Introduction to

Helmholtz Alliance

PHYSICS AT THE TERASCALE

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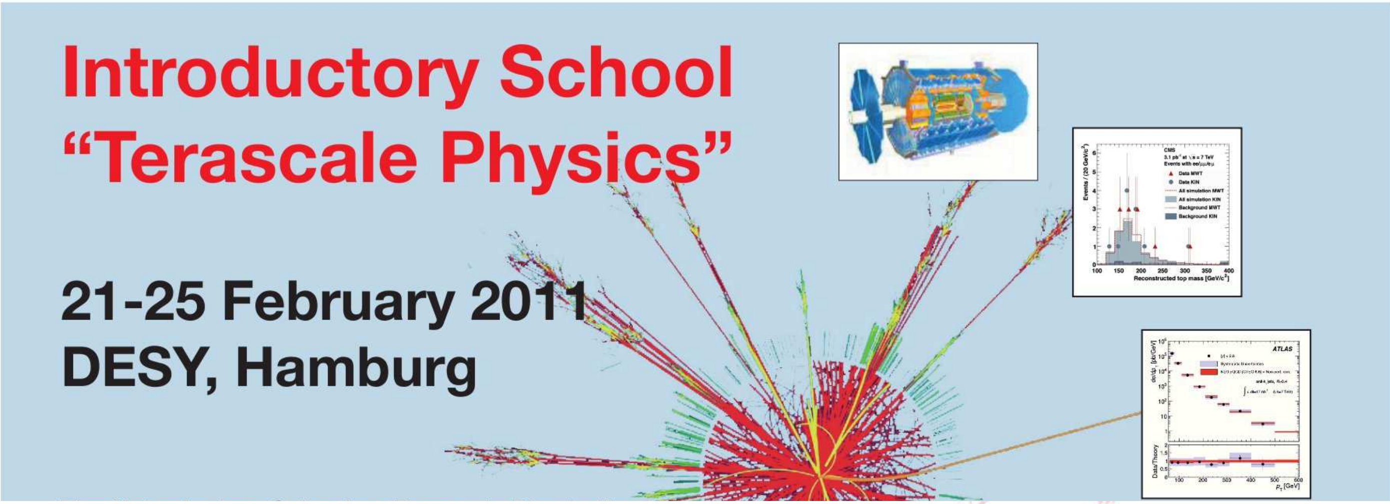
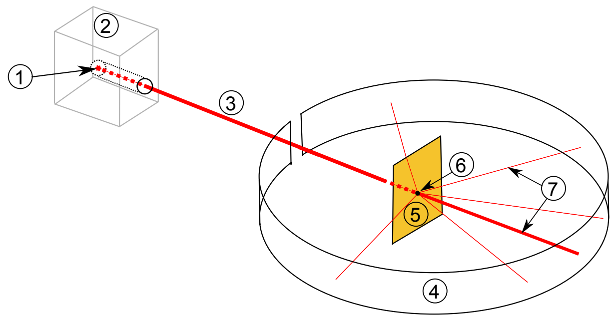


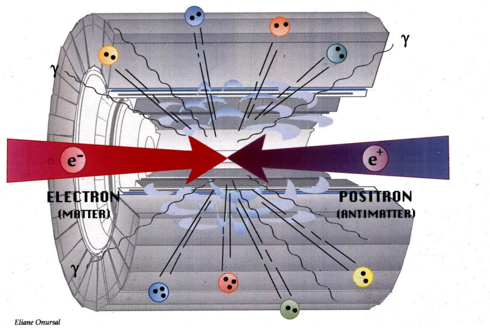
Daniel Wicke
(Bergische Universität Wuppertal)

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
  $\Rightarrow$ Scattering experiments
  - Fixed Target (beam on probe)
    e.g. Rutherford
  - Collider (collision of two beams)
    modern expts at energy frontier





- Probing shortest possible distances requires use the highest possible energies
  (c.f. de Broglie wavelength)
  - Unit: $1\,\mathrm{eV}$, Energy reached by an electron in electric field difference of a $1\,\mathrm{V}$.

What is the Terascale?

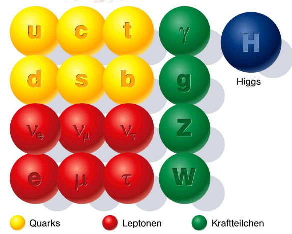
- Technologically, with colliders, we can reach $\mathcal{O}(\text{TeV})$
  - Linear Collider: $0.5 \ldots 1$ TeV
  - Large Hadron Collider: up to 14 TeV (but protons aren't fundamental)

- $\mathcal{O}(\text{TeV})$ is also the scale where we expect to learn more about the SM

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

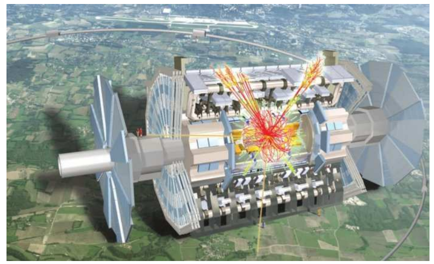
Part I: The Standard Model of Particle Physics



- 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 $\frac{1}{2}$)

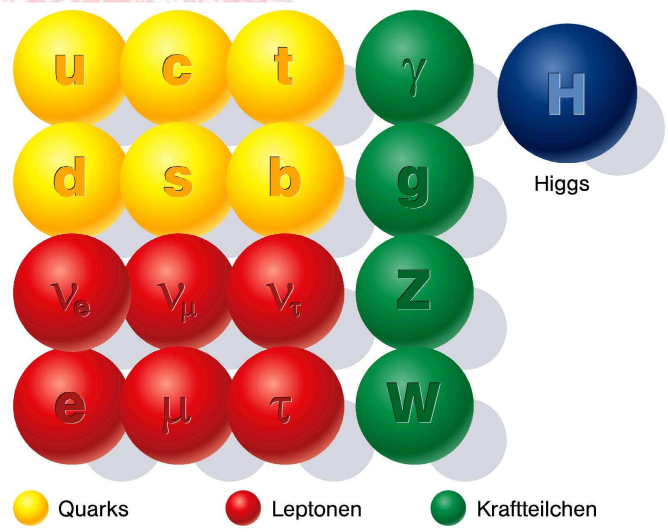
- Ordinary Matter Additional Generations Charge

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



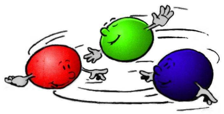
Higgs (Scalar, Spin 0)

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:

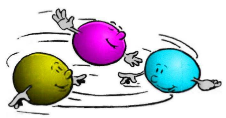
3 Quarks



Proton (uud), Neutron (udd)

Anti-baryons:

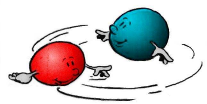
3 Anti-quarks



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

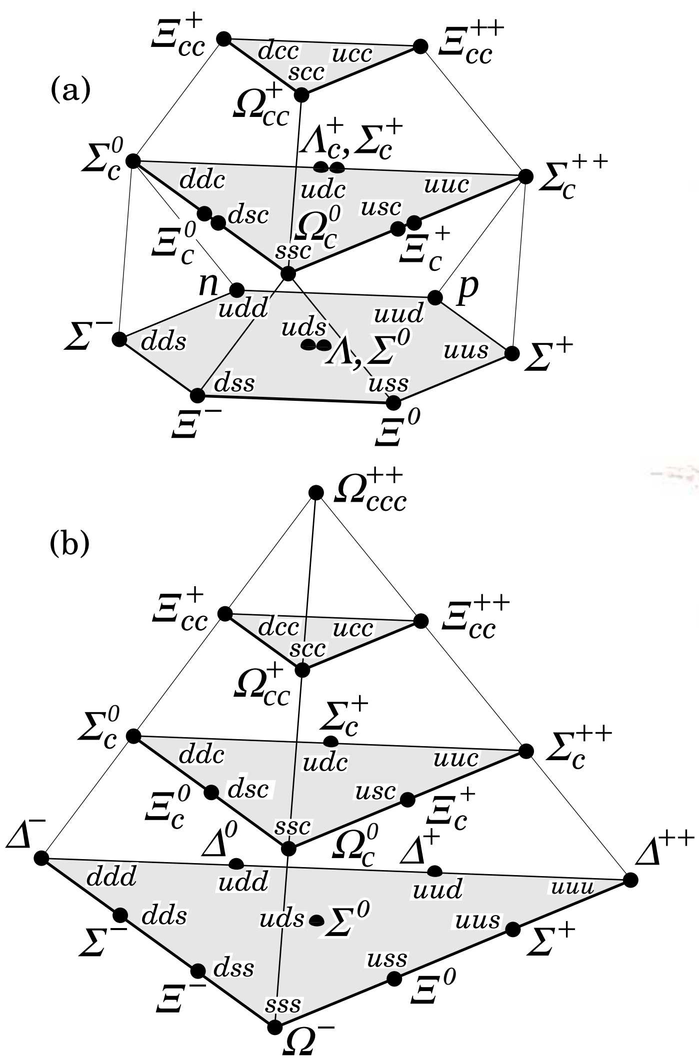
Mesons:

1 Quark and 1 Anti-quark



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

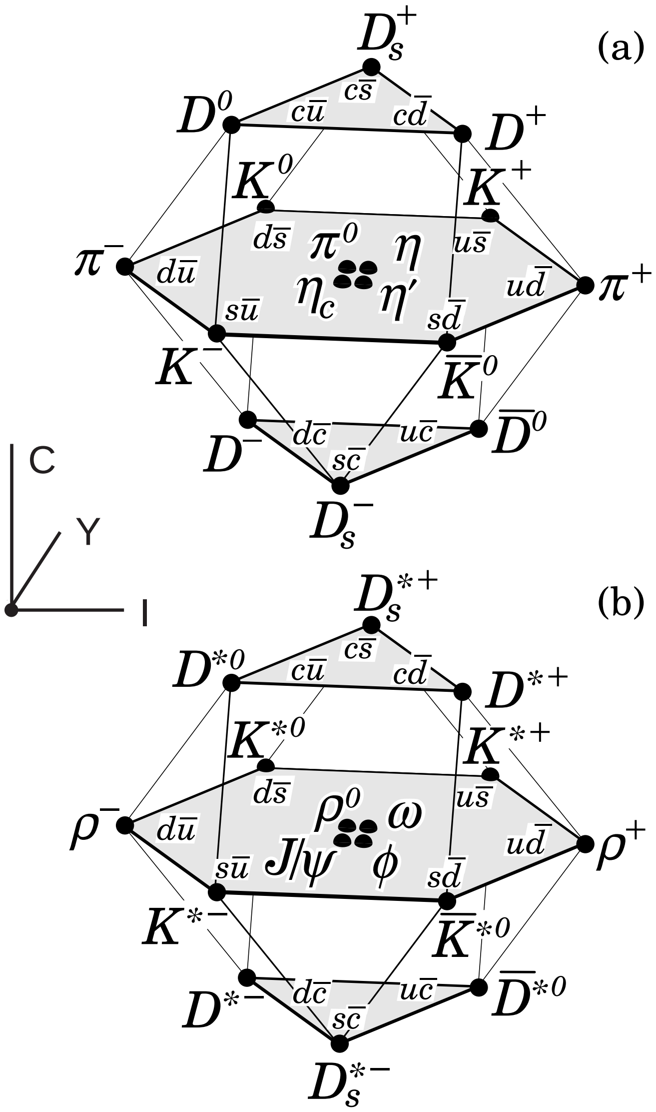
Baryon Multiplets



- 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"

$\Rightarrow$ We really need 3 colours

Meson Multiplets



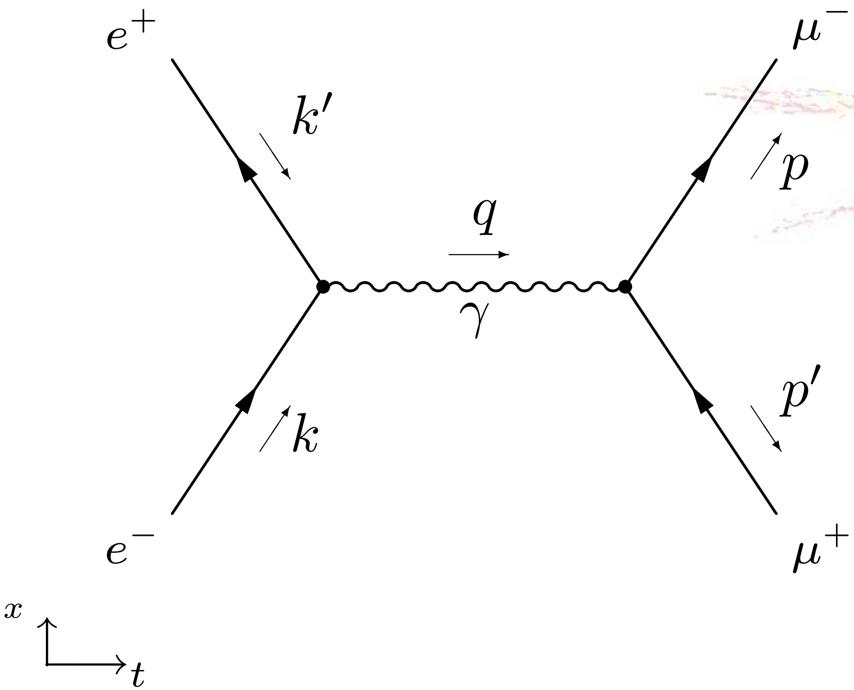
- Quark and Anti-quark can be combined to form spin 0 or 1 mesons.
- Two multiplets of mesons which have the same spin but varying quark content

Interactions

Feynman Diagrams

. . . as a graphical represenation 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 presciption to compute processes of elementary particles:

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

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

with

$$\left.\begin{array}{rcl} j_e & = & \text{flux density of incoming particles} \\ d\Phi & = & \text{phase space element} \end{array}\right\} \text{process independent}$$

$$\left.\begin{array}{rcl} \mathcal{M} & = & \text{matrix element} \end{array}\right\} \text{process dependent}$$

$\mathcal{M}$ is computed from Feynman diagrams

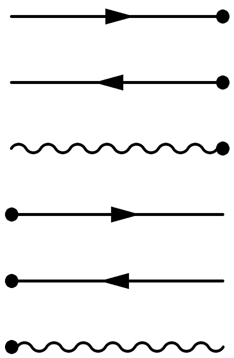
– each diagram represents a mathematical term
– $\mathcal{M}$ is the sum all possible diagrams which depict $A + B \to C + D$.

Which diagrams are allowed? What are their mathematical terms?

Building blocks of Feynman diagrams

External lines

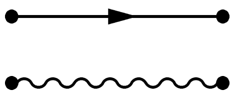
Mathematical term



incoming fermion
incoming anti-fermion
incoming photon
outgoing fermion
outgoing anti-fermion
outgoing photon

plane waves

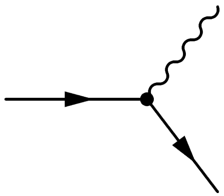
Internal lines



propagating (anti)fermions (4-mom. p) — "$\dfrac{m + p}{p^2 - m^2 + i\delta}$"

propagating photon (4-momentum q) — "$\dfrac{1}{q^2 - M^2 + i\Gamma}$"

Vertices



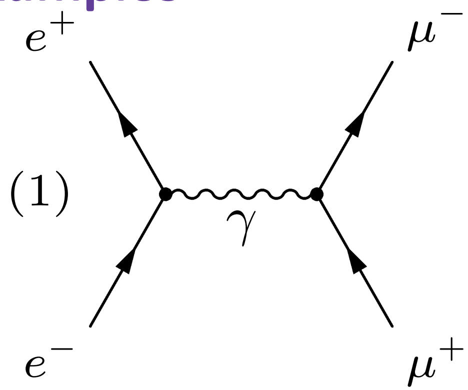
interaction of photon with (anti)fermion (charge e) — $\sim e$

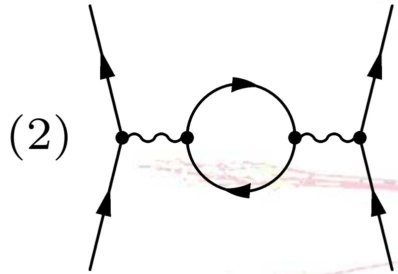
Drawing Feynman diagrams

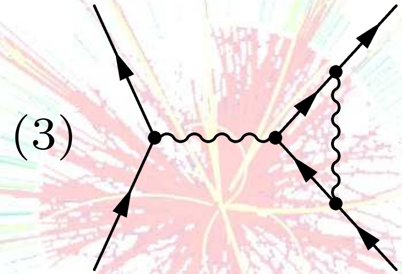
These building blocks can be combined (almost) arbitrarily:

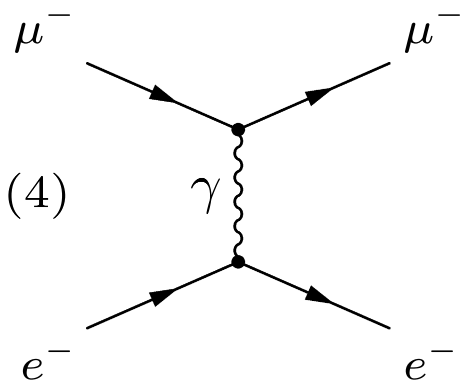
- Vertices need to be connected to the indicated number and type of lines
- Fermion lines need to keep their direction

Examples









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

(2) Quantum correction (loop) in propagator

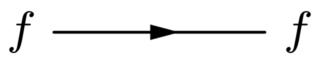
(3) Quantum correction (loop) at vertex

(4) Electron-Muon scattering

The Electromagnetic Interaction

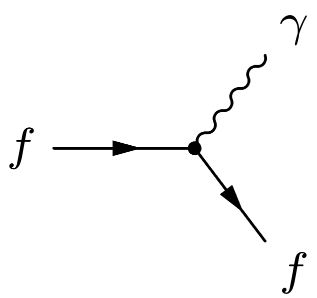
In terms of Feynman diagrams the electromagnetism is described by

- For brevity one line per particle type.
- Implicitly included: the variation of incoming, outgoing and internal



- Fermions

- Photons

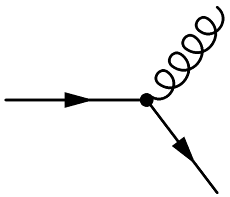


$\sim \quad z\,e$

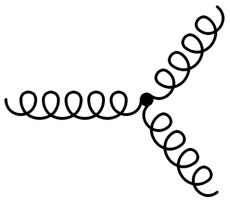
- and their interaction vertex
  - Fermion (charge ze) radiating a photon
  - Photon splitting to two fermions
  - To fermions annihilating to a photon

(depending on the time direction in the diagram)

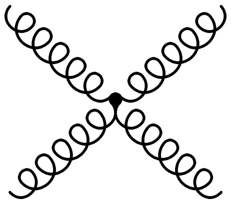
The Strong Nuclear Force



$\sim \quad g_s$



$\sim \quad g_s$



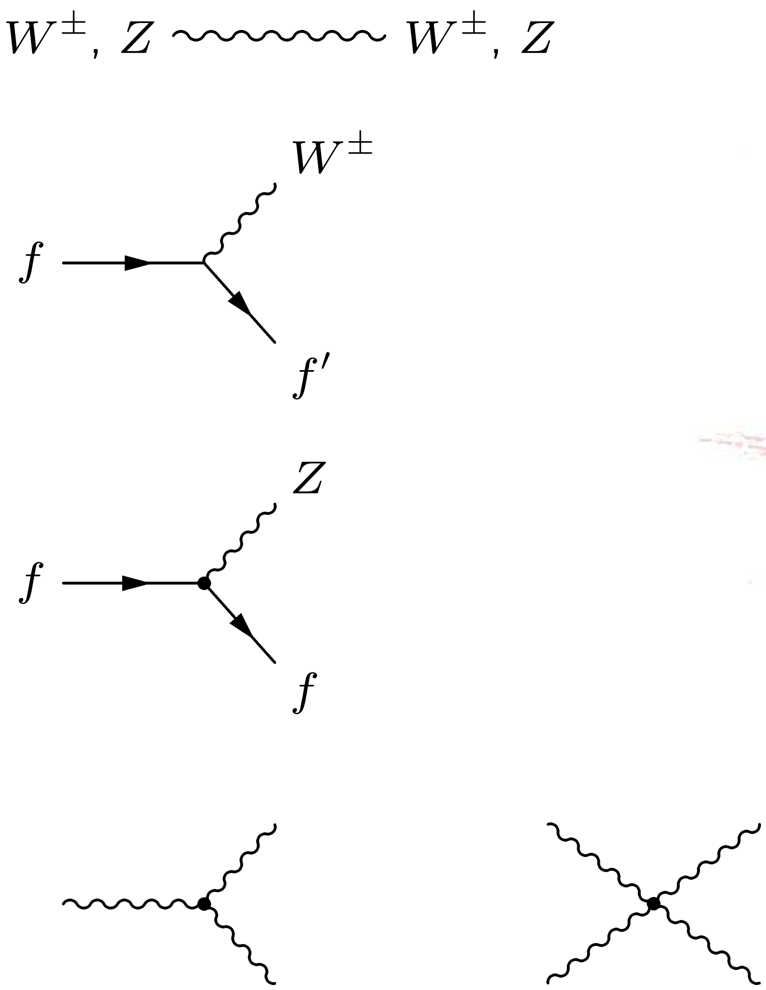
$\sim \quad g_s^2$

- 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 stroug coupling

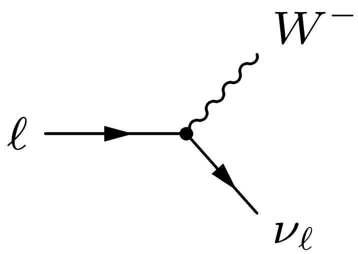
Note:
Summing the 3 colours or 8 gluons will give extra "colour factors" to the vertices

The Weak Nuclear Force

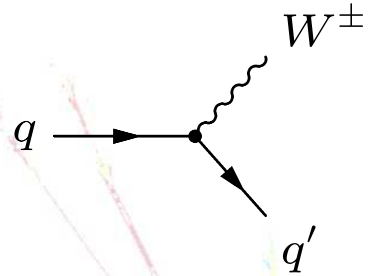


- Three gauge bosons: W^+, W^-, Z
- Fermion-$W^\pm$-vertex
  - Only for left-handed fermions
  - May change generation for quarks (flavour changing)
- Fermion-Z-vertex
  - At different strength for left- and right-handed fermions
  - No flavour change (FCNC) possible
- Triple boson coupling (ZW^+W^-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

The Cabbibo-Kobayiashi-Maskawa Matrix



$\sim g$



$\sim g\, V^{\mathrm{CKM}}_{qq'}$

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

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

(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

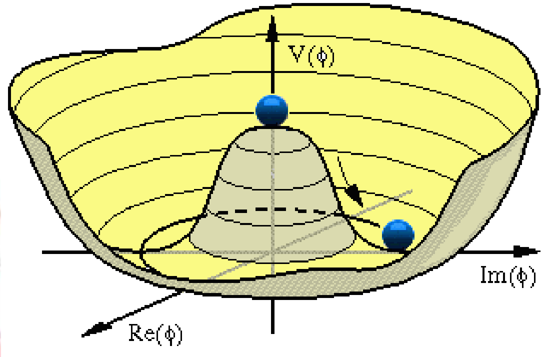
But since 2000 we know that such neutrino mixing exists and is strong

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)

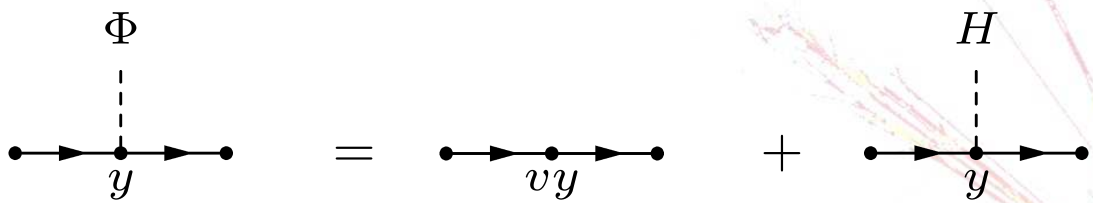
  Rewrite Φ as $\Phi = \begin{pmatrix} 0 \\ v \end{pmatrix} + \begin{pmatrix} \phi_1 + i\phi_2 \\ h + i\phi_3 \end{pmatrix}$

- $\phi_{1,2,3}$ 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

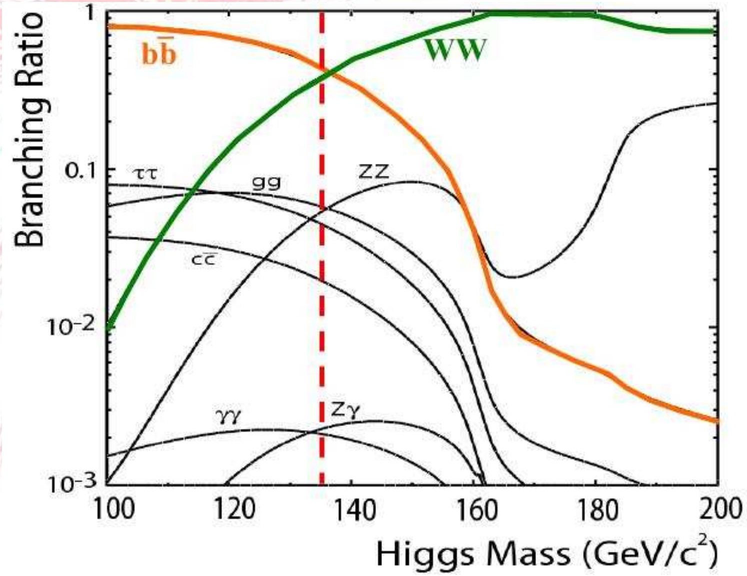
- Apply rewriting of Φ to Higgs-Fermion coupling:



- Coupling of the physical Higgs to a Fermion is proportional to the Fermion mass

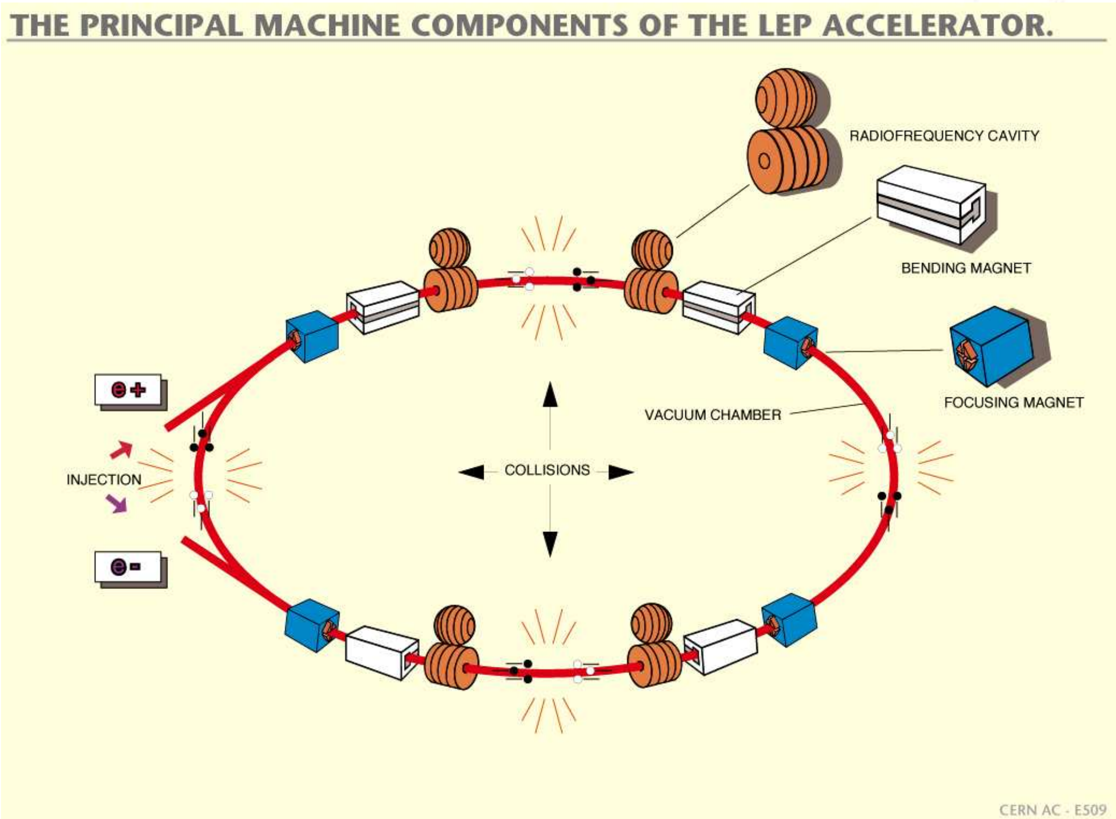
- Coupling to gauge bosons is "stronger"

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

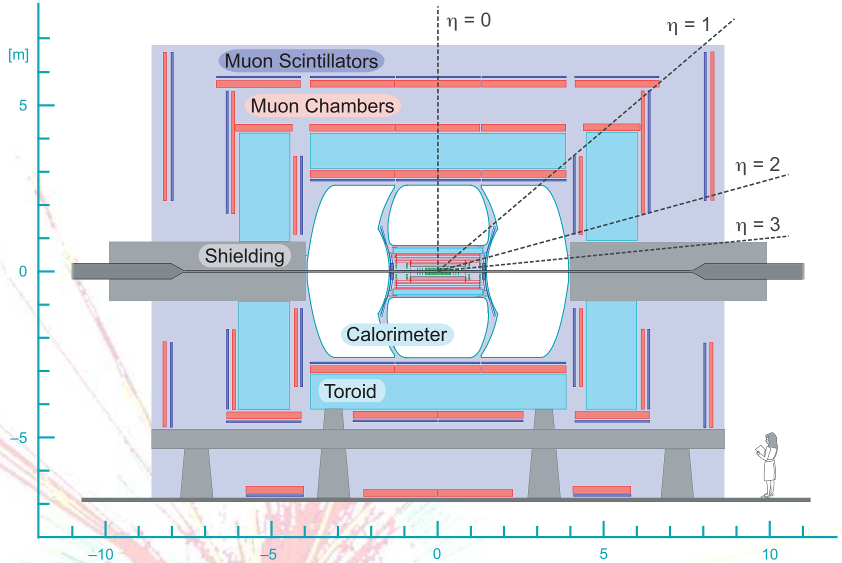
The Concept of a Collider



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

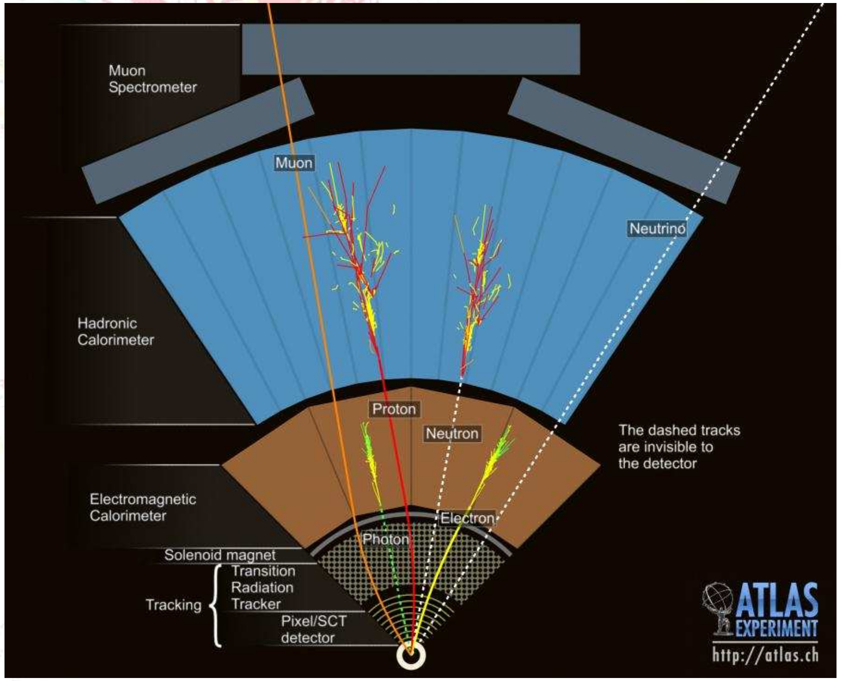
- Colliding
  Straight sections with focussing elements to stear to collision

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

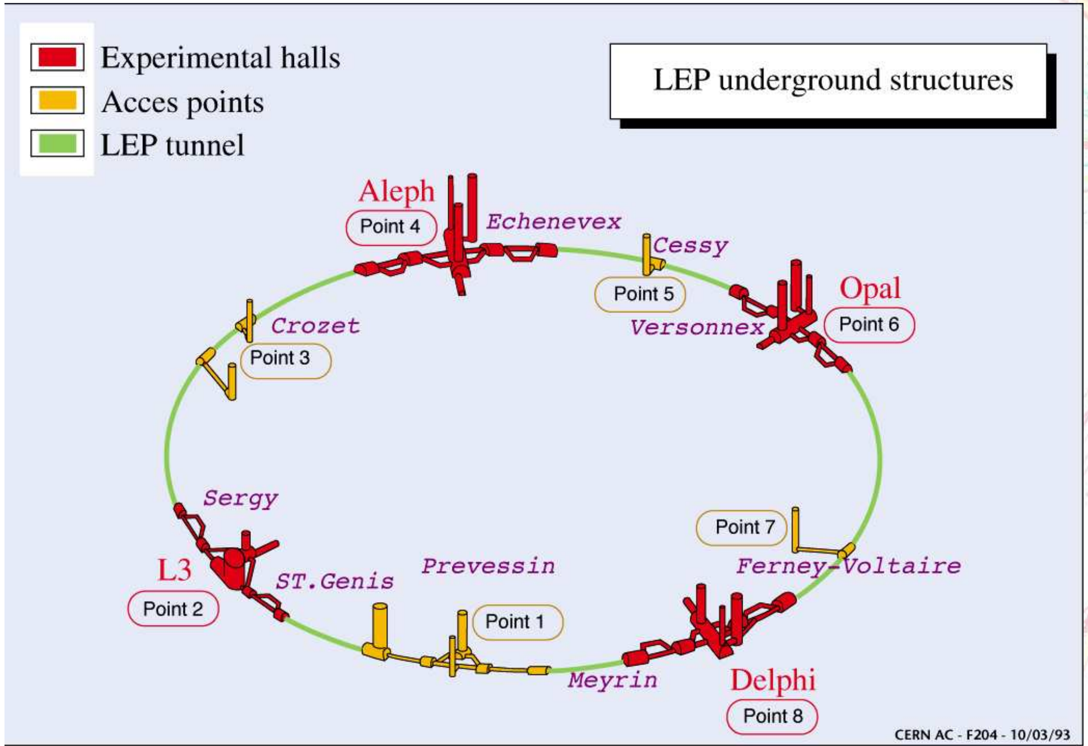


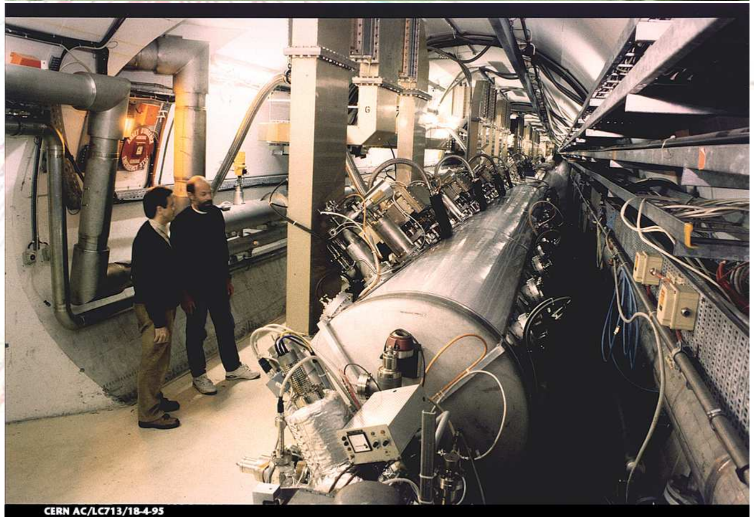
ATLAS: Same conceptual components

- different realisation

Large Electron Positron Collider (LEP)

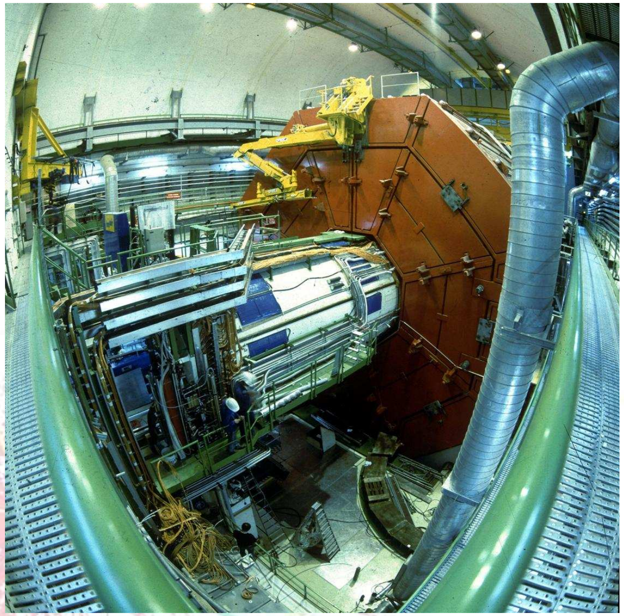
- Circumfence $27\,\text{km}$
- LEP1 $1989 - 1995$: $\sqrt{s} \simeq 91\,\text{GeV}$
- LEP2 $1996 - 2001$: $\sqrt{s} \simeq 130 \ldots 210\,\text{GeV}$





The LEP Experiments

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



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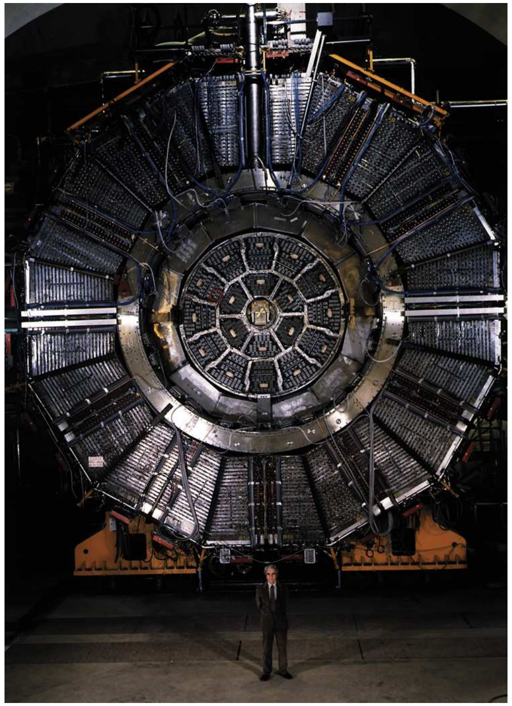
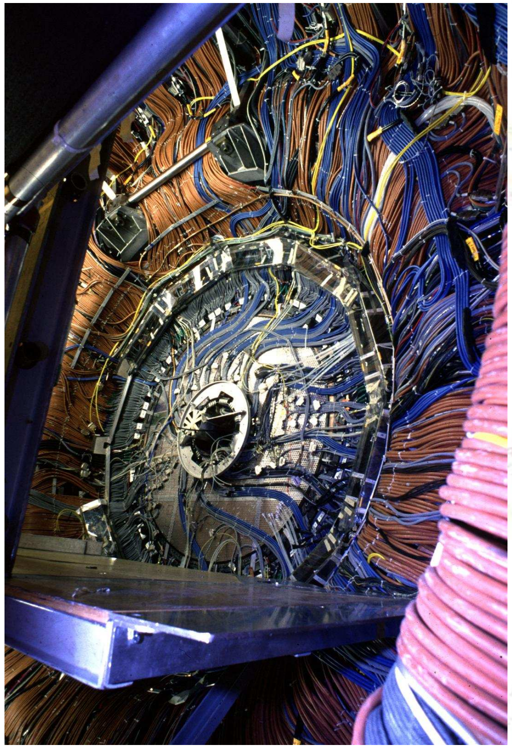
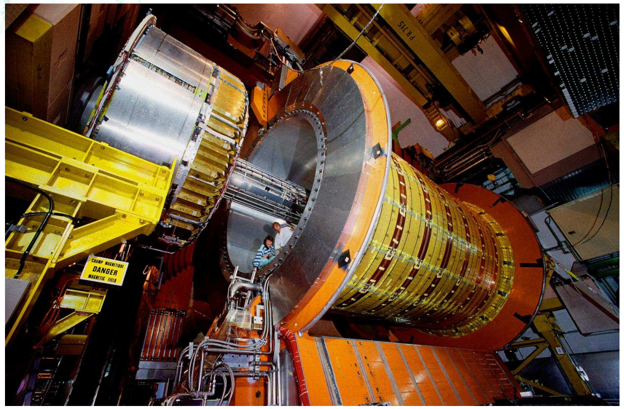


ALEPH



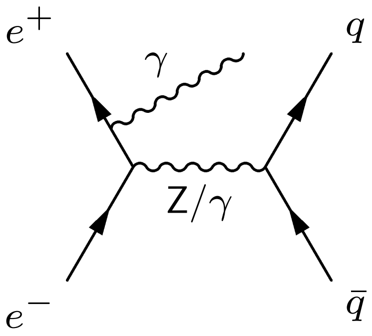
DELPHI

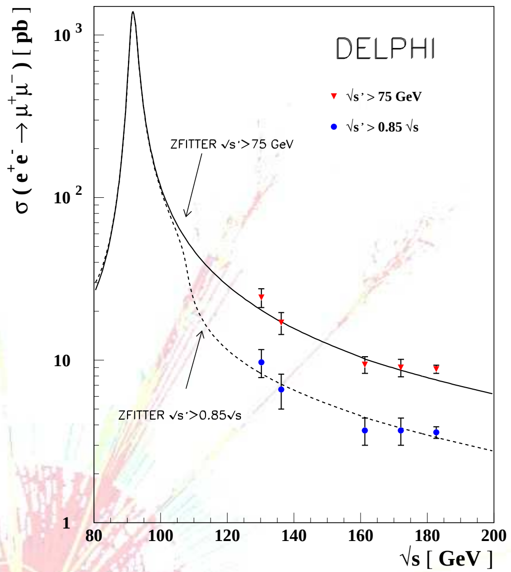


OPAL

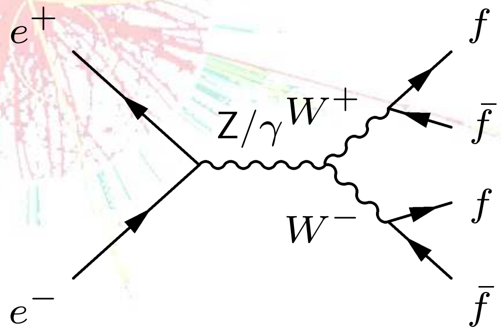
Basic Processes at LEP

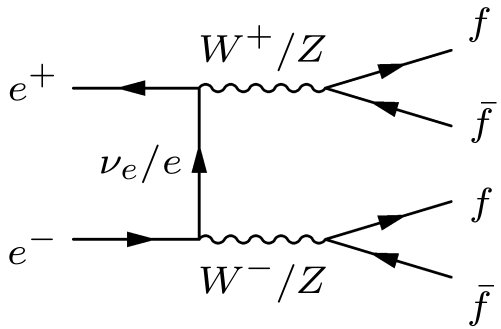
- LEP1 $\sqrt{s} \simeq 91\,\text{GeV}$ is dominated by Z production:





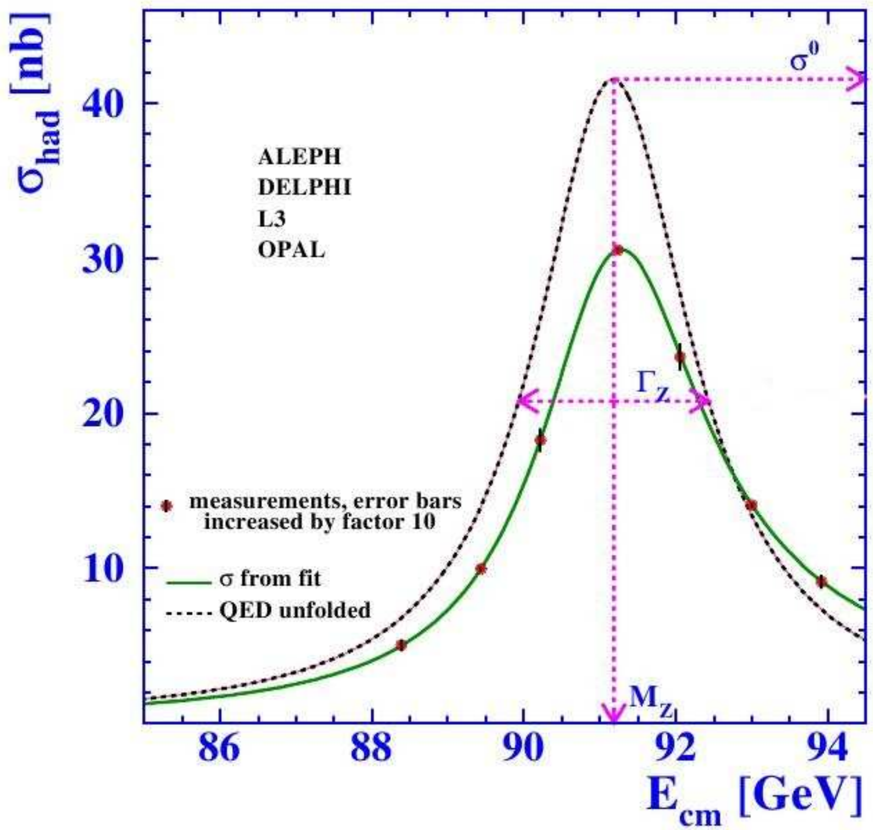
- LEP2 runs with increased beam energies three processes become more and more important:
  - Initial state photon radiation more important "Z-returns"
  - Above $\sqrt{s} \simeq 160\,\text{GeV}$ W-pair production
  - Above $\sqrt{s} \simeq 180\,\text{GeV}$ Z-pair production



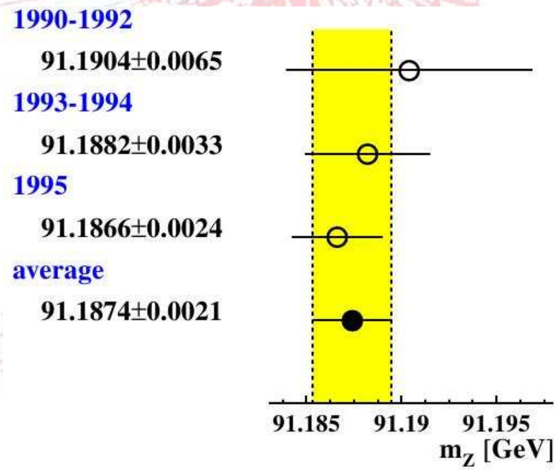


Z-Boson Mass and Width

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



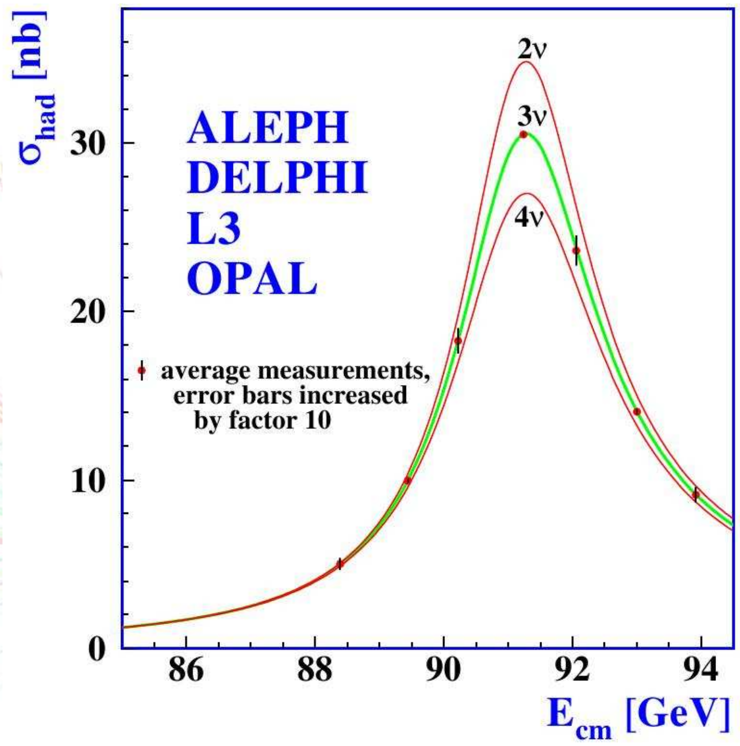
- LEP was run at ~ 7 energies near M_Z
  - Exact knowledge of $\sqrt{s}$ required
- The data are shown with error-bars that are increased by a factor of 10.
- Radiative correction modify the shape



$\Gamma = 2.4953 \pm 0.0023$ GeV

$M_Z = 91.187 \pm 0.0021$ GeV

Number of Neutrinoflavours



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

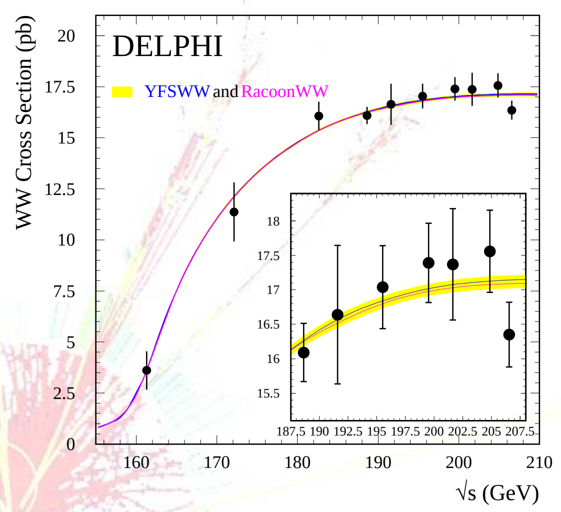
The number of neutrinos that occur in $Z \to \nu\bar{\nu}$ is $N_\nu = 2.9840 \pm 0.0082$.

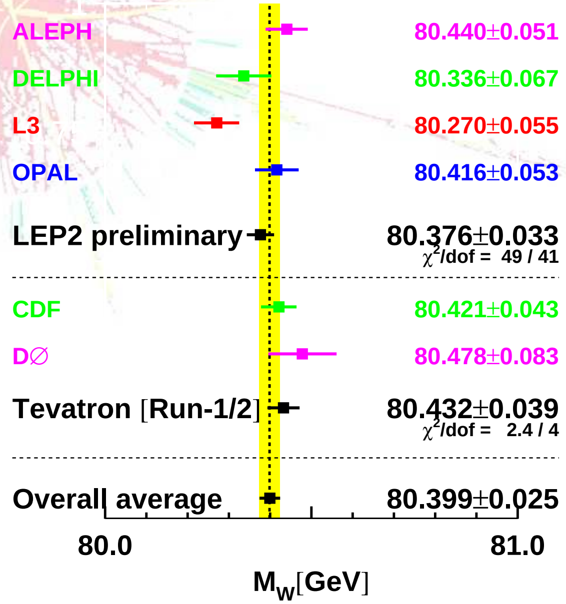
W Boson Mass (at LEP)

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 $\sqrt{s}=161...208\,$GeV ($e/\mu/\tau$+jets and 4jets)
  - apply energy momentum conservation
  - apply equality of W^+- and W^--mass
  - $\Rightarrow$ Build invariant mass from fitted objects





Combintation 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

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

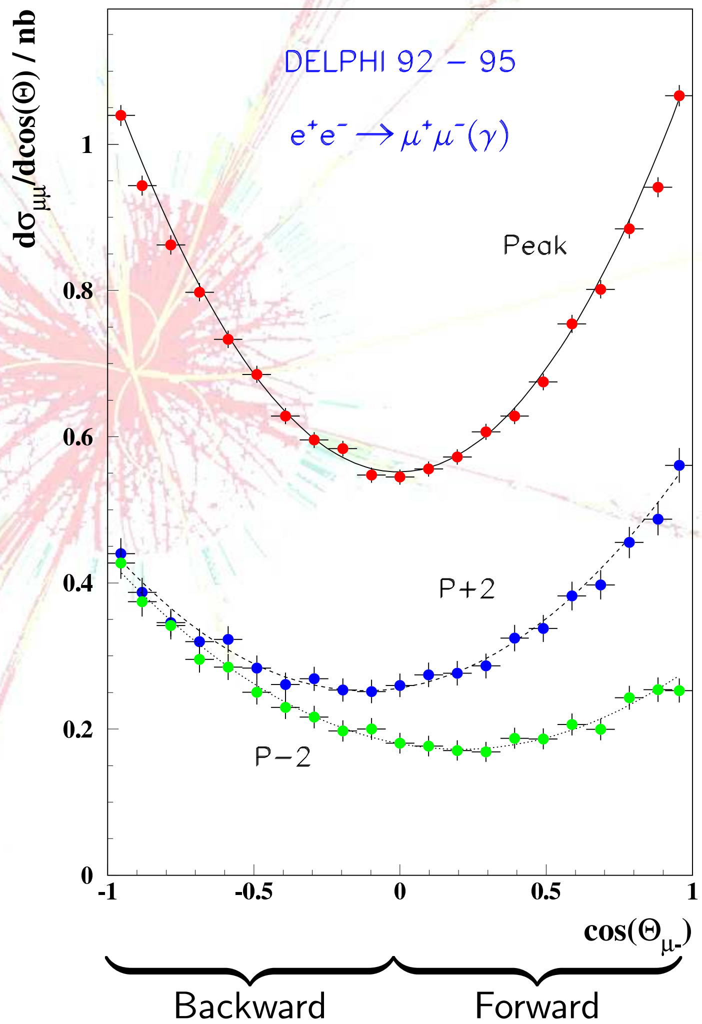
- The forward-backward asymmetry

$$A_{\mathrm{FB}}^{(0,\mu)} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}} = 0.0169 \pm 0.0013$$

strongly depends on $\sin^2\theta_W$

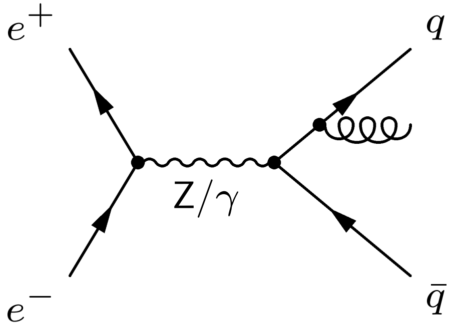
- Compare $\sin^2\theta_W$ obtained from asymmetry with the one from the Boson masses

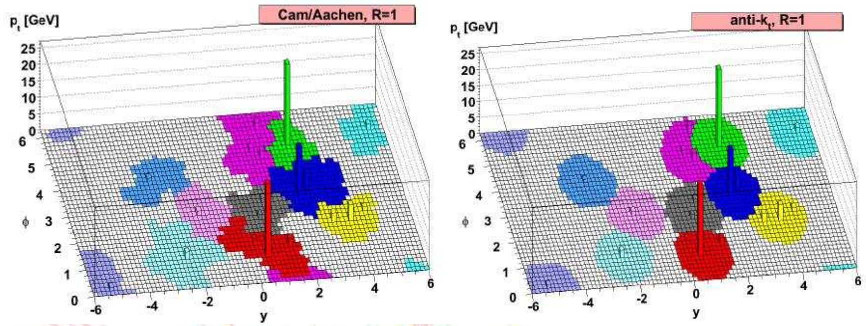
$\Rightarrow$ Excellent consistency (μ: 0.5σ, b: 2.5σ)



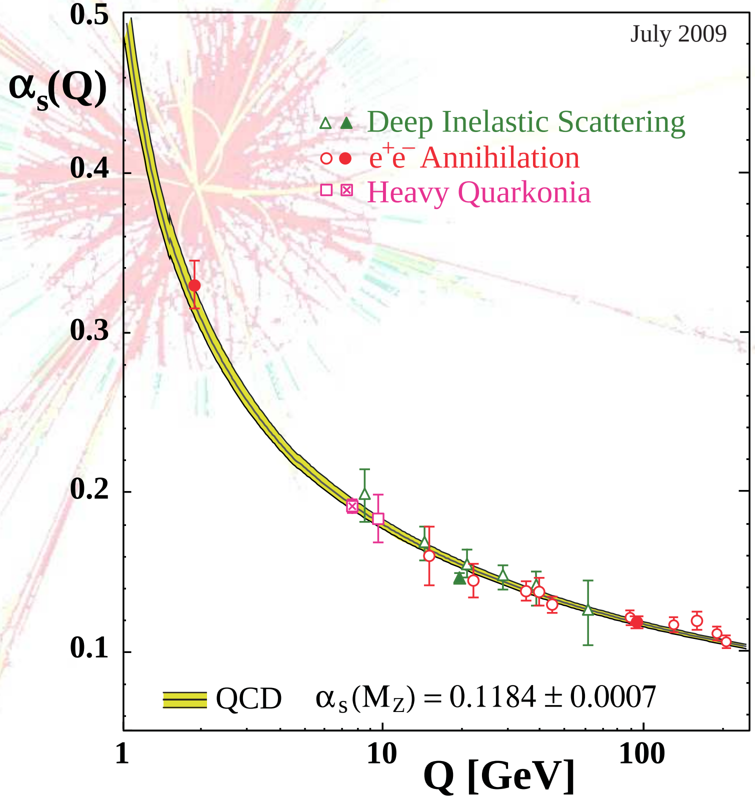
The strong coupling: α_s

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



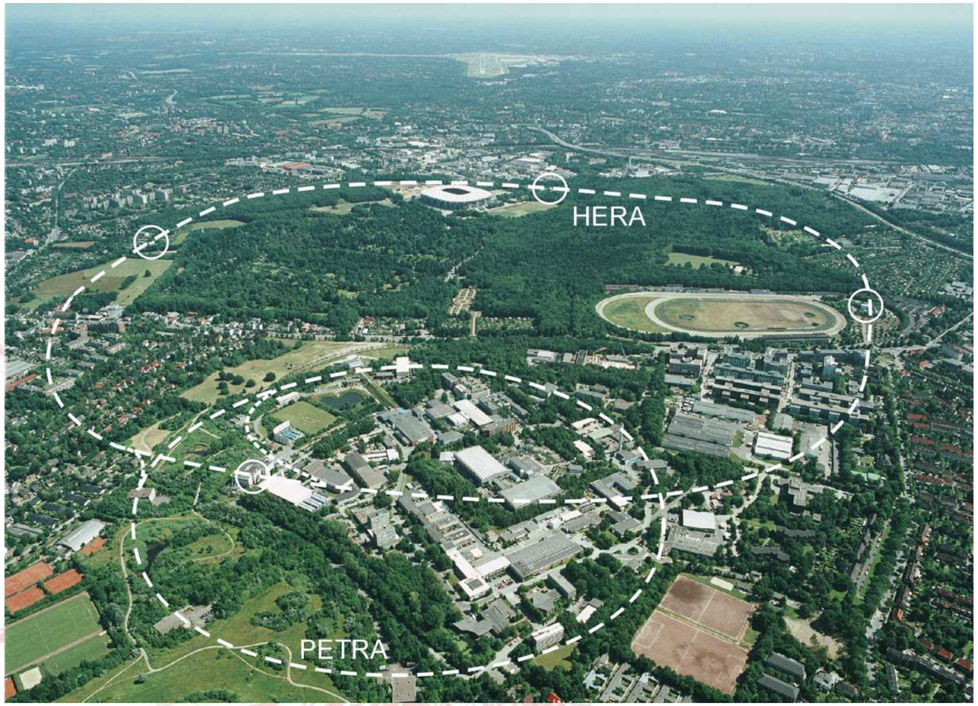


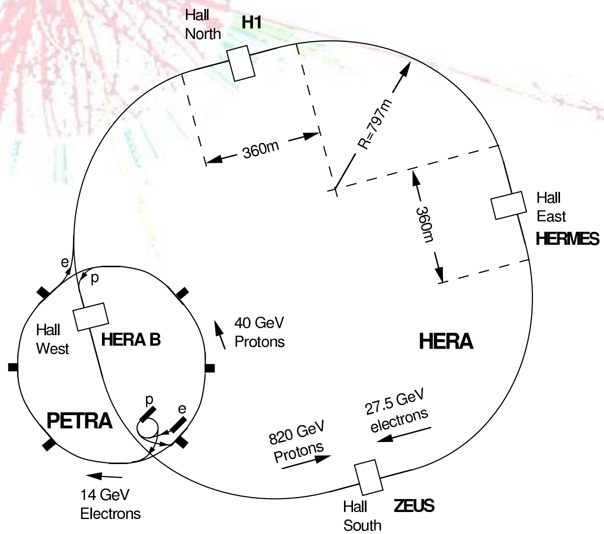
- But quarks fragment to Hadrons
- Observables are jets, sprays of hadrons
- One needs to specify what is meant by a jet
  - Many definitions exist (c.f. upper figure).
  - They are different observables.
  - All will depend on α_s
- The strong coupling is energy dependent
  $\alpha_s = 0.1184 \pm 0.007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



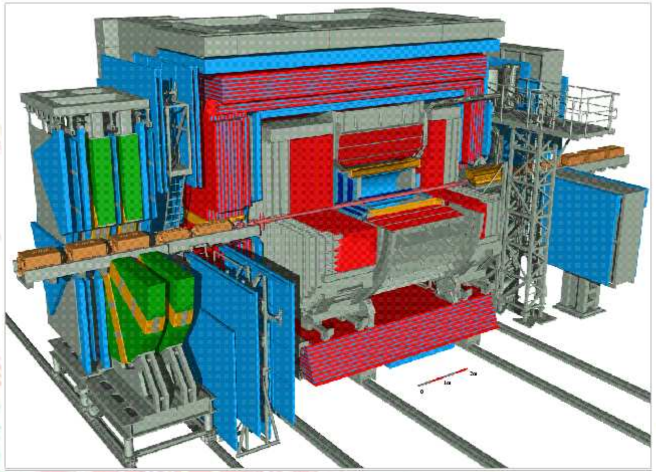
HERA

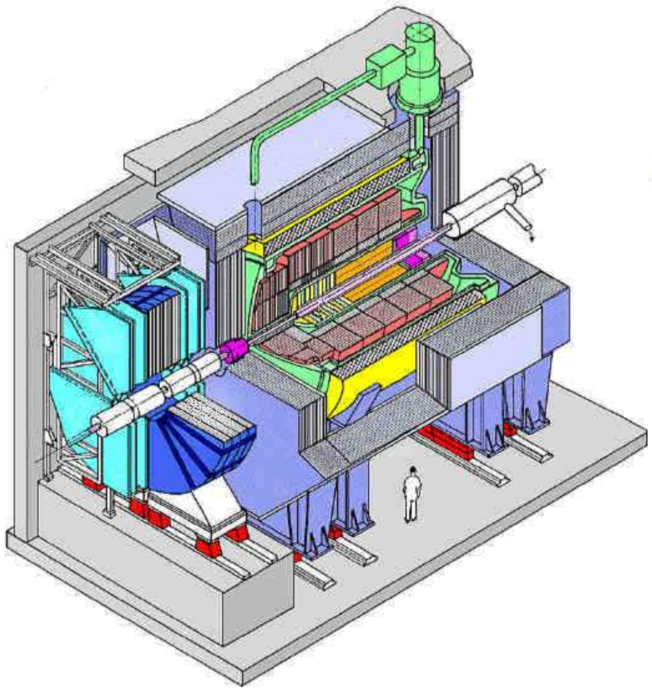
- HERA is a $e^{\pm}p$ collider
- Circumference of $6.3\,\mathrm{km}$
- HERA-I (1992-2000)
  - until 1997
    $27.5\,\text{GeV} \times 820\,\text{GeV} \Rightarrow \sqrt{s} = 300\,\text{GeV}$
  - from 1998
    $27.5\,\text{GeV} \times 920\,\text{GeV} \Rightarrow \sqrt{s} = 318\,\text{GeV}$
- 2001-2002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

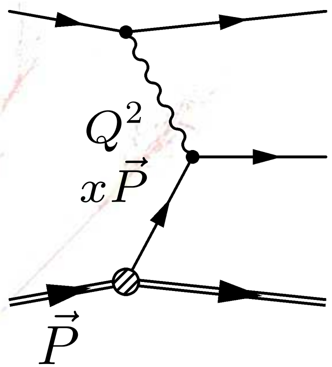
HERA-B
Specialised in B Physics

HERMES
Specialised in Proton Spin

about $500\,\text{pb}^{-1}$ per experiment

Parton Density

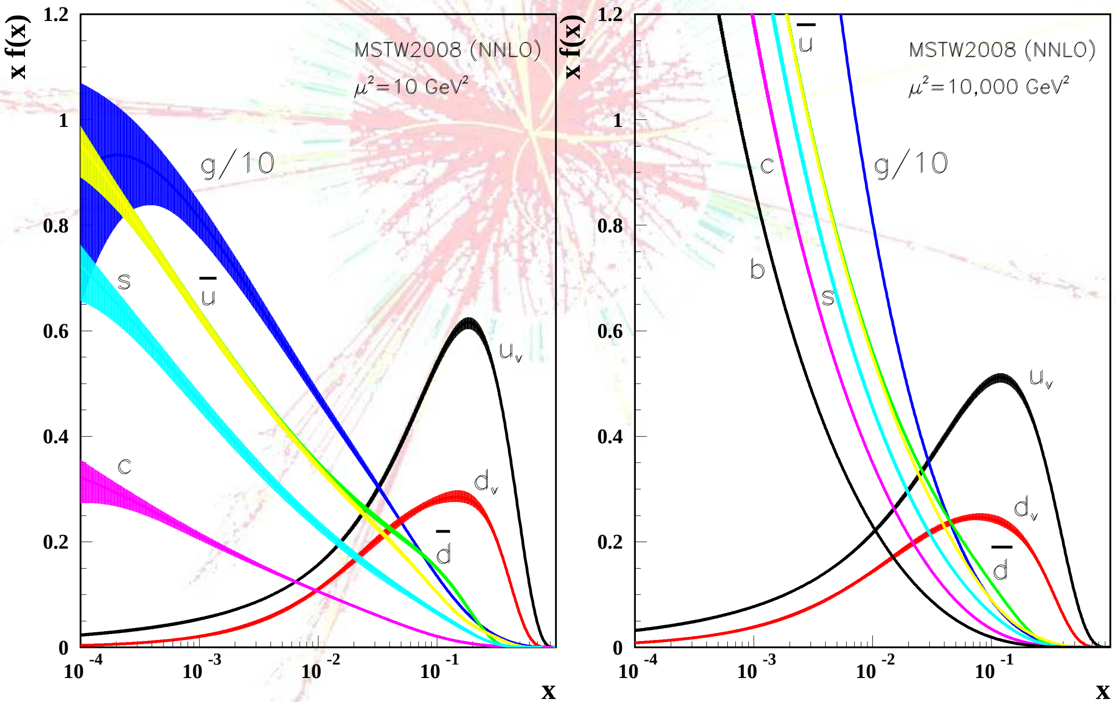
- At high energies contents of proton is probed
- Only one parton participates in reaction with $e^{\pm}$
- This will only carry a fraction (x) of the proton momentum



- 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)

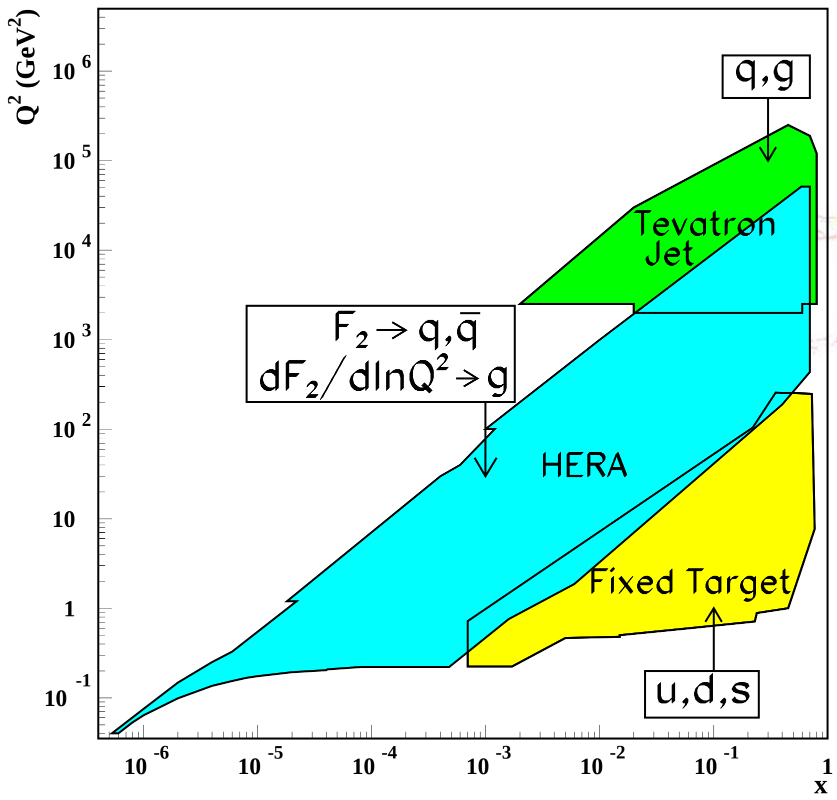
  the more details we see (more splittings $\Rightarrow$ more partons with lower x)

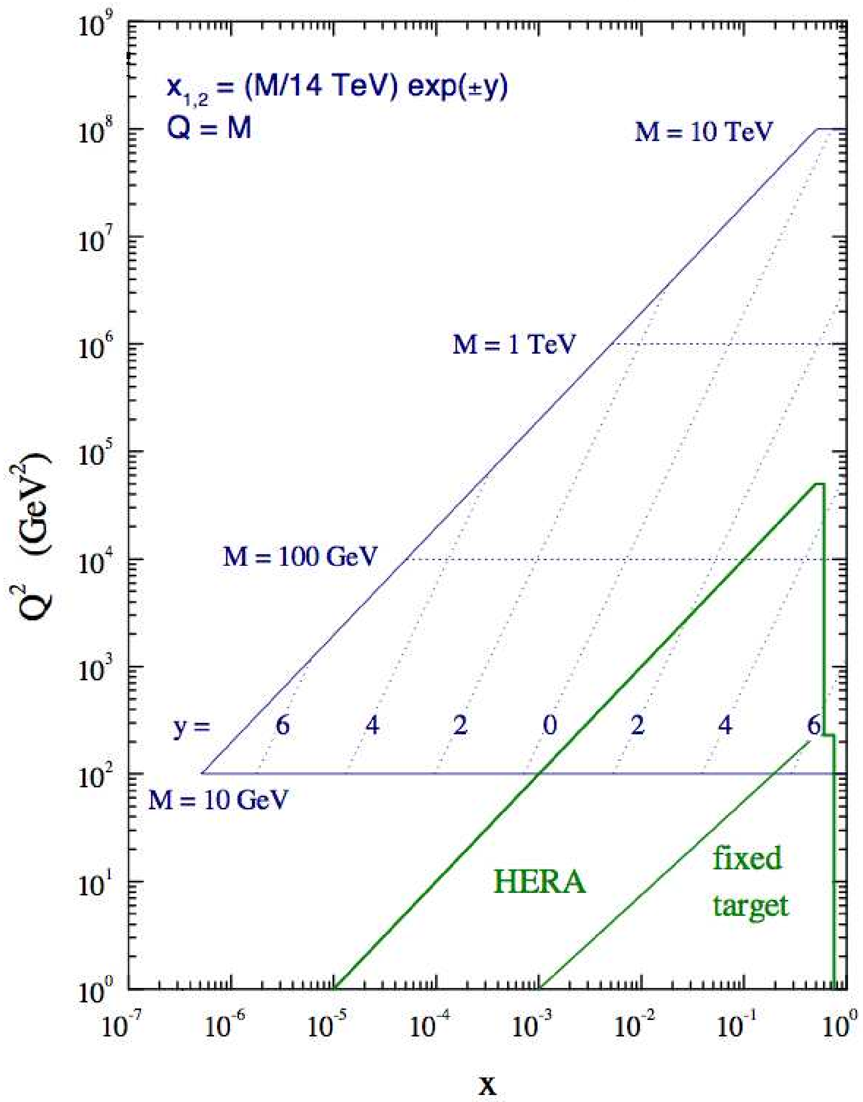
  "Scaling violation"



Kinematic Range of Hera vs. LHC

- Low x results from Hera

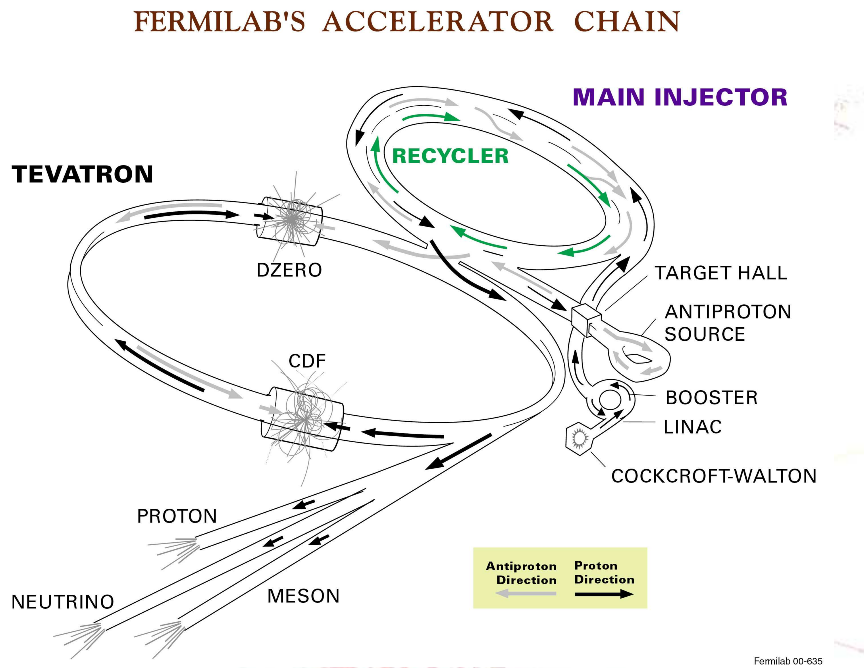


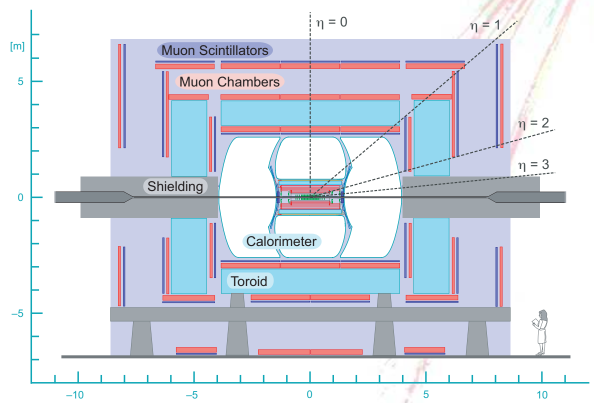


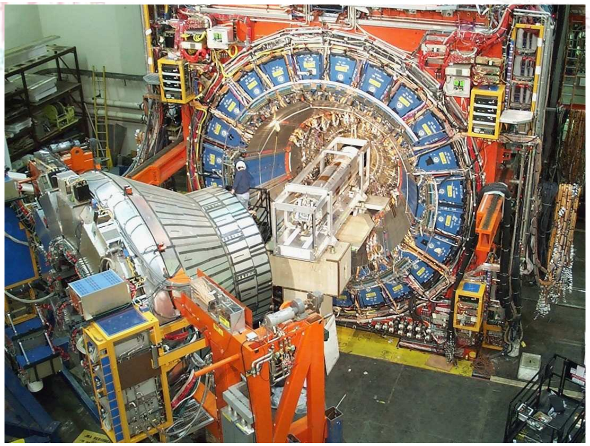
The $p\bar{p}$ Accelerator Tevatron

- Circumfence 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.

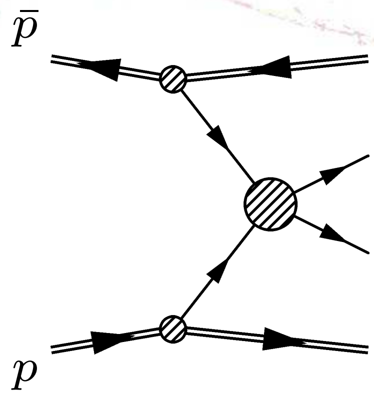
  $\mathcal{L} \sim 7\,\text{fb}^{-1}$ on tape.







The Tevatron



- Now PDF need to be applied at both sides.

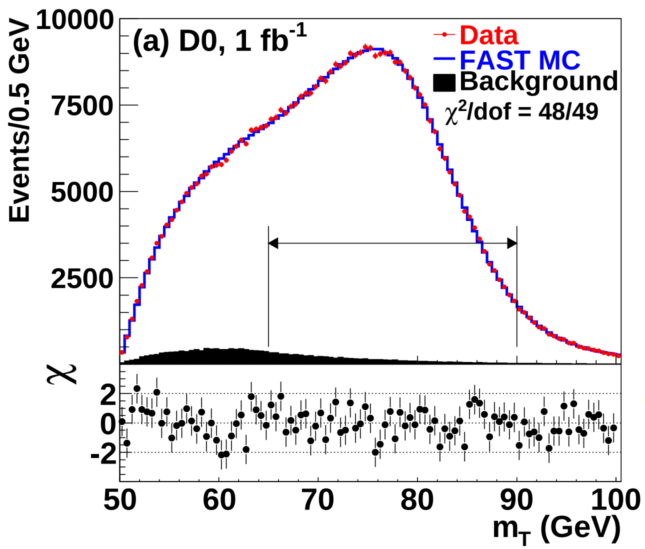
W-Boson Mass (at the Tevatron)

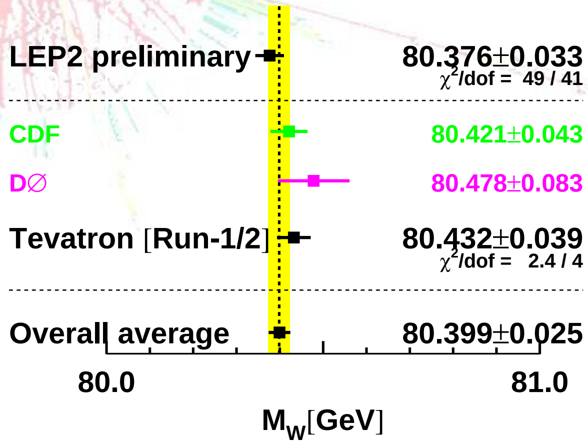
- Only leptonic decay can be found in hadron collisions

- Momentum conservation only applicable in transverse plane
  $\Rightarrow$ Only p_x and p_y accessible for neutrino

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

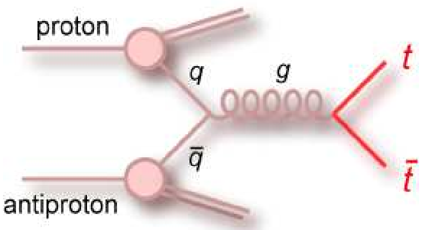
Combintation of all LEP experiments and Tevatron
$M_W = 80.399 \pm 0.025\,\text{GeV}$



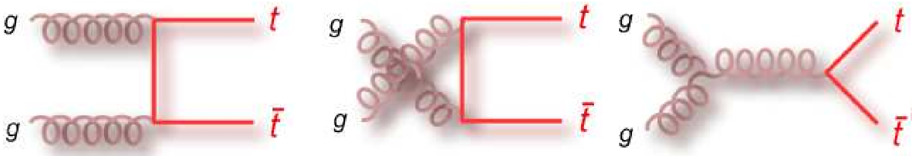


Top Quark Production at the Tevatron

Strong top production

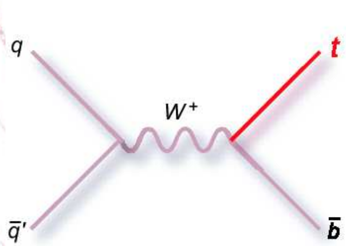


$$
\begin{array}{ll}
85\% & q\bar{q} \to t\bar{t} \\
15\% & gg \to t\bar{t}
\end{array}
$$



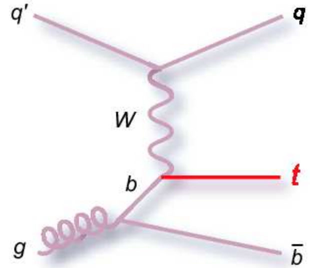
$\sigma(t\bar{t}) \simeq 7.46\text{pb}$

Weak top production



Drell-Yan

s-channel

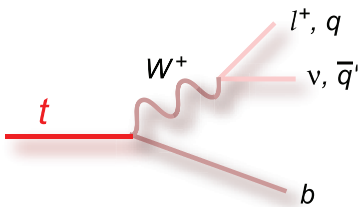


W-g fusion

t-channel

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

Top Quark Decay



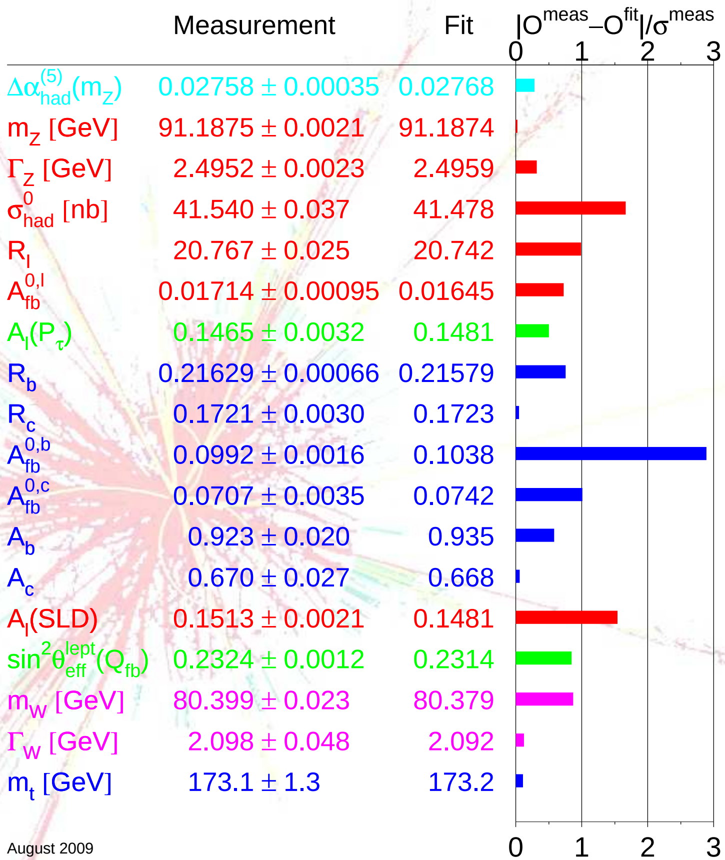
$\sim 100\%$ to $W + b$

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

Fits of Electroweak Parameters

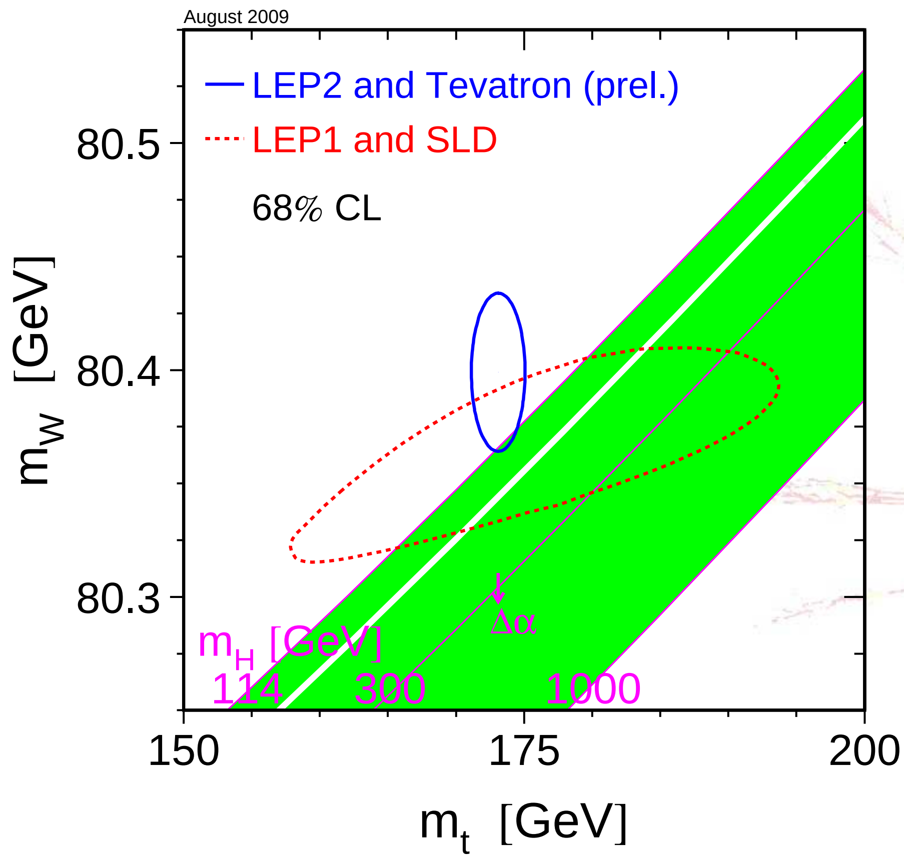
- Precision measurements of electroweak obs.
  - Strong coupling
  - Z mass and width
  - W mass and width
  - t mass
  - Asymmetries,. . .

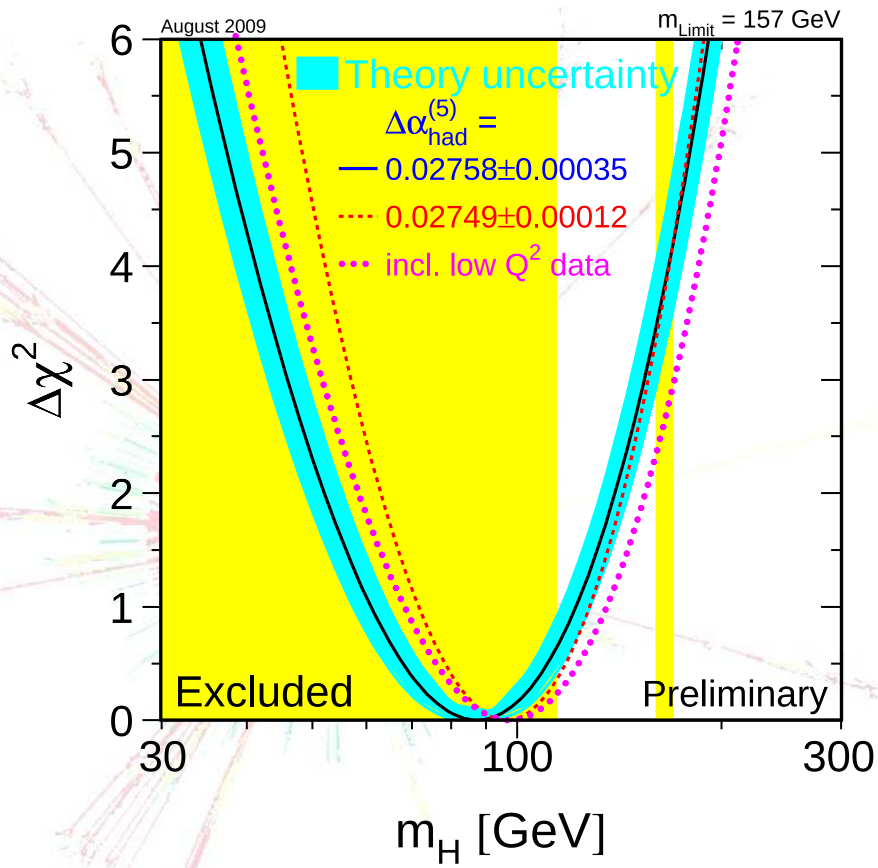
  are related directly or in loop diagrams
- All data are in excellent agreement
- Biggest deviation 3σ (1 of 18)



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

Top and W Mass in Elektroweak Fits



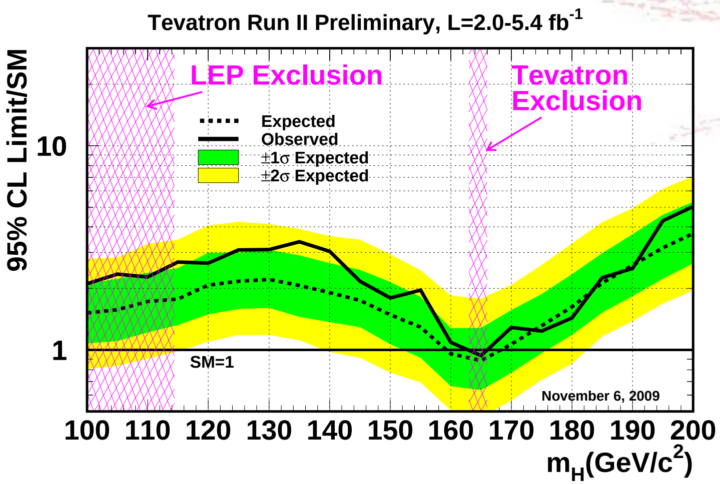


Combined m_W and m_t results touch SM-range only barely

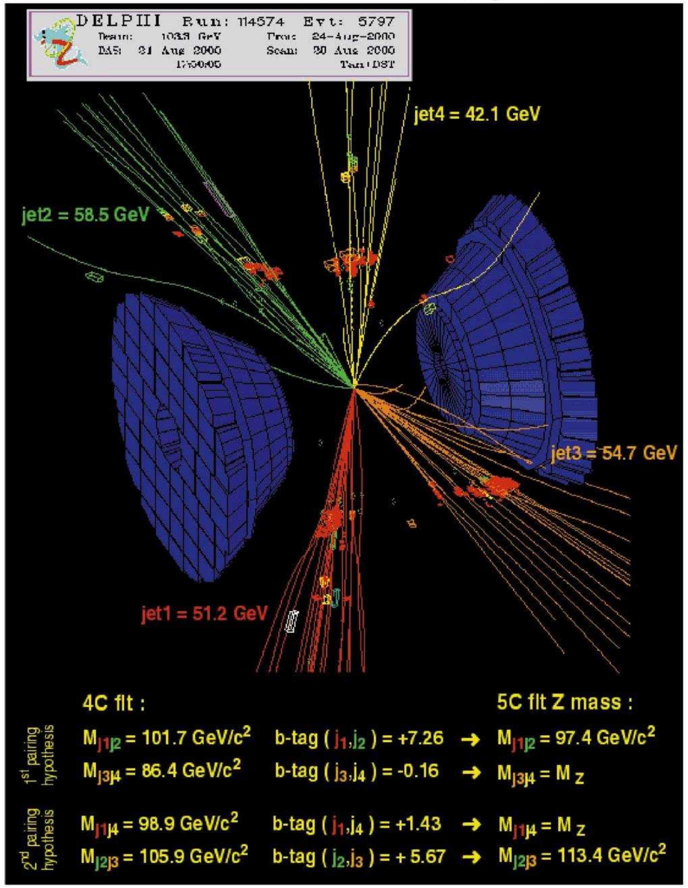
Projection to Higgs mass $M_H \leq 157\,\text{GeV}$ $(95\%\text{CL})$

Higgs Limits

- LEP (low M_H): $e^+e^- \to Z \to ZH \to q\bar{q}b\bar{b}$
  - $M_H > 114.4\,$GeV
- Tevatron (high M_H): $p\bar{p} \to H \to WW$
  - $M_H = 162\ldots166\,$GeV excluded at 95%C.L.



DELPHI Higgs candidate:



Expected luminosity at the Tevatron not sufficient for discovery.

Open Questions in Particle Physics

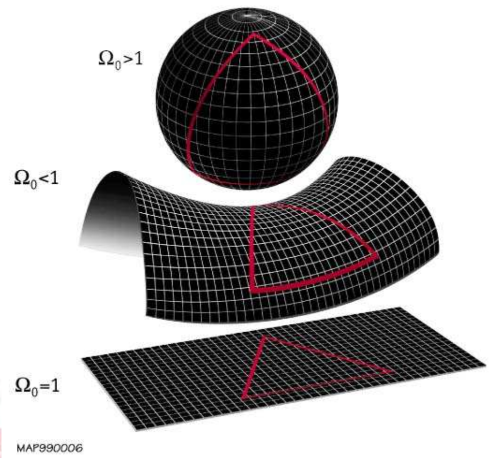
- How can we incorporate gravity?

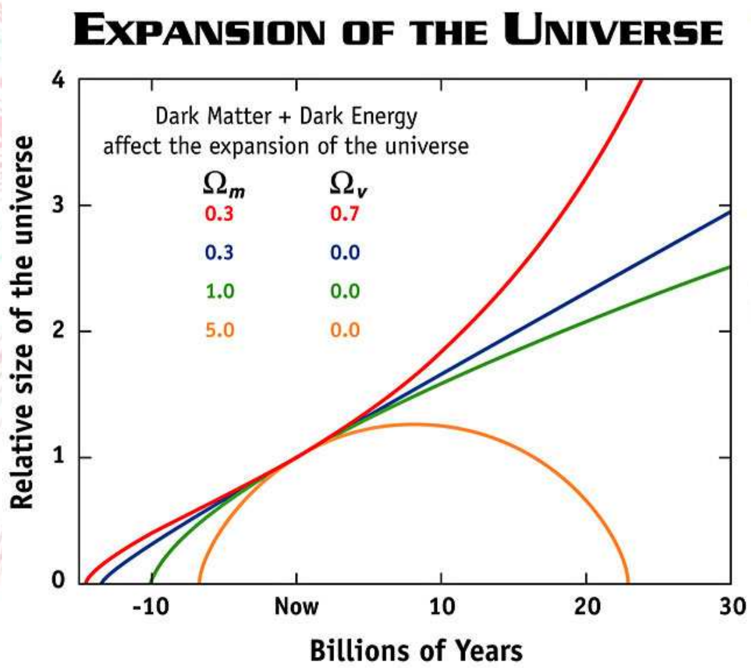
- Is the Higgs mechanism the right idea?
  - Why is the Higgs so light?
    (It should receive huge radiative corrections, "hierarchy problem")

- Why are the charges quantised?

Cosmology in a Nutshell

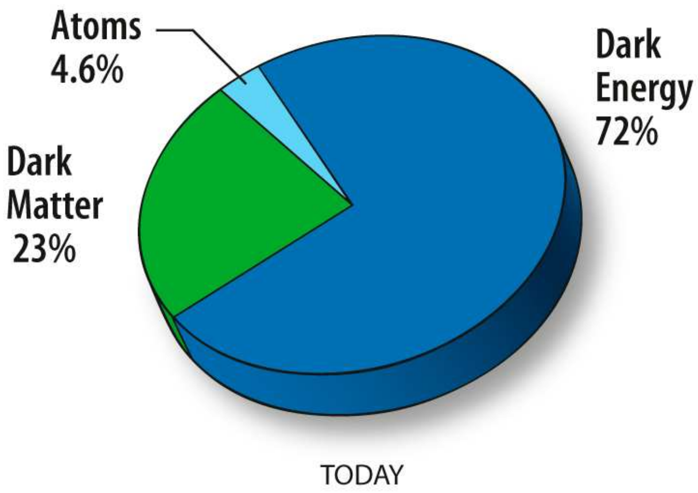
- The Universe started in Big Bang
- Described by Einsteins General Relativity
- Space time could be
  - Flat
  - Negatively curved
  - Positively curved
- Its expansion could be
  - accelerating forever
  - decelerating, but expanding forever
  - decelerating and collaps
- Governed by energy and matter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

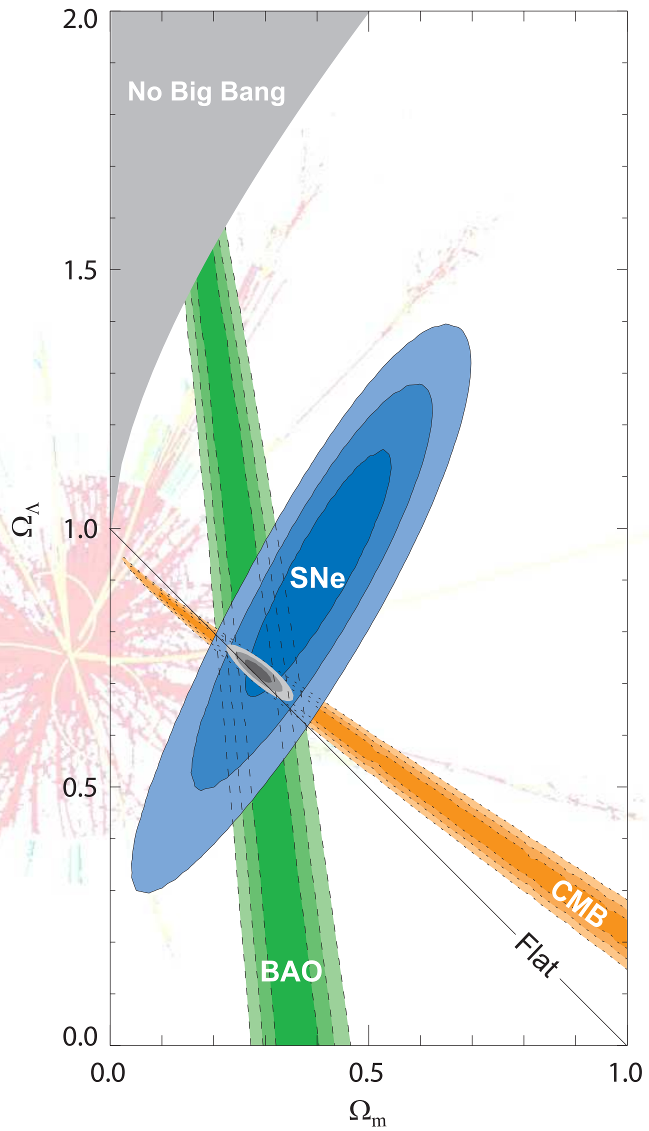




Cosmology: Experimental Status

- 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 phyiscs at the Terascale can solve some of these problems

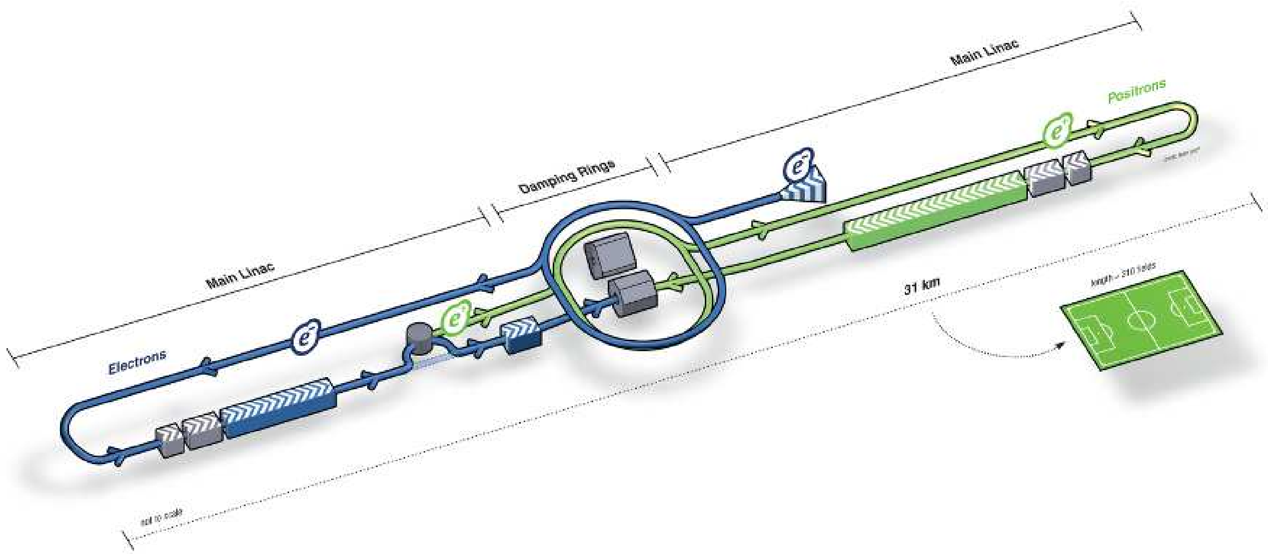
The International Linear Collider

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. $30\,\text{km}$
- Extreme focus ($5\,\text{nm}$) required

Status: Research and Design ongoing

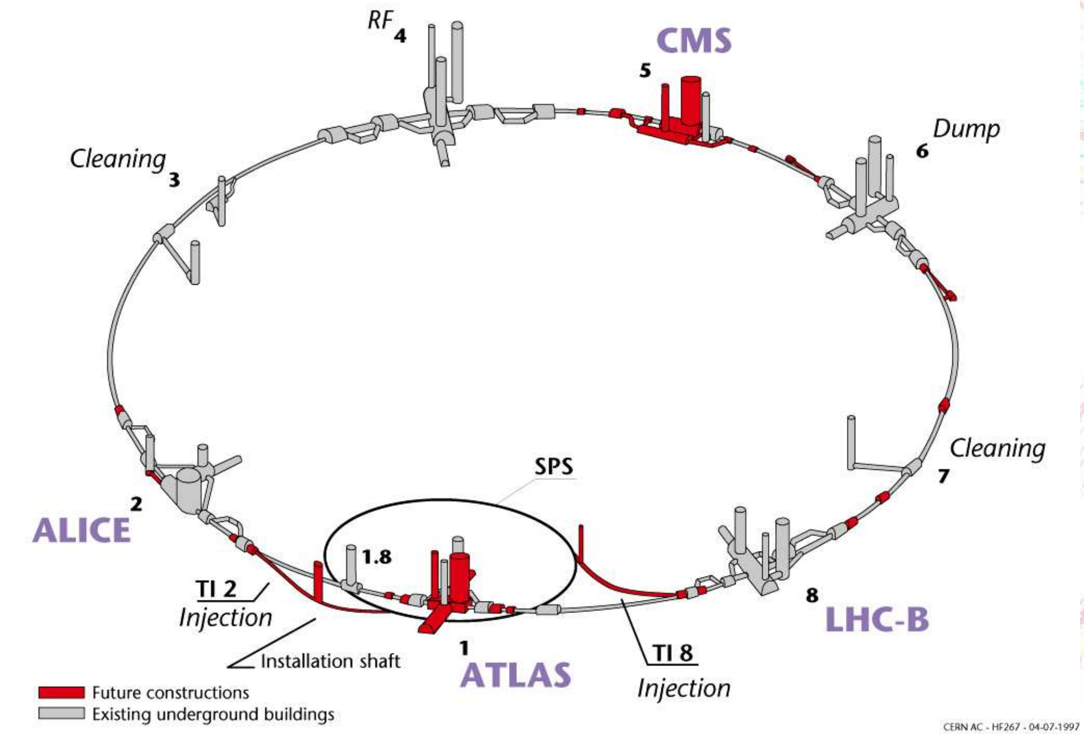
Tech. Design Report end of 2012

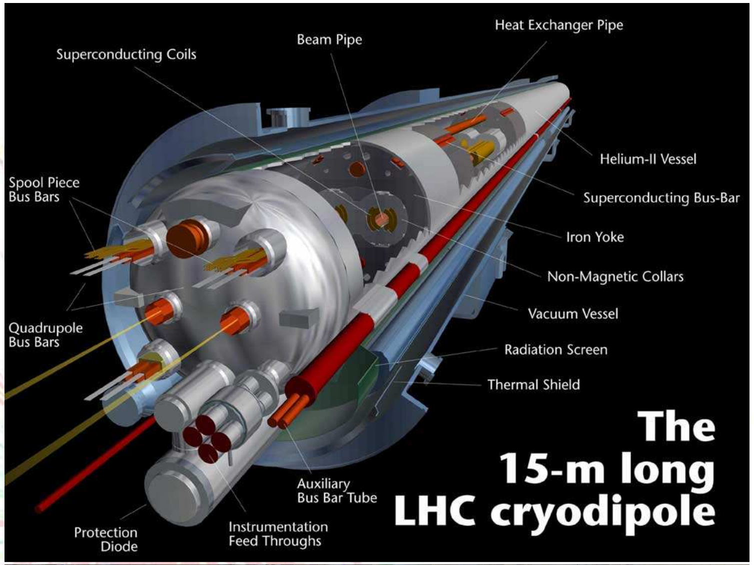
The Large Hadron Collider

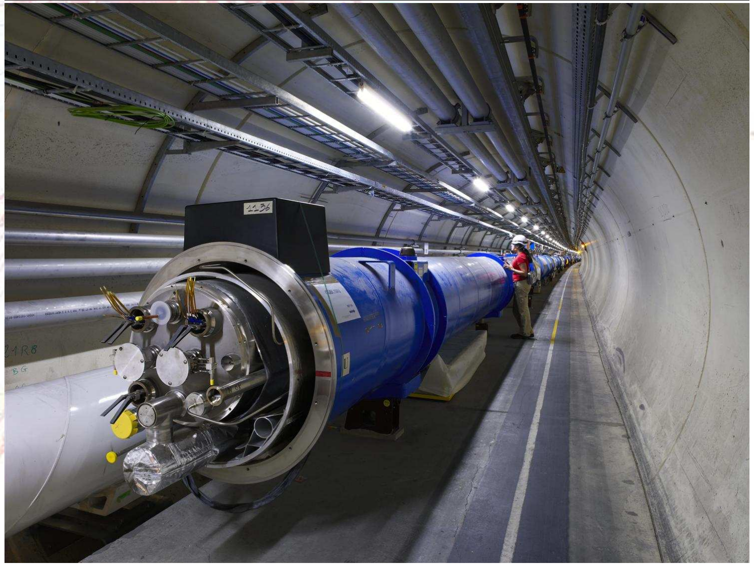
LHC

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

Layout of the LEP tunnel including future LHC infrastructures.

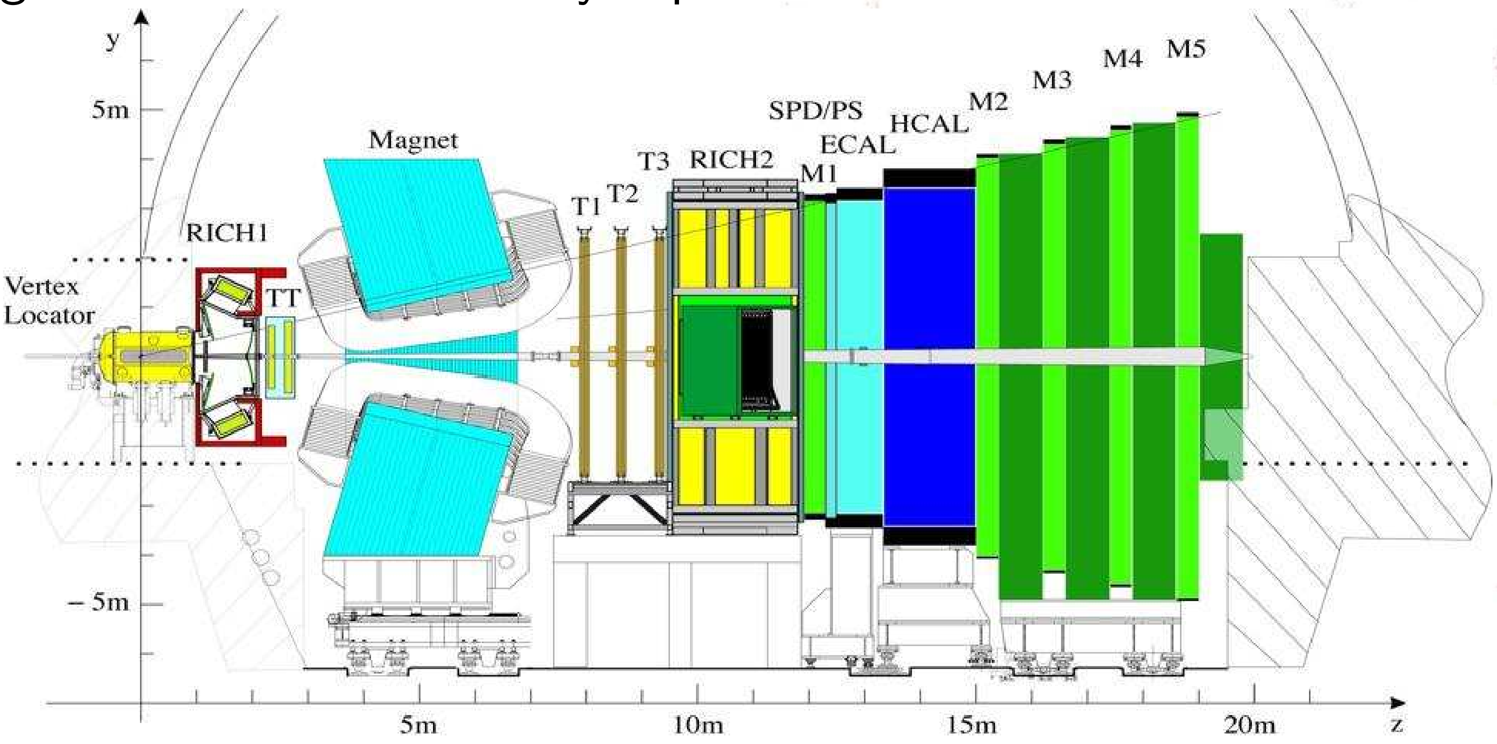






LHCb

The Large Hadron Collider beauty experiment

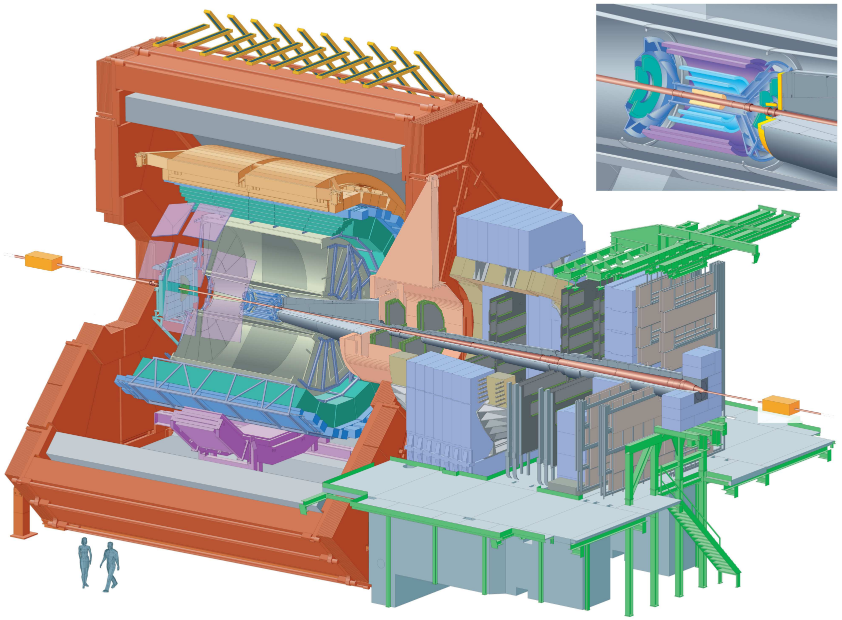


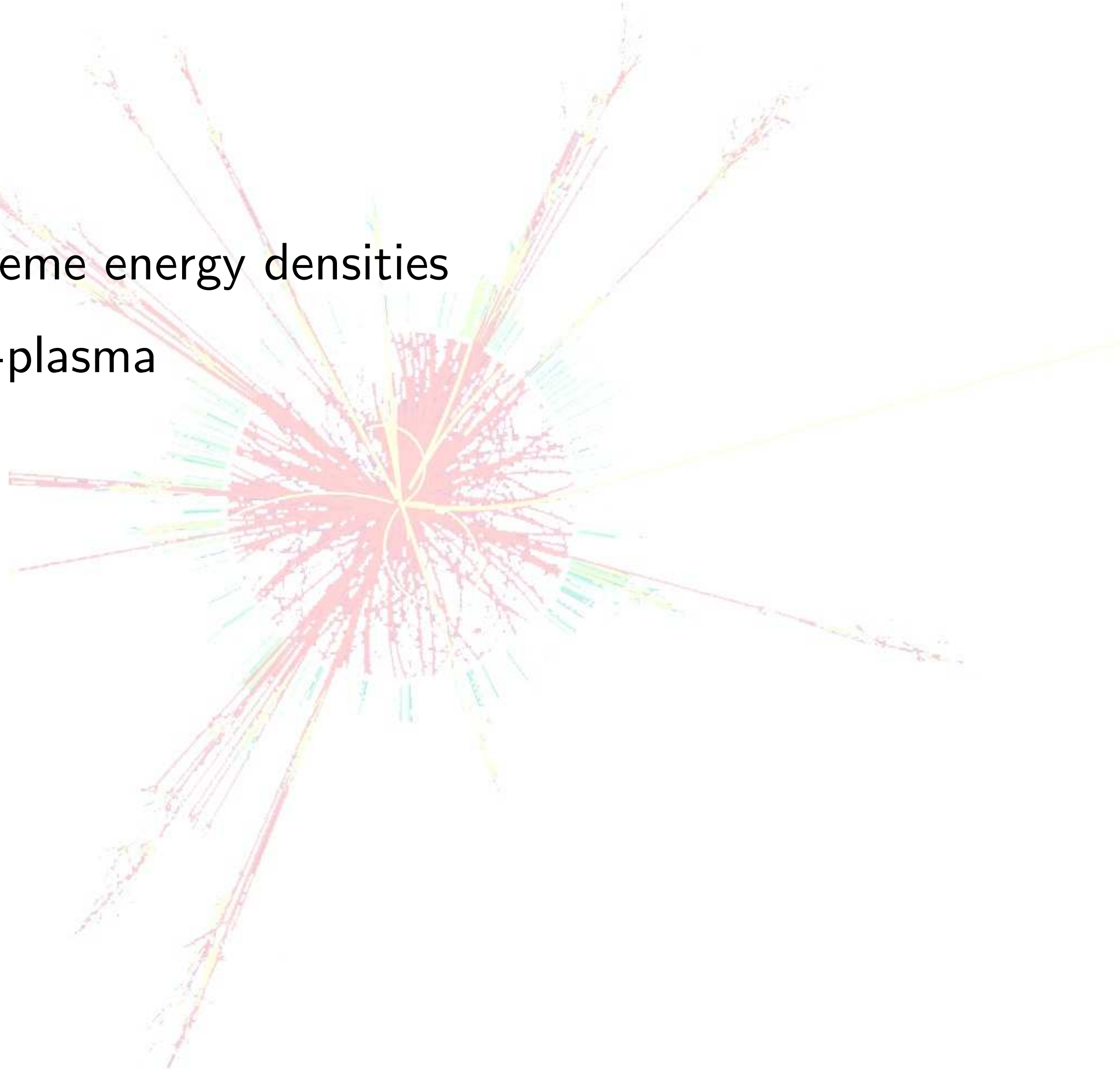
- Interaction point at one end of detector
- Only forward region equipped
- Specialises on b physics

ALICE

A Large Ion Collider Experiment

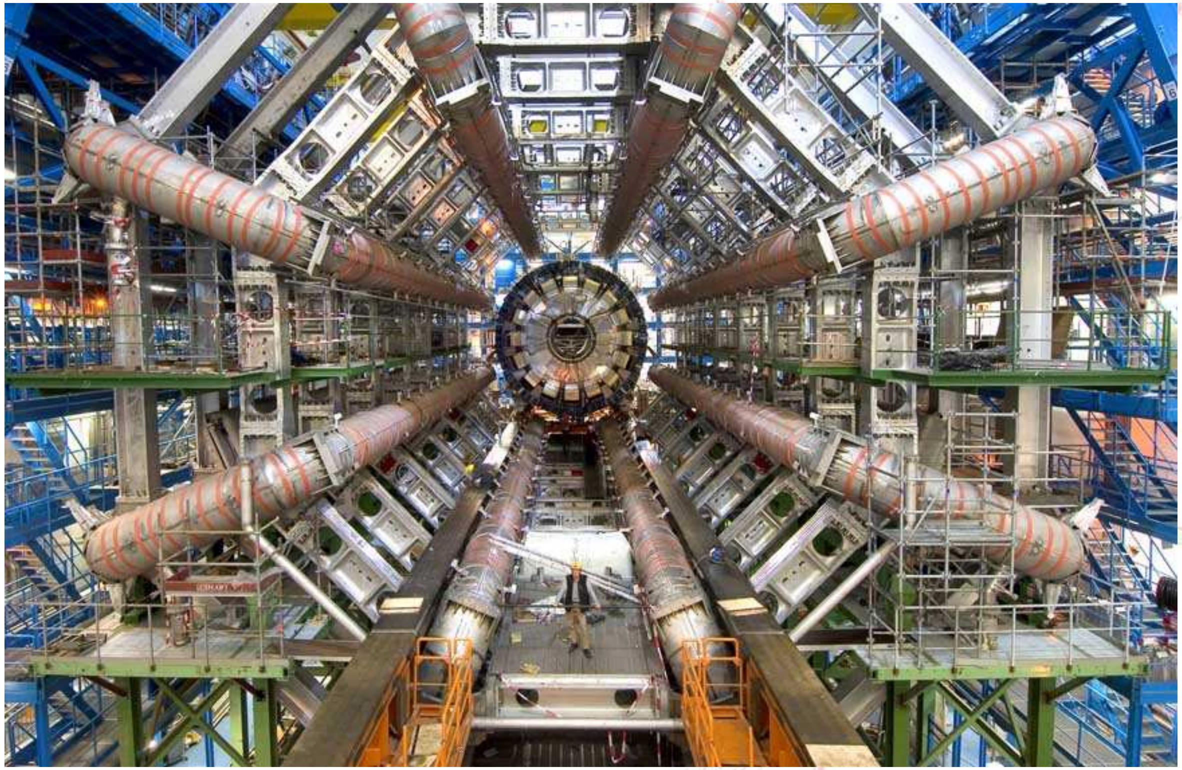
- Specialises on heavy ion collision
- Strongly interacting matter at extreme energy densities
- New phase of matter: quark-gluon-plasma





ATLAS

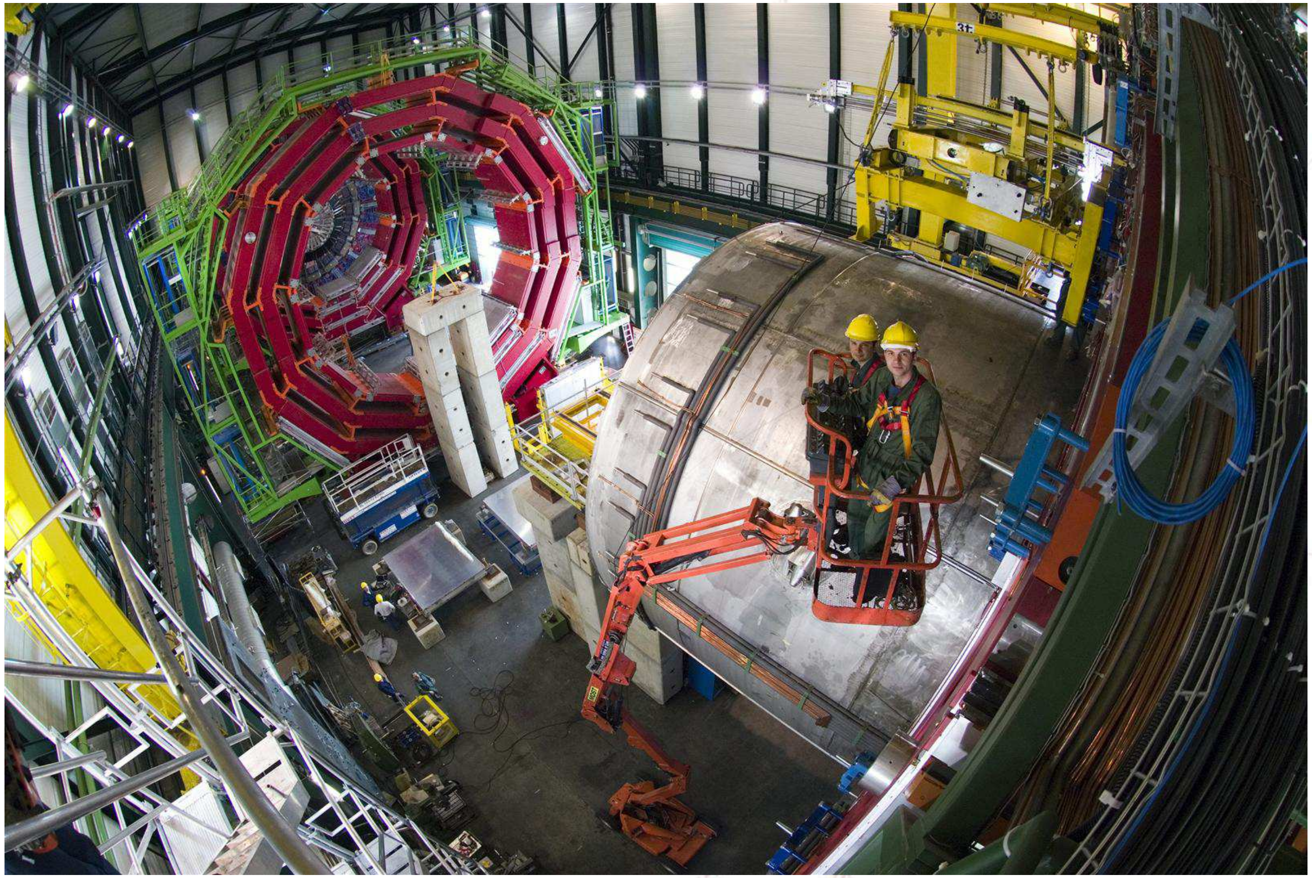
(Originally for "A Toroidal LHC ApparatuS")



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

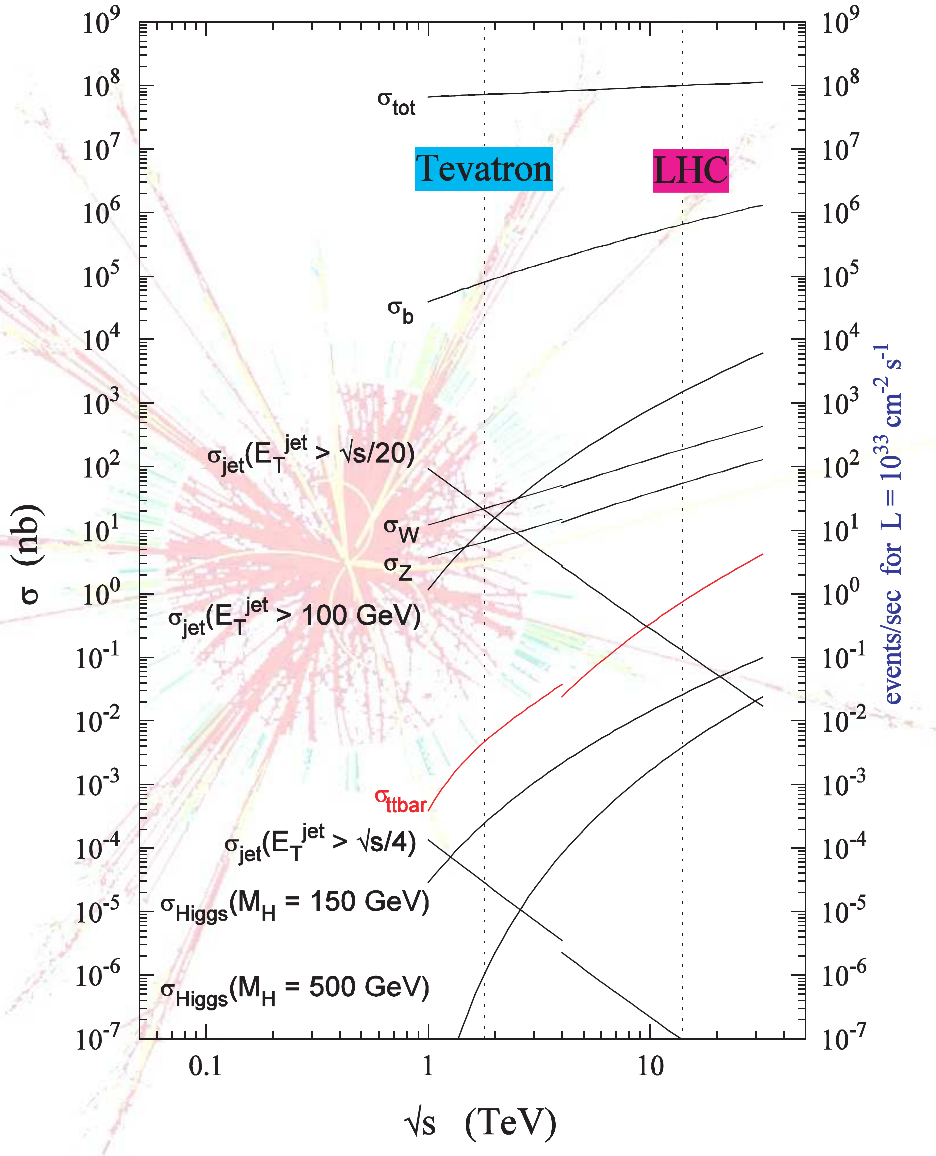
CMS

The Compact Muon Solenoid Experiment



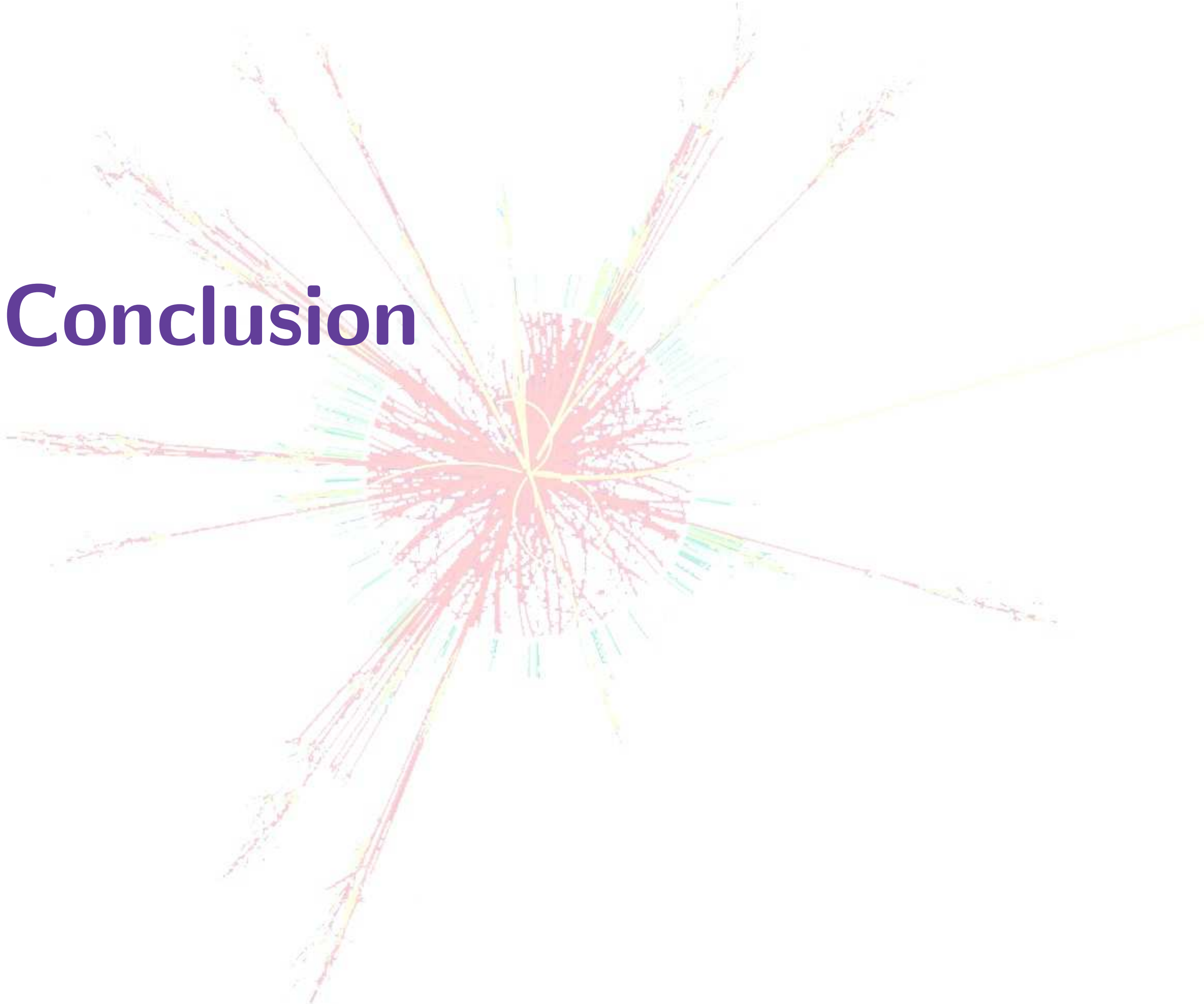
- Heaviest of the LHC experiments
- General purpose 4π detector
- Aims to find Higgs
- . . . and to find new physics

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)