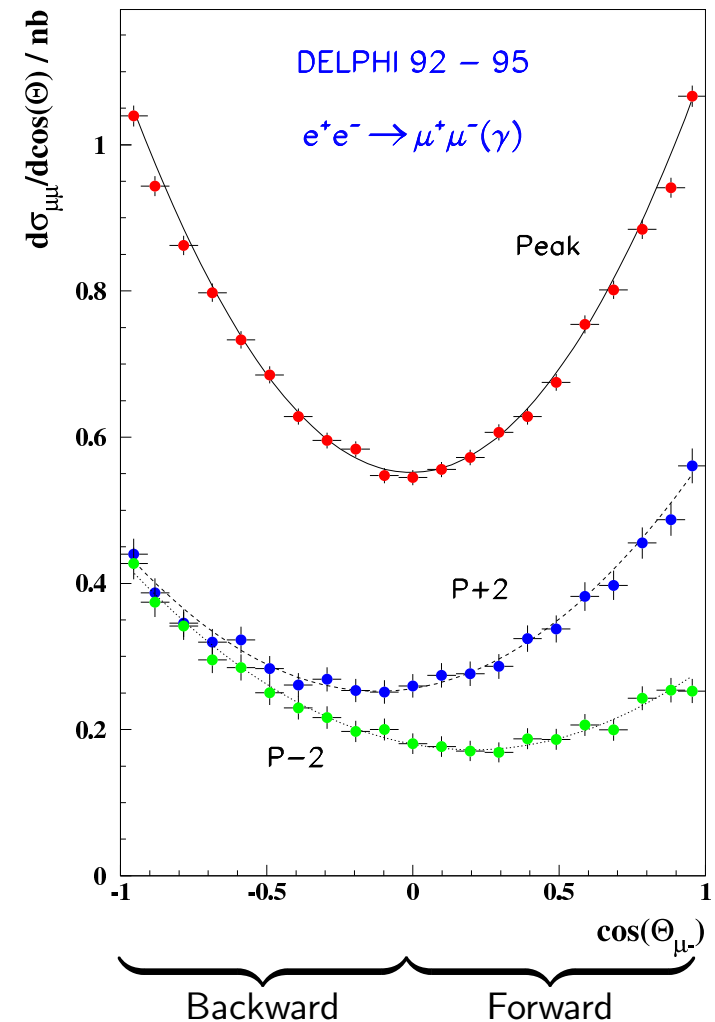
- The forward-backward asymmetry

$$A_{\text{FB}}^{(0,\mu)} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = 0.0169 \pm 0.0013$$

strongly depends on $\sin^2 \theta_W$

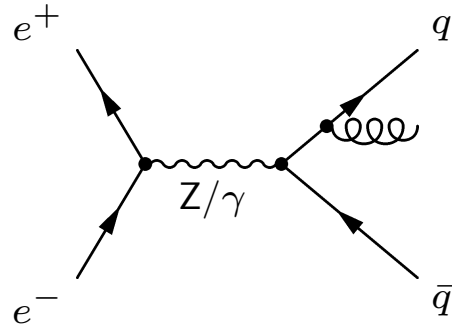
- Compare $\sin^2 \theta_W$ obtained from asymmetry with the one from the Boson masses

⇒ Excellent consistency (μ : 0.5σ , b : 2.5σ)

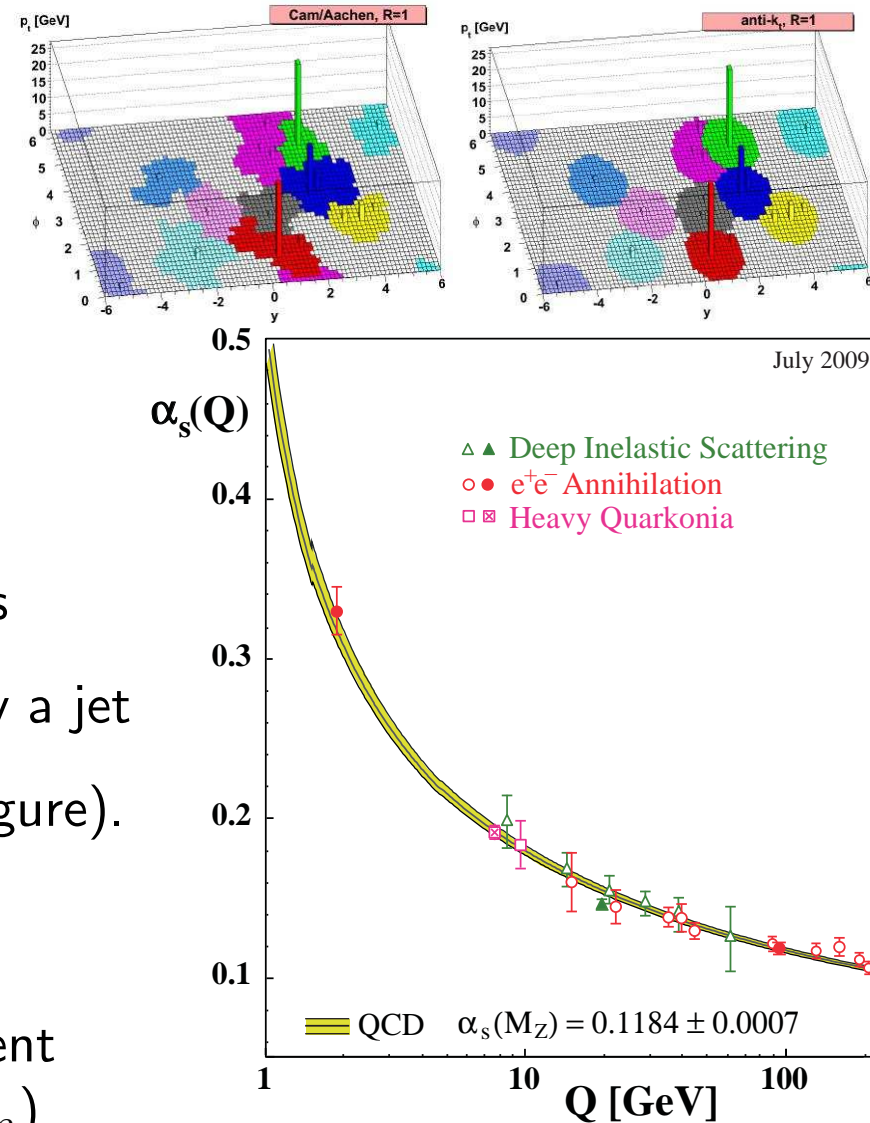


The strong coupling: α_s

- How often do $q\bar{q}$ radiate a gluon?

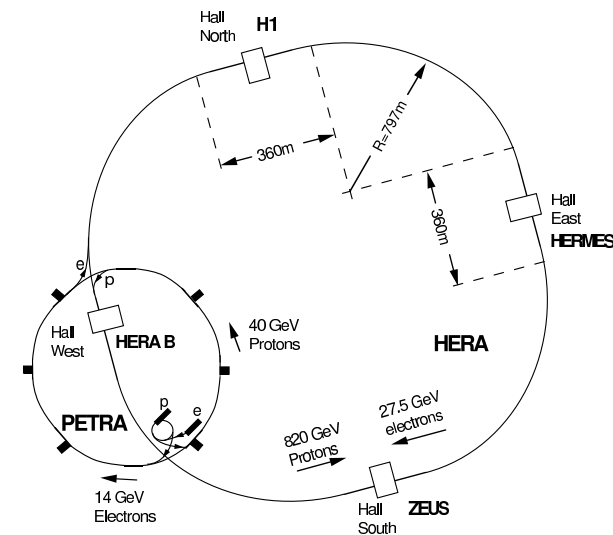


- But quarks fragment to Hadrons
- Observables are jets, sprays of hadrons
- One needs to specify what is meant by a jet
 - Many definitions exist (c.f. upper figure).
 - They are different observables.
 - All will depend on α_s
- The strong coupling is energy dependent
 $\alpha_s = 0.1184 \pm 0.007 \quad (\sim 16 \times \alpha_{\text{em}})$

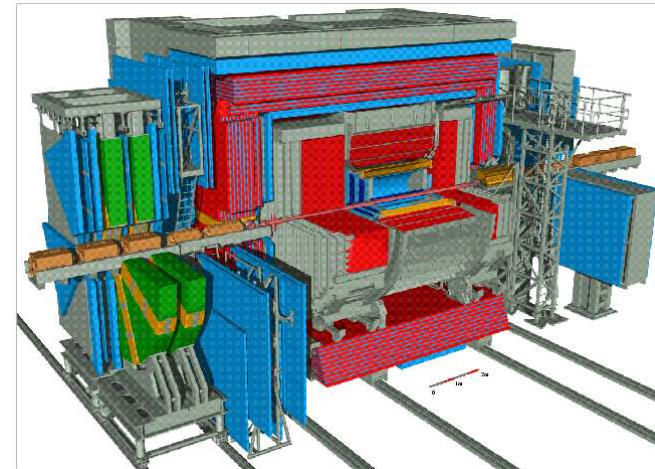


HERA

- HERA is a $e^{\pm}p$ collider
- Circumference of 6.3 km
- HERA-I (1992-2000)
 - until 1997
 $27.5 \text{ GeV} \times 820 \text{ GeV} \Rightarrow \sqrt{s} = 300 \text{ GeV}$
 - from 1998
 $27.5 \text{ GeV} \times 920 \text{ GeV} \Rightarrow \sqrt{s} = 318 \text{ GeV}$
- 2001-2002 Luminosity upgrade
- HERA-II 2003-2007
 - $27.5 \text{ GeV} \times 920 \text{ GeV} \Rightarrow \sqrt{s} = 318 \text{ GeV}$



HERA Experiments



H1, ZEUS

Omni-purpose 4π detectors

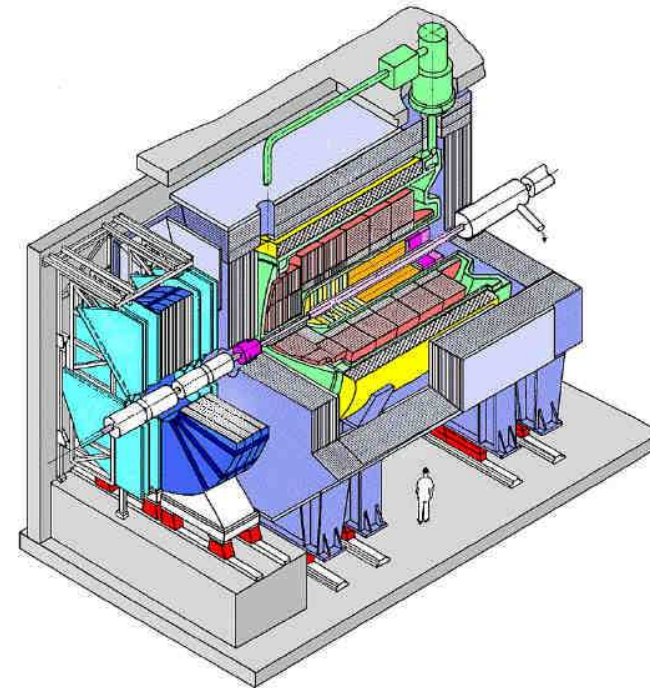
HERA-B

Specialised in B Physics

HERMES

Specialised in Proton Spin

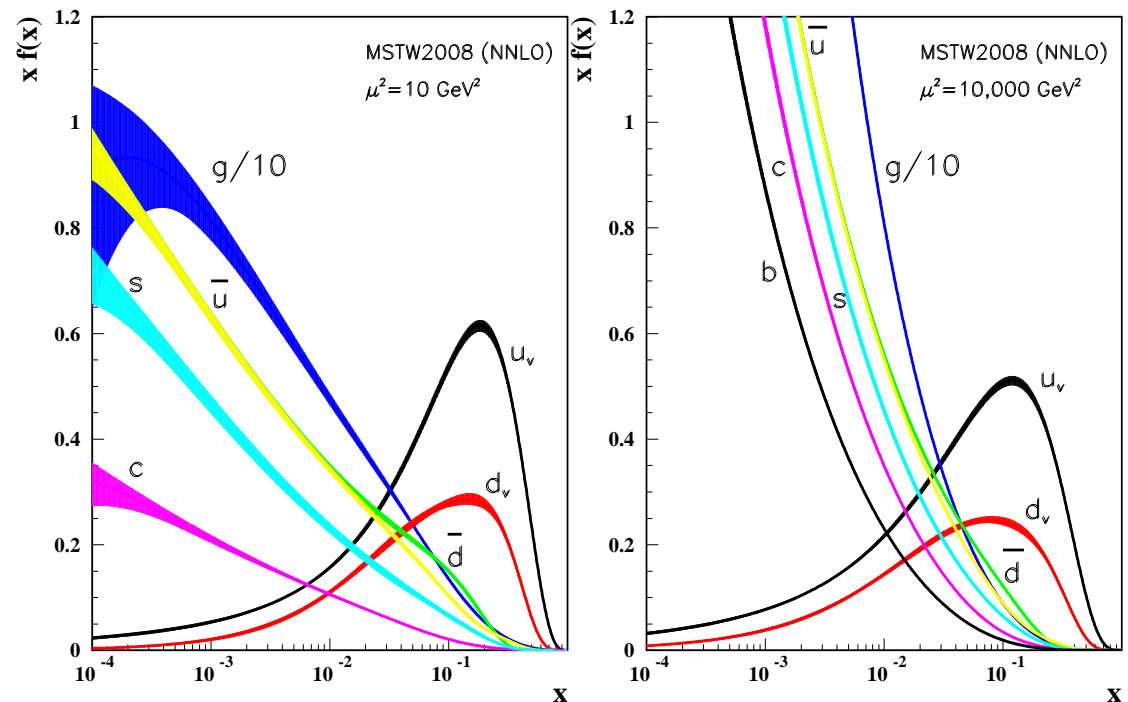
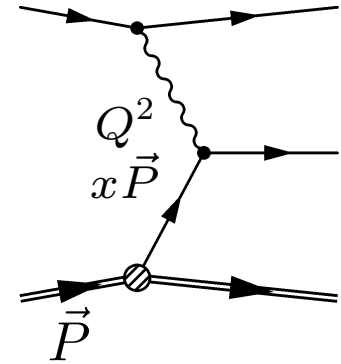
about 500 pb^{-1} per experiment



Parton Density

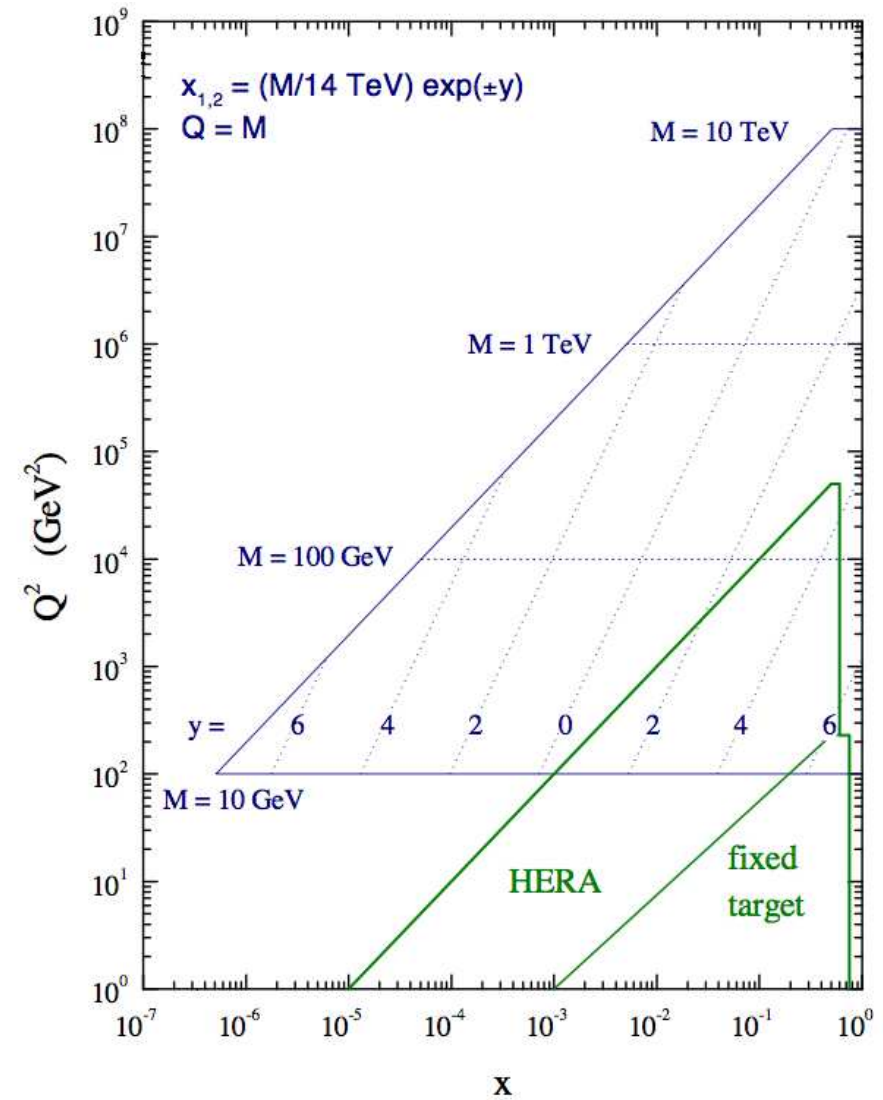
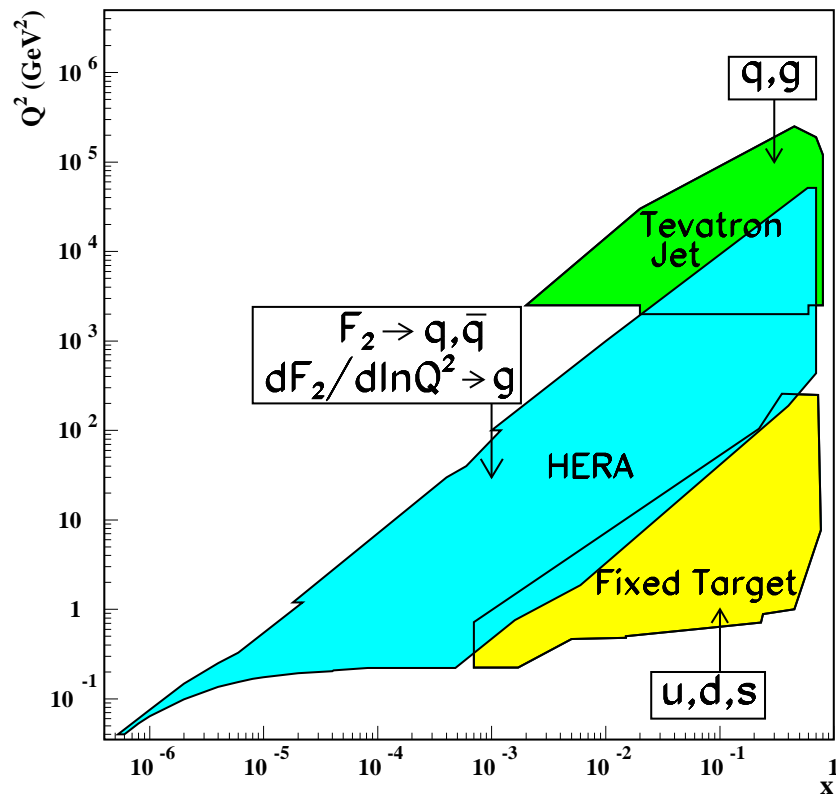
- At high energies contents of proton is probed
- Only one parton participates in reaction with e^\pm
- This will only carry a fraction (x) of the proton momentum
- PDFs describe how likely one finds a parton p at fraction x , when probing at scale Q^2
- The more precise we look (higher Q^2) the more details we see (more splittings \Rightarrow more partons with lower x)

“Scaling violation”



Kinematic Range of Hera vs. LHC

- Low x results from Hera

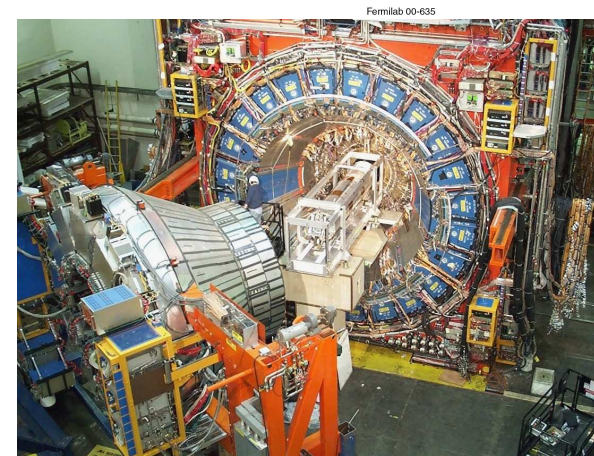
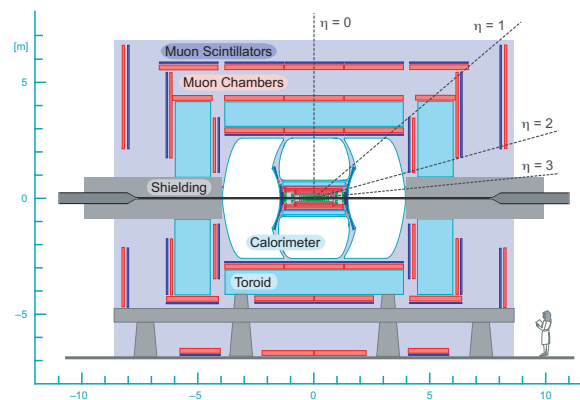
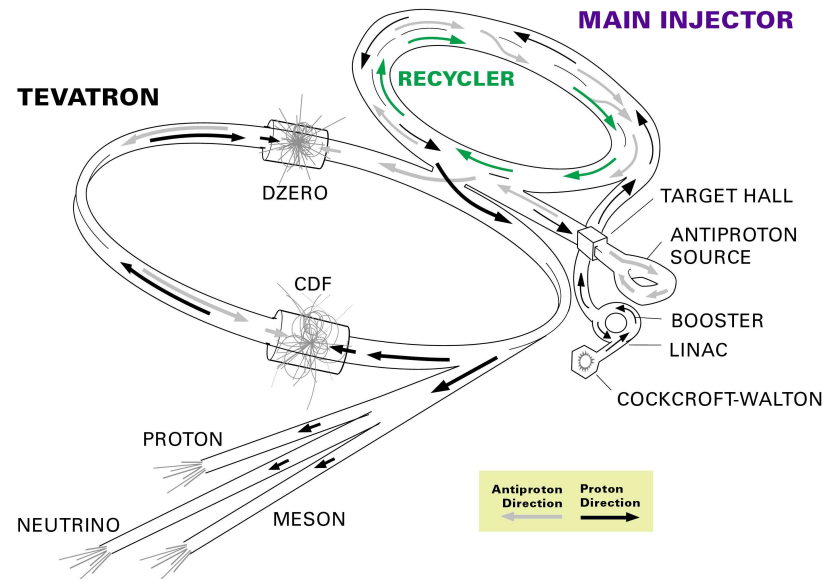


The $p\bar{p}$ Accelerator Tevatron

- Circumference 6.4 km.
- $p\bar{p}$ collisions
- Run I (1987-1995)
Collision energy 1.8 TeV
- Run II (since 2001)
Collision energy 1.96 TeV
- 2 experiments, CDF and DØ, record events.

$\mathcal{L} \sim 7 \text{ fb}^{-1}$ on tape.

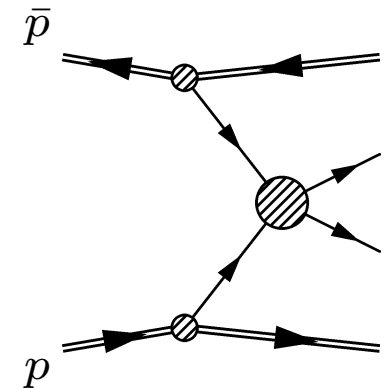
FERMILAB'S ACCELERATOR CHAIN



The Tevatron



- Now PDF need to be applied at both sides.



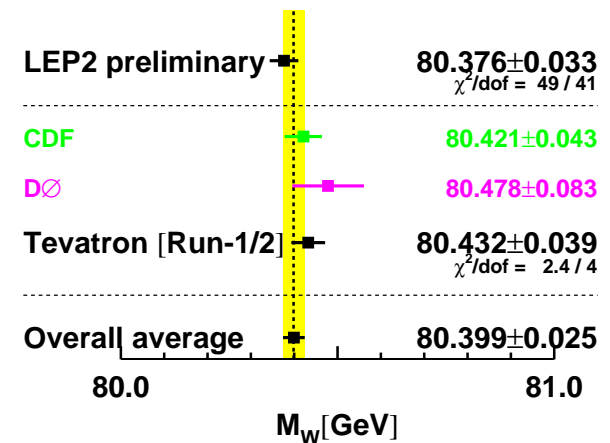
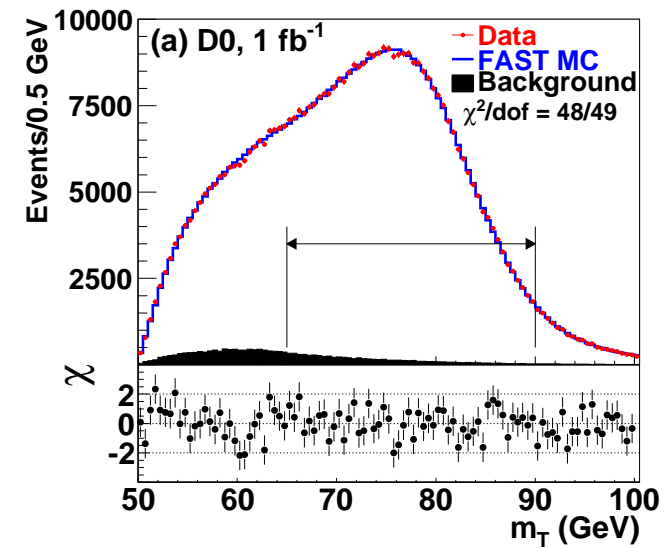
W-Boson Mass (at the Tevatron)

- Only leptonic decay can be found in hadron collisions
- Momentum conservation only applicable in transverse plane
 \Rightarrow Only p_x and p_y accessible for neutrino
- Reconstruct transverse mass

$$m_T^2 = 2p_T^e p_T^\nu (1 - \cos \phi)$$

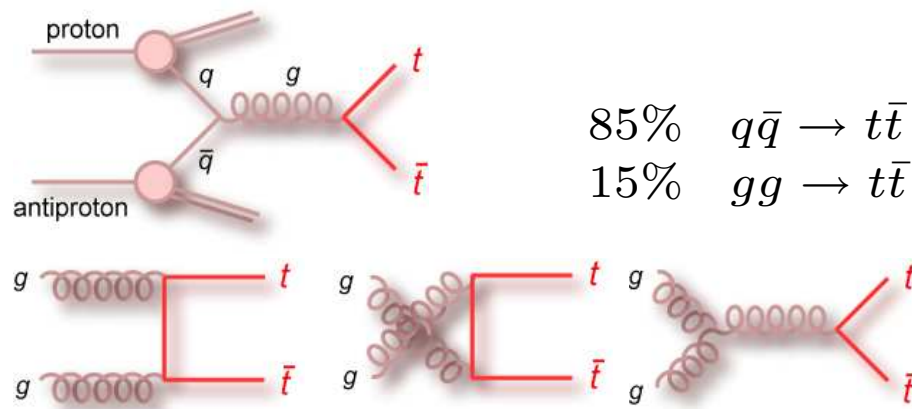
Combination of all LEP experiments and Tevatron

$$M_W = 80.399 \pm 0.025 \text{ GeV}$$



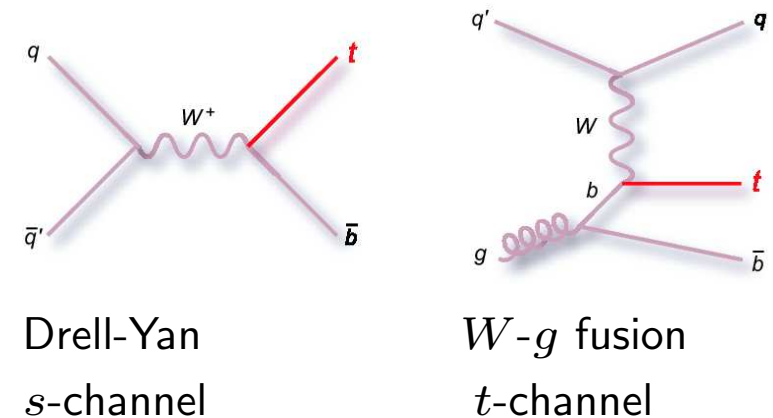
Top Quark Production at the Tevatron

Strong top production



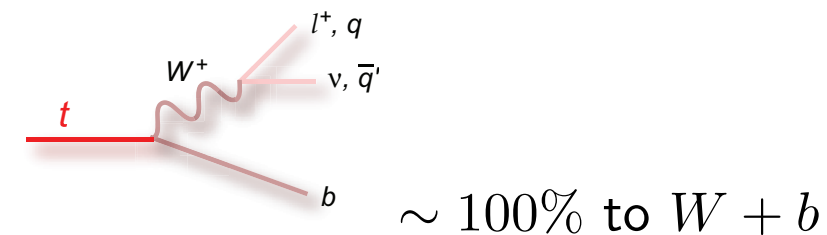
$$\sigma(t\bar{t}) \simeq 7.46\text{pb}$$

Weak top production



$$\sigma(t) = 3.46\text{pb} = 1.12\text{pb} + 2.34\text{pb}$$

Top Quark Decay



- Top discovered 1995 (CDF and D0)
- Weak production observed 2009
- $m_t = 173.1 \pm 0.6(\text{stat}) \pm 1.1(\text{syst}) \text{ GeV}$
best known quark mass

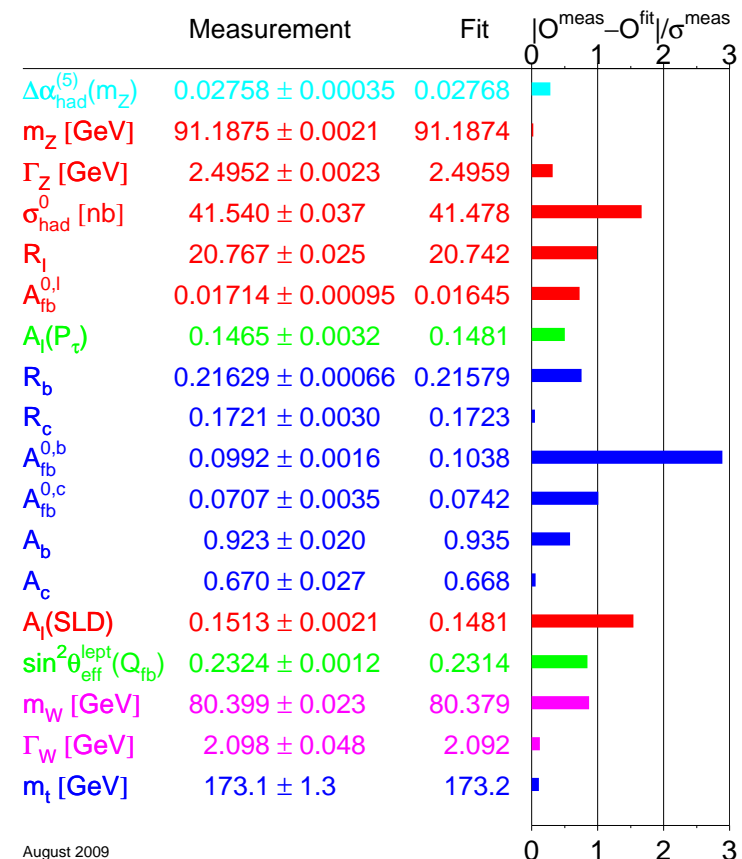
Fits of Electroweak Parameters

- Precision measurements of electroweak obs.

- Strong coupling
- Z mass and width
- W mass and width
- t mass
- Asymmetries, . . .

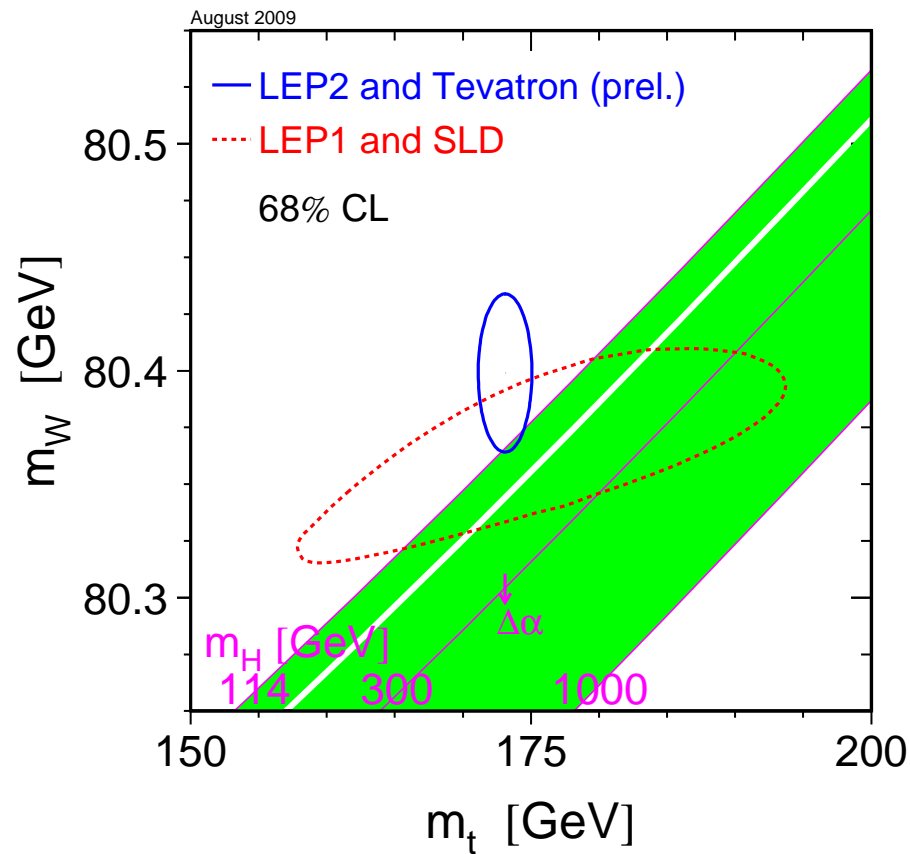
are related directly or in loop diagrams

- All data are in excellent agreement
- Biggest deviation 3σ (1 of 18)

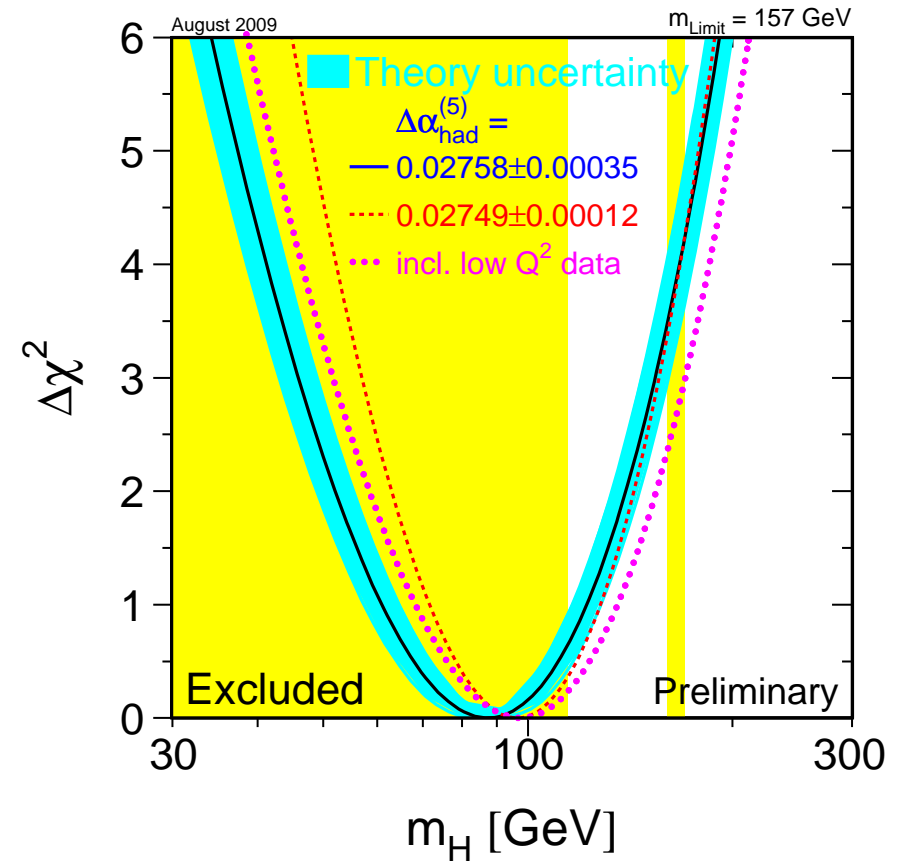


Fantastic success of the SM, especially given the experimental precision!

Top and W Mass in Elektroweak Fits



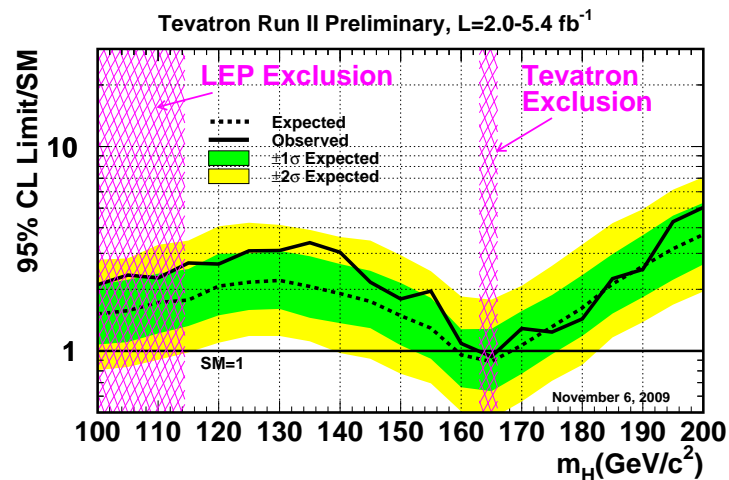
Combined m_W and m_t results
 touch SM-range only barely



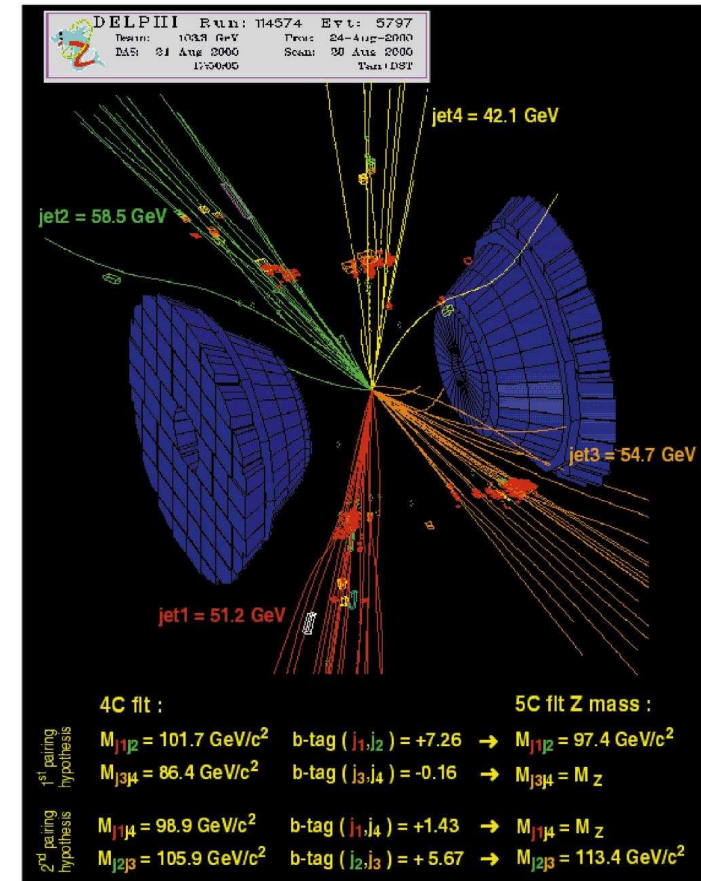
Projection to Higgs mass
 $M_H \leq 157 \text{ GeV (95\%CL)}$

Higgs Limits

- LEP (low M_H): $e^+e^- \rightarrow Z \rightarrow ZH \rightarrow q\bar{q}b\bar{b}$
 - $M_H > 114.4 \text{ GeV}$
- Tevatron (high M_H): $p\bar{p} \rightarrow H \rightarrow WW$
 - $M_H = 162 \dots 166 \text{ GeV}$ excluded at 95%C.L.



DELPHI Higgs candidate:



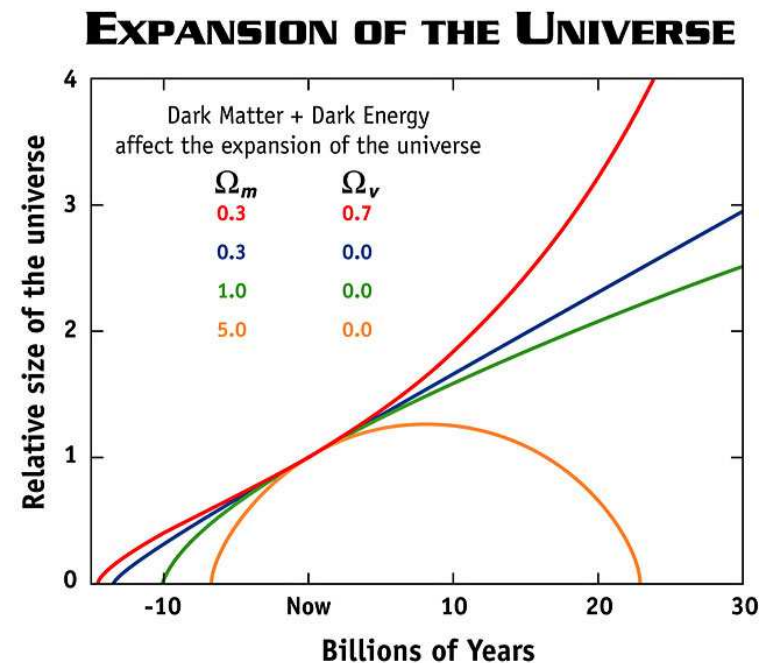
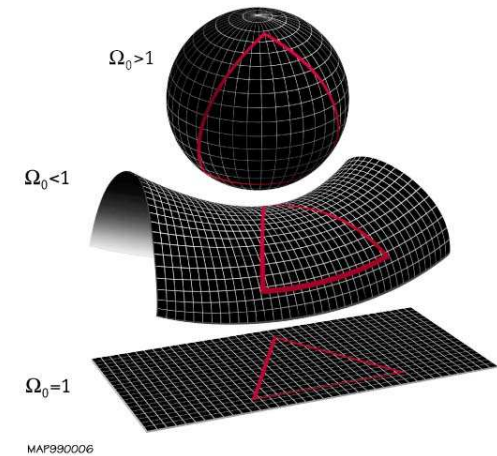
Expected luminosity at the Tevatron not sufficient for discovery.

Open Questions in Particle Physics

- How can we incorporate gravity?
- Is the Higgs mechanism the right idea?
 - Why is the Higgs so light?
(It should receive huge radiative corrections, “hierarchy problem”)
- Why are the charges quantised?

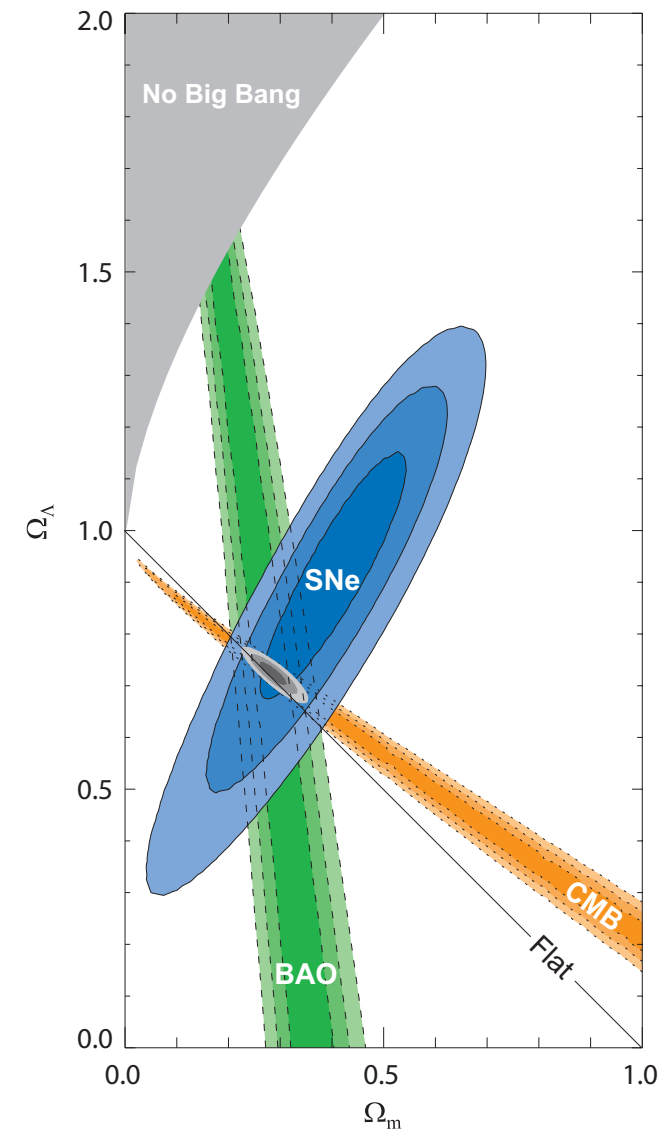
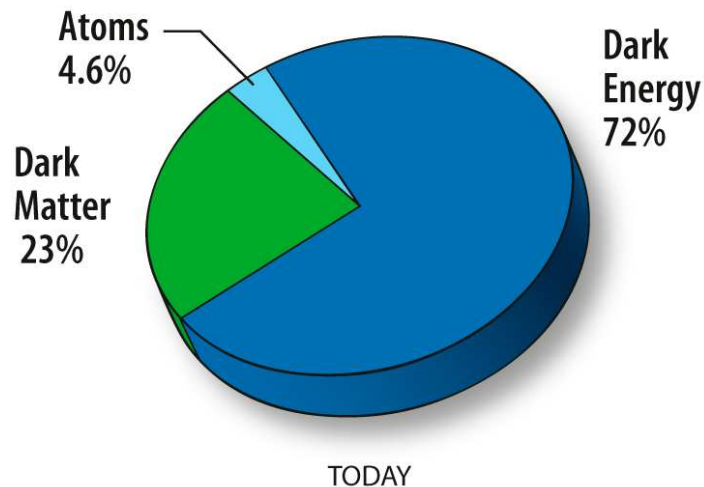
Cosmology in a Nutshell

- The Universe started in Big Bang
- Described by Einsteins General Relativity
- Space time could be
 - Flat
 - Negatively curved
 - Positively curved
- Its expansion could be
 - accelerating forever
 - decelerating, but expanding forever
 - decelerating and collaps
- Governed by energy and matter content
 - $\Omega = \Omega_m + \Omega_\Lambda \quad (= 1 \Leftrightarrow \text{flat})$



Cosmology: Experimental Status

- Measurement of the
 - Cosmic Microwave Background (CMB)
 - Supernovae escape speed (SNe)
 - Barionic Matter distribution (BAO)
- The universe is flat and expansion accelerates
- Only $\sim 5\%$ of the universe is made of atoms



What is Dark Matter and Dark Energy composed of?

\Rightarrow New Physics!?

Open Questions in Particle Physics

- How can we incorporate gravity?
- Is the Higgs mechanism the right idea?
 - Why is the Higgs so light?
(It should receive huge radiative corrections, “hierarchy problem”)
- Why are the charges quantised?
- What is Dark Matter?
- What is Dark Energy?
- Why does the universe contain (nearly) no anti-matter?

...

New physics at the Terascale can solve some of these problems

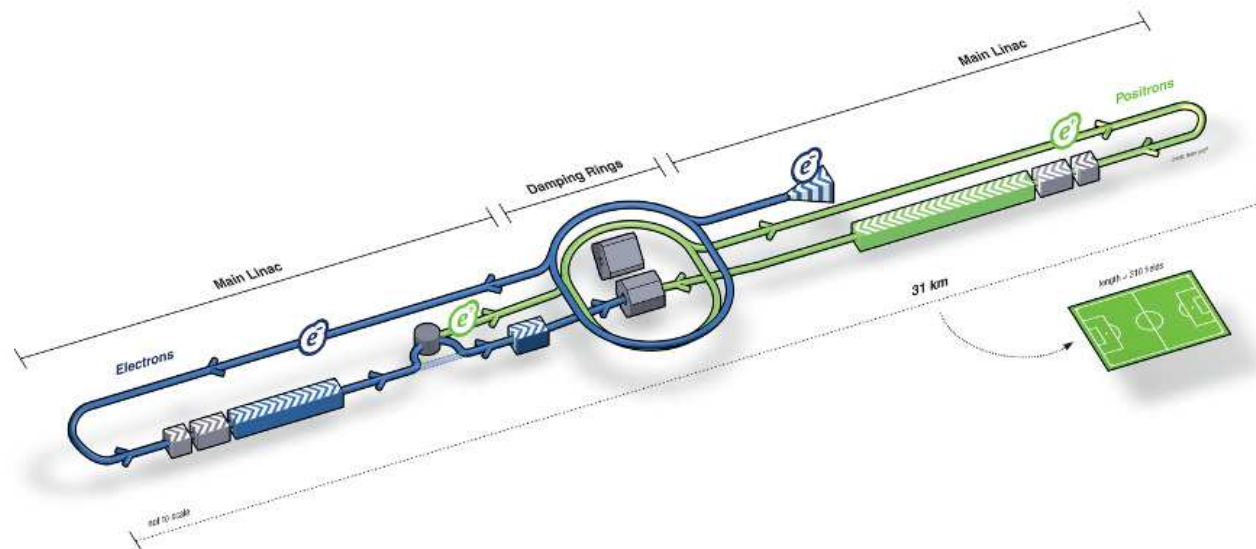
The International Linear Collider

International Linear Collider

An e^+e^- -collider would be ideal to address all these questions

- full use of beam energy, due to elementary beam particles
- no annoying effects of coloured hadron remnants

But synchrotron radiation prevents $\mathcal{O}(1 \text{ TeV})$ with a ring \Rightarrow Build linear collider



- Required length: approx. 30 km

- Extreme focus (5 nm) required

Status: Research and Design ongoing

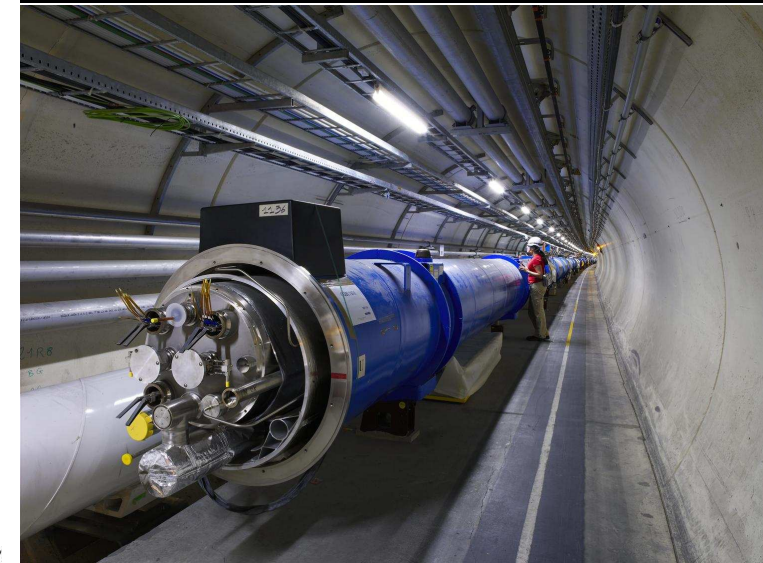
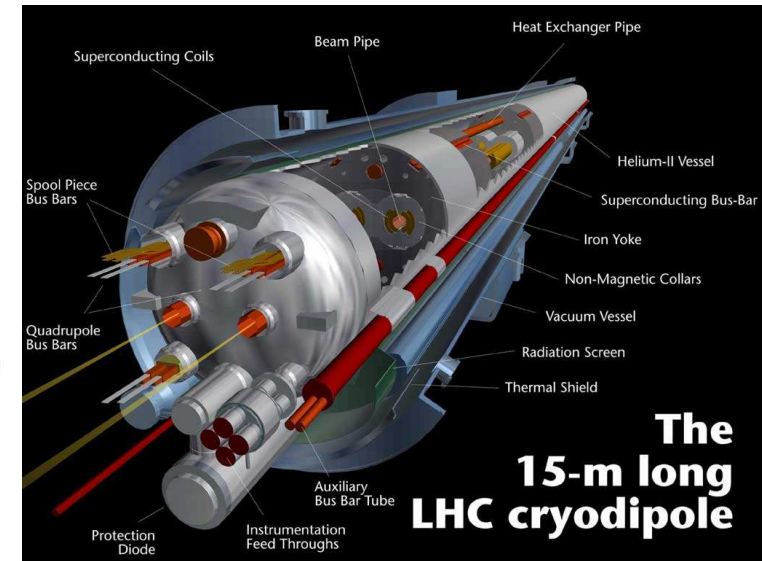
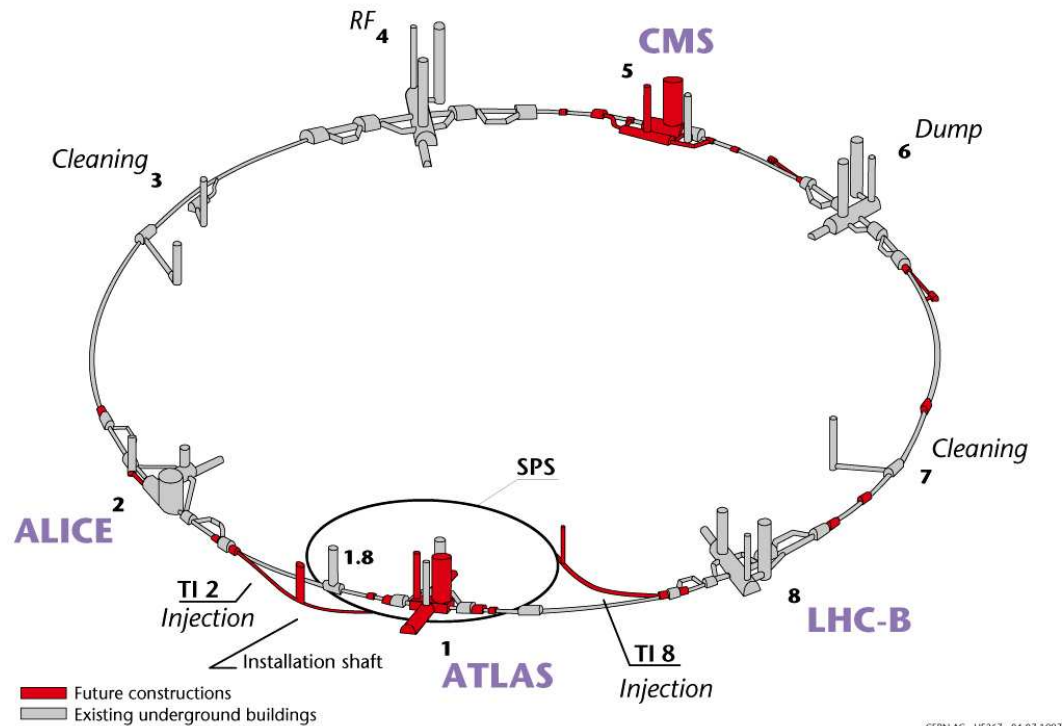
Tech. Design Report end of 2012

The Large Hadron Collider

LHC

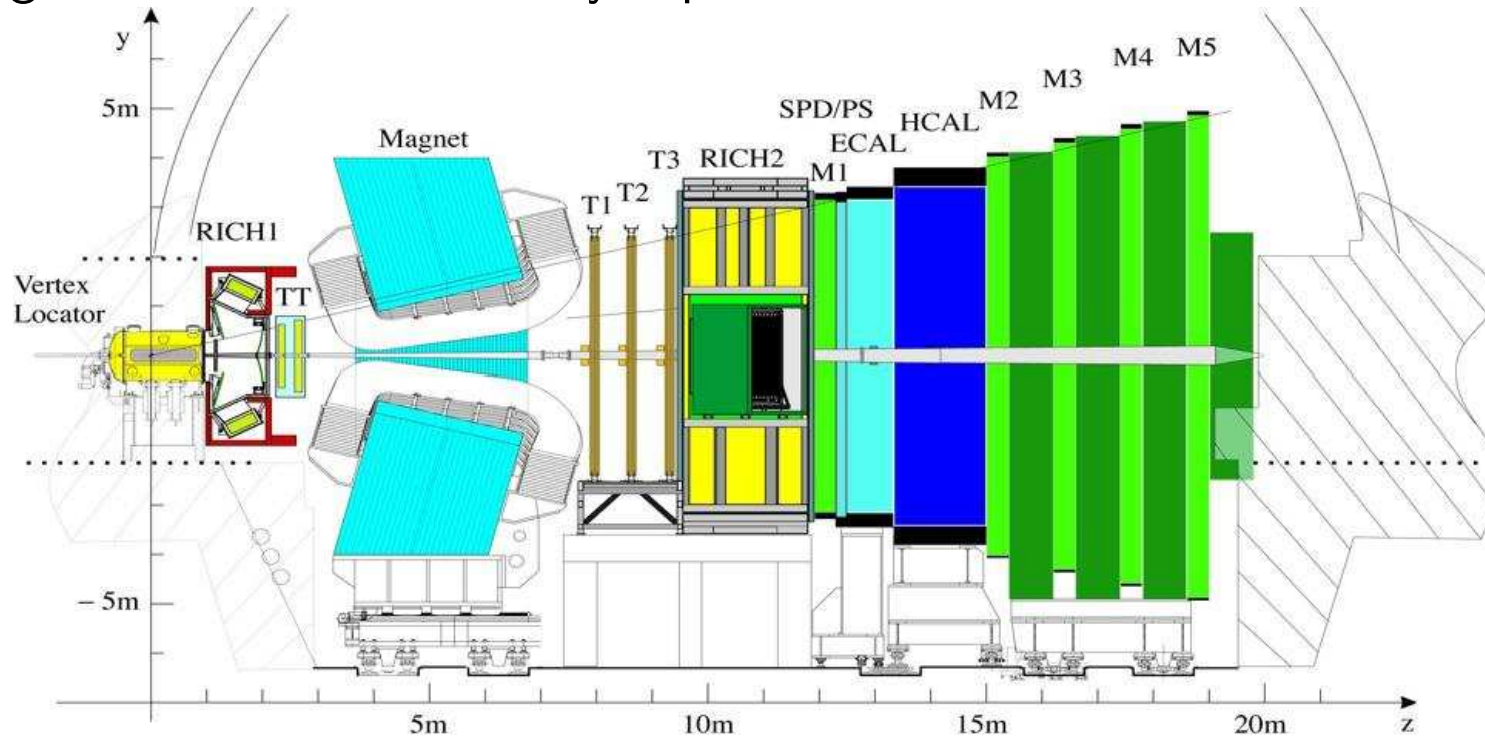
- Proton-Proton collider
- Circumference 27 km (old LEP tunnel)
- $\sqrt{s} = 7 \text{ TeV}$ (–2011), then 14 TeV

Layout of the LEP tunnel including future LHC infrastructures.



LHCb

The Large Hadron Collider beauty experiment

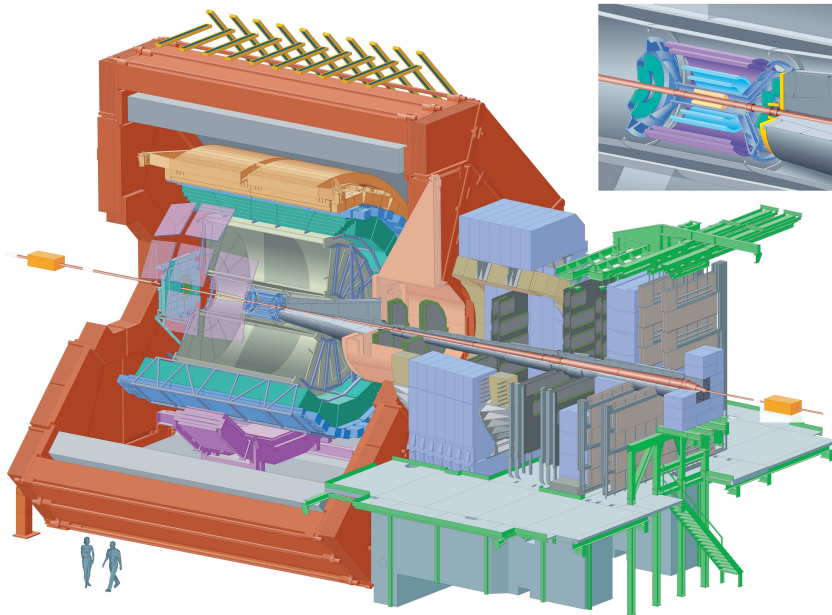


- Interaction point at one end of detector
- Only forward region equipped
- Specialises on b physics

ALICE

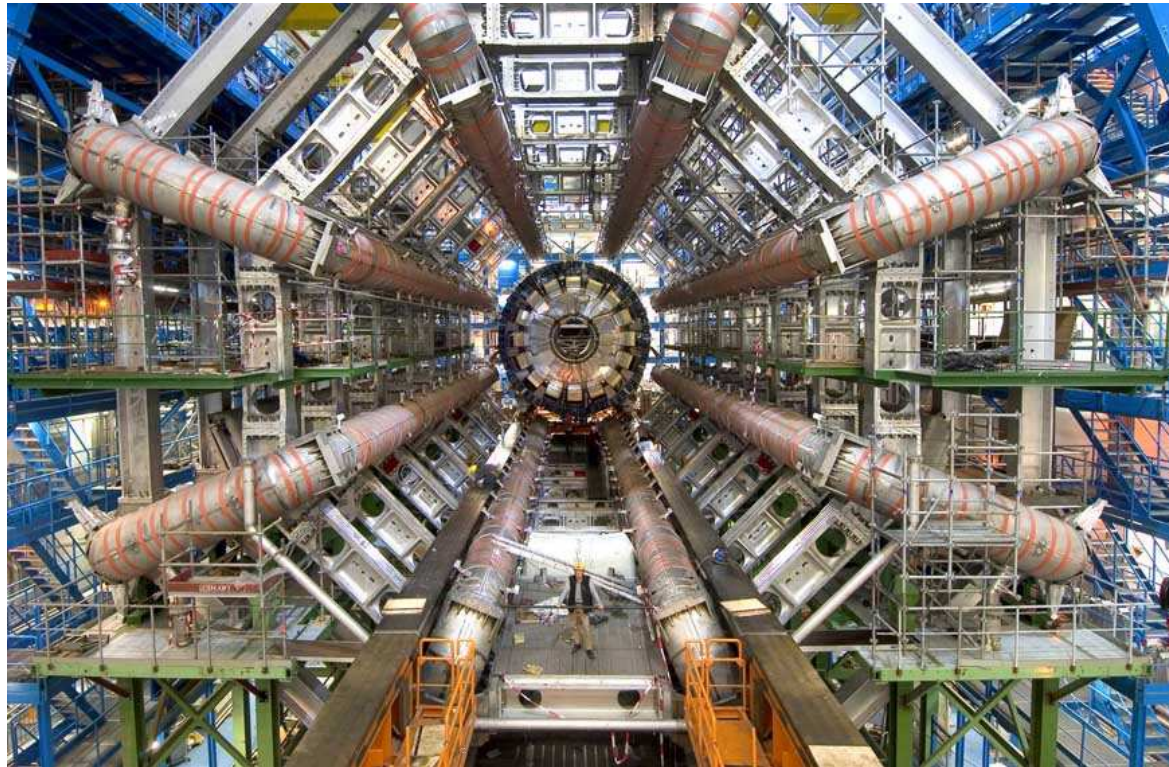
A Large Ion Collider Experiment

- Specialises on heavy ion collision
- Strongly interacting matter at extreme energy densities
- New phase of matter: quark-gluon-plasma



ATLAS

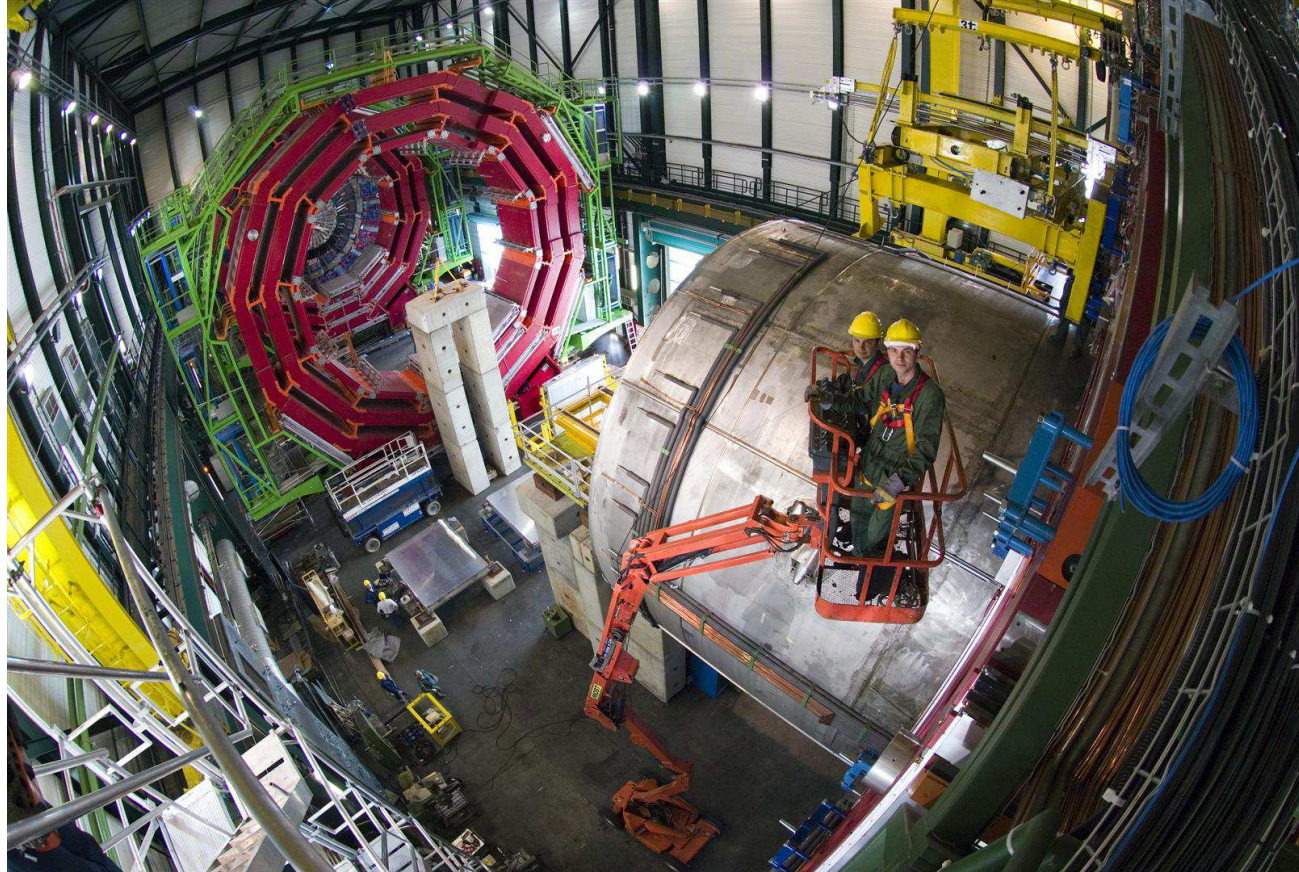
(Originally for “A Toroidal LHC ApparatuS”)



- Biggest of the four main experiments; General purpose 4π detector
- Aims to find the Higgs
- . . . and new physics

CMS

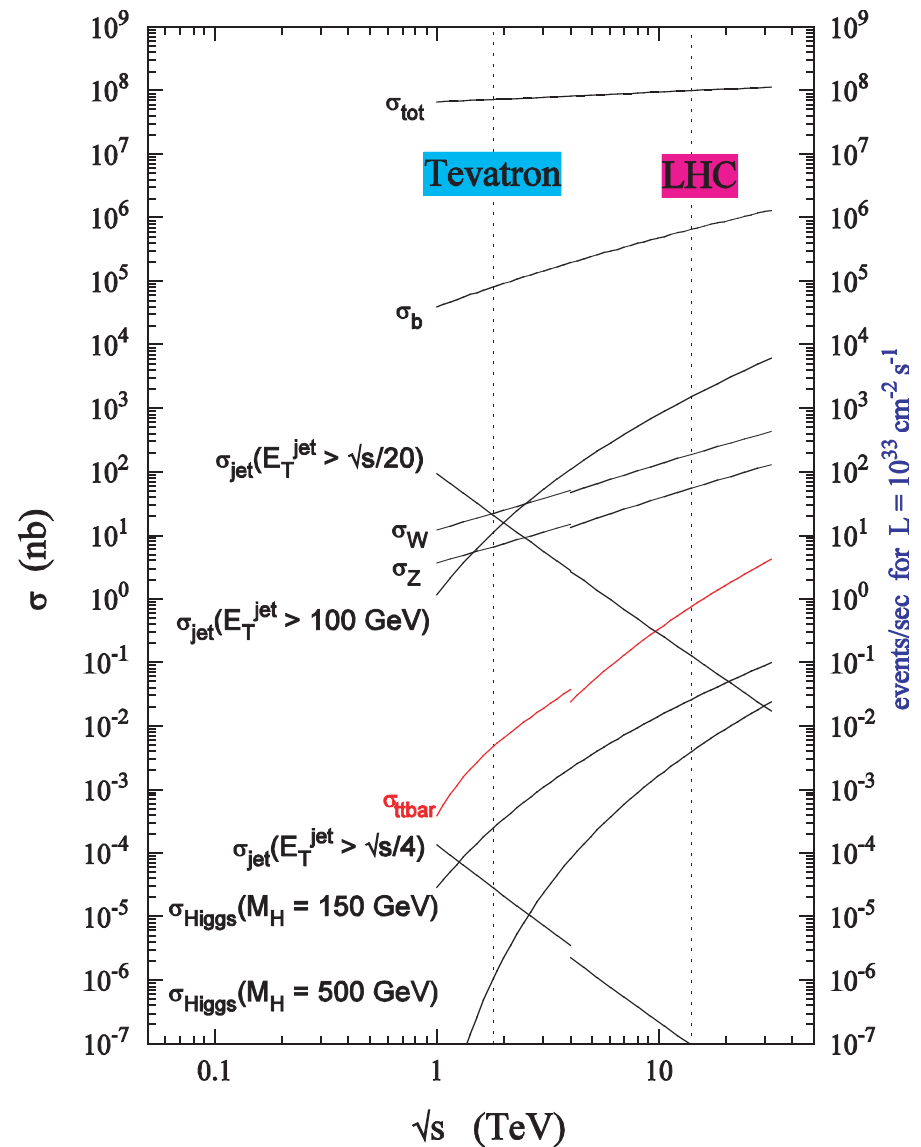
The Compact Muon Solenoid Experiment



- Heaviest of the LHC experiments
- General purpose 4π detector
- Aims to find Higgs
- . . . and to find new physics

Goals of the LHC

- Find the Higgs
 - High energy yield higher σ_H
 - ... and covers full allowed range
- Find new physics
 - explaining Dark Matter
 - explaining Dark Energy
 - explaining matter domination
- Cross-check with precise SM results



Conclusion

The LHC Rap (Alpinekat)