Hunting for Precision at High Energies

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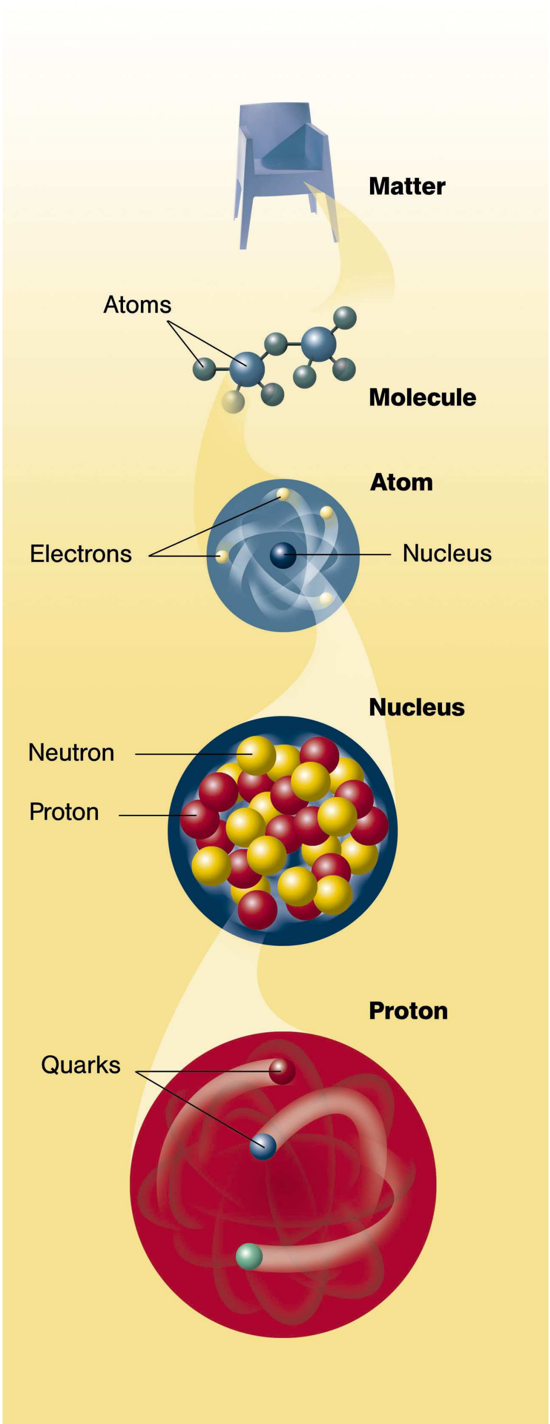
What we have learned: The Standard Model

Why we need Precision

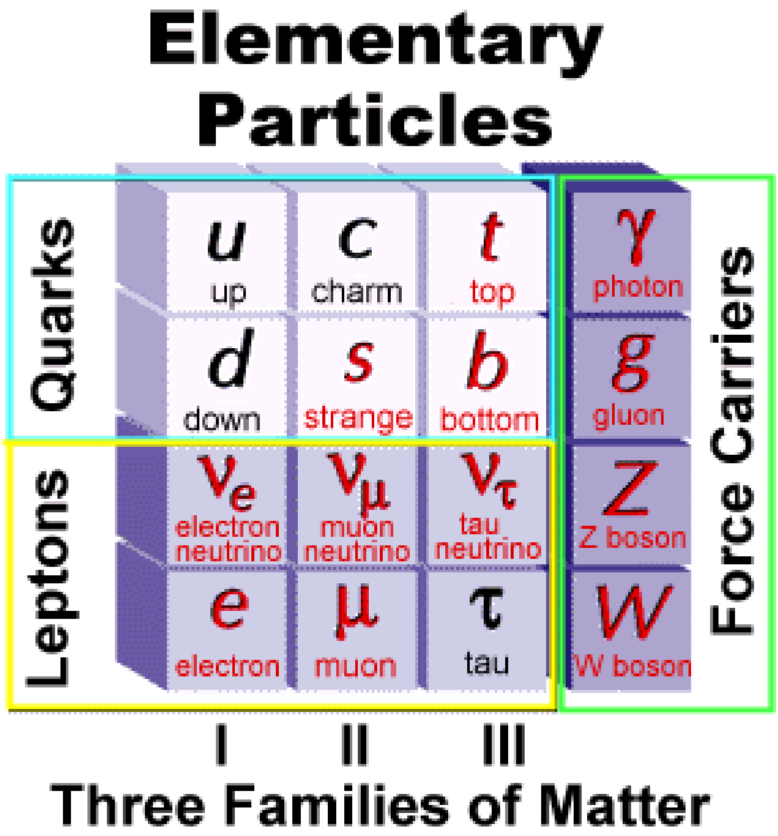
International Cooperation

Conclusions

The Standard Model

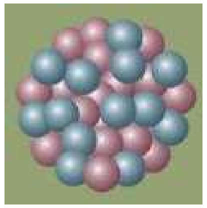
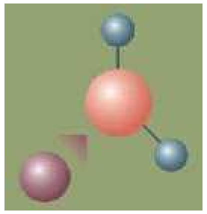
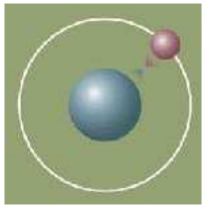
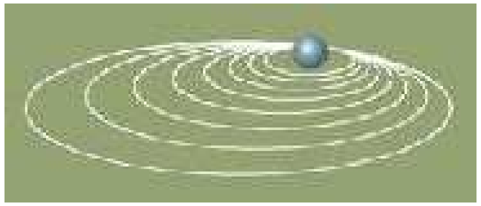


Matter



Forces

Basic Principles

Forces	 *Strong*	 *Weak*	 *Electromagnetic*	 *Gravitational*
Responsible for	Nuclear Stability	Radioactivity	Chemistry	Earth, Solar system ...
Experienced by	Quarks	Quarks, Leptons	Electrically charged	All
Force Carriers	**Gluons***	W^+, W^-, Z	γ	irrelevant at typical
Symmetry	SU(3)	SU(2)	U(1)	subatomic distances
Coupling	g_3	g_2	g_1	... but **new ideas**

* Gluons first *seen* at PETRA (DESY Hamburg) 1979

Basic Principles

- **Relativistic Quantum Field Theory**
- **Gauge Symmetry** [Glashow, Salam, Weinberg '60s $\rightsquigarrow$ Nobel Prize '79]
- **Higgs mechanism**: **origin of masses** **Higgs particle needed!!**

  Massive W and Z predicted and discovered at CERN!

  [C. Rubbia & S. van der Meer '83 $\rightsquigarrow$ Nobel Prize '84]

Why we need Precision

Historical perspective:

	Precision measurements of ...			led to ...	
1600	Planetary motion	[T. Brahe]	1609	Kepler Laws	[J. Kepler]
			1666	Classical Gravity	[I. Newton]
1881	Speed of light	[A. Michelson]	1905	Special Relativity	[A. Einstein]
1900	Blackbody spectrum	[Kurlbaum, Rubens]	1900	1st Quantum Theory	[M. Planck]
1885	Atomic spectral series	[J. Balmer]	1925	Quantum Mechanics	[W. Heisenberg]
			...		[Schrödinger; Pauli; ...]
1950	K–meson system		1956	P violation	[Lee, Yang]
...			1964	CP violation	[Christenson *et al*]
			1970	Charm	[Glashow, Iliopoulus, Maiani]
1969	Deep inelastic scattering	[Friedman, Kendall, Taylor]	1973	QCD	[Gross, Wilczek; Politzer]

Precision tests of the Standard Model

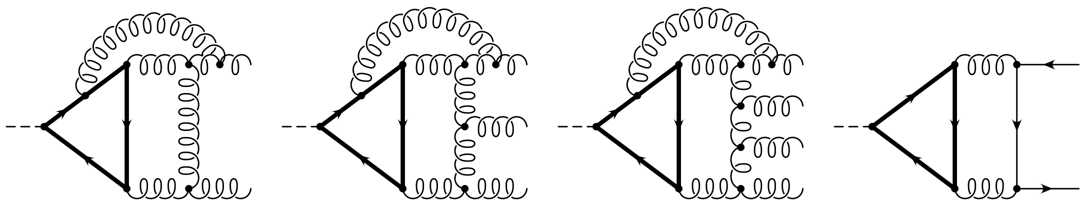
Accurate experiments $\leftrightarrow$ **precise theoretical predictions**

at the level of *quantum corrections*

The **Standard Model** is **renormalizable** $\rightarrow$ preserves its *predictive* power at the quantum level

['t Hooft & Veltman '72 $\rightsquigarrow$ Nobel Prize '99]

Very complex calculations: diagramatic approach with **loops** and **legs**



- ▷ **precision tests of QCD**
- ▷ **way to the top quark discovery** and **hint at the Higgs mass**
- ▷ **anomalous magnetic moments** of electron and muon

Precision tests of QCD couplings run with the energy
asymptotic freedom of strong interactions

The running of the strong coupling to 4 loops

$$Q^2 \frac{da_s}{dQ^2} = -\beta_0 a_s^2 - \beta_1 a_s^3 - \beta_2 a_s^4 - \beta_3 a_s^5 \ \ldots \qquad [a_s \equiv \alpha_s/4\pi]$$

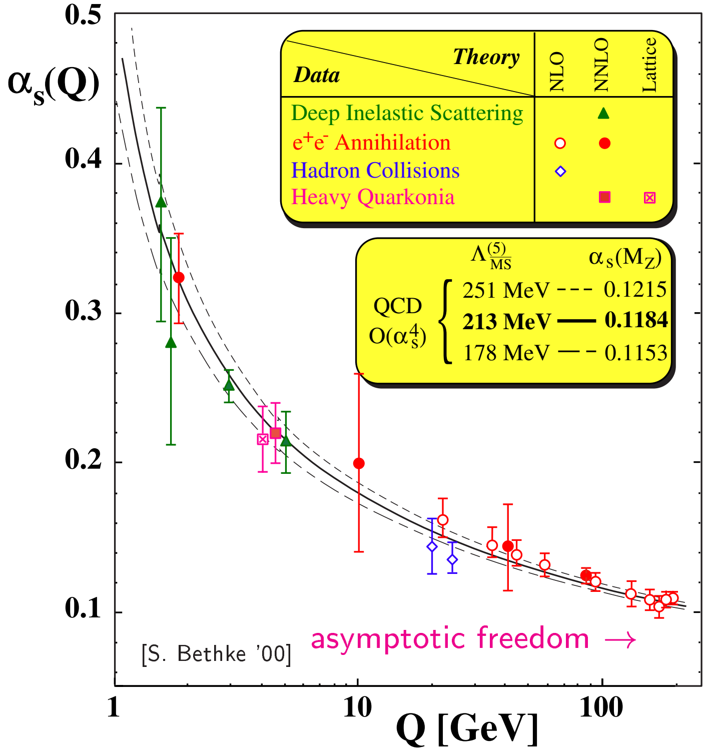
≈ 50000 diagrams!

1973 : $\beta_0 = 11 - \frac{2}{3} N_f$

1974 : $\beta_1 = 102 - \frac{38}{3} N_f$ ◁

1979 : $\beta_2 = \frac{2857}{2} - \frac{5033}{18} N_f + \frac{325}{54} N_f^2$

1997 : $\beta_3 = \frac{36389979 - 9705249 N_f + 450585 N_f^2 + 2186 N_f^3}{1458} + \frac{288684 - 19524 N_f + 6472 N_f^2}{81} \zeta_3$



Anomalous dimension to 3 loops

10846 diagrams!

◁

$\Downarrow$

needed to extract a precise gluon density and to determine α_s with a theory error of 1%

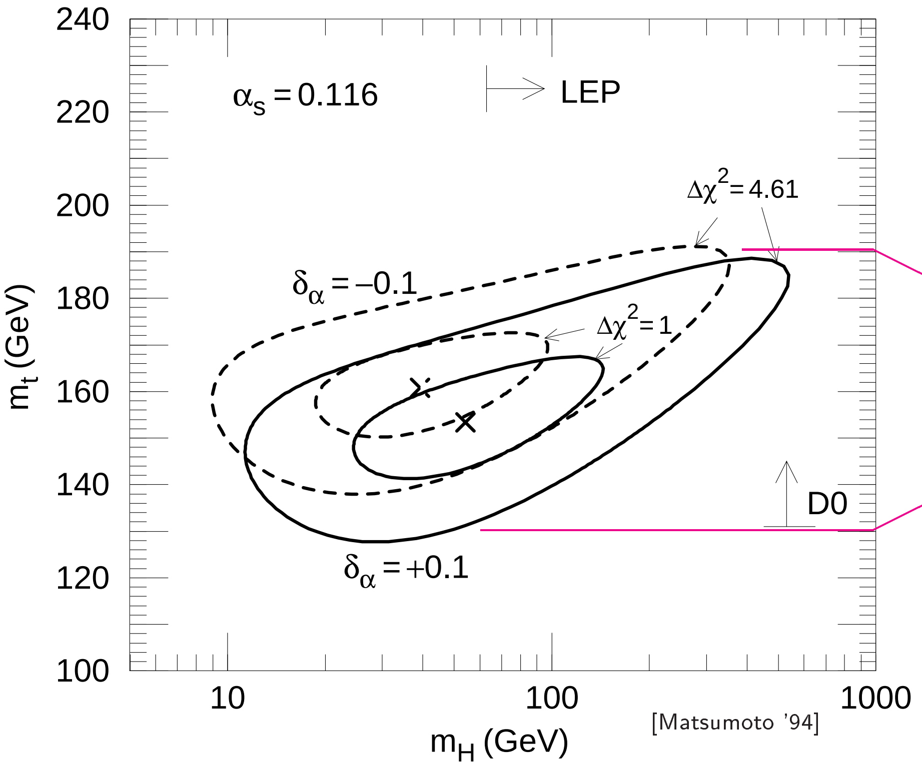
goal of HERA experiments

The top quark discovery great success of precision tests

Quantum corrections sensitive to heavy masses $(t,\, H,\, \ldots)$

Precision tests

Just before top quark discovery (1994)



$130 \text{ GeV} \lesssim m_t \lesssim 190 \text{ GeV}$

Top quark discovered at Tevatron (1995)

$m_t \approx 175$ GeV

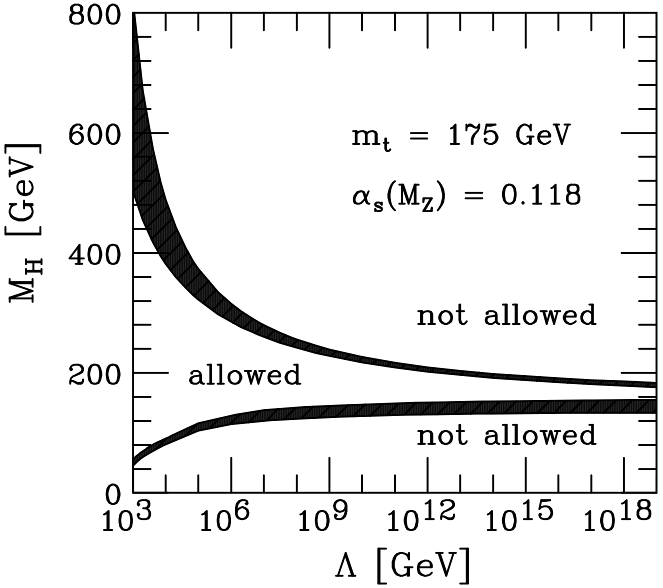
Today	
Precision tests	$m_t = 178.1^{+10.4}_{-8.3}$ GeV
Direct observation	$m_t = 174.3 \pm 5.1$ GeV

A hint at the Higgs mass

the missing link of the Standard Model: will the success of top quark story repeat?

Theory only

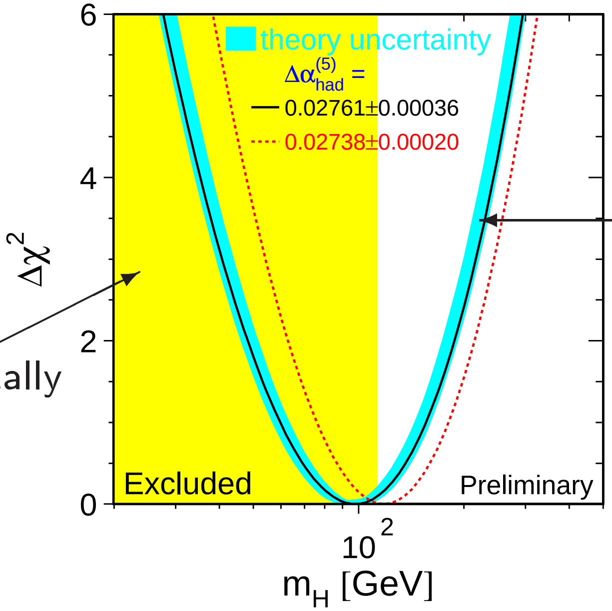
[T. Hambye & K. Riesselmann '97]



$50\ \text{GeV} \lesssim M_H \lesssim\ 750\ \text{GeV}$

Theory + precision data

[ZFITTER and others]



Experimentally excluded

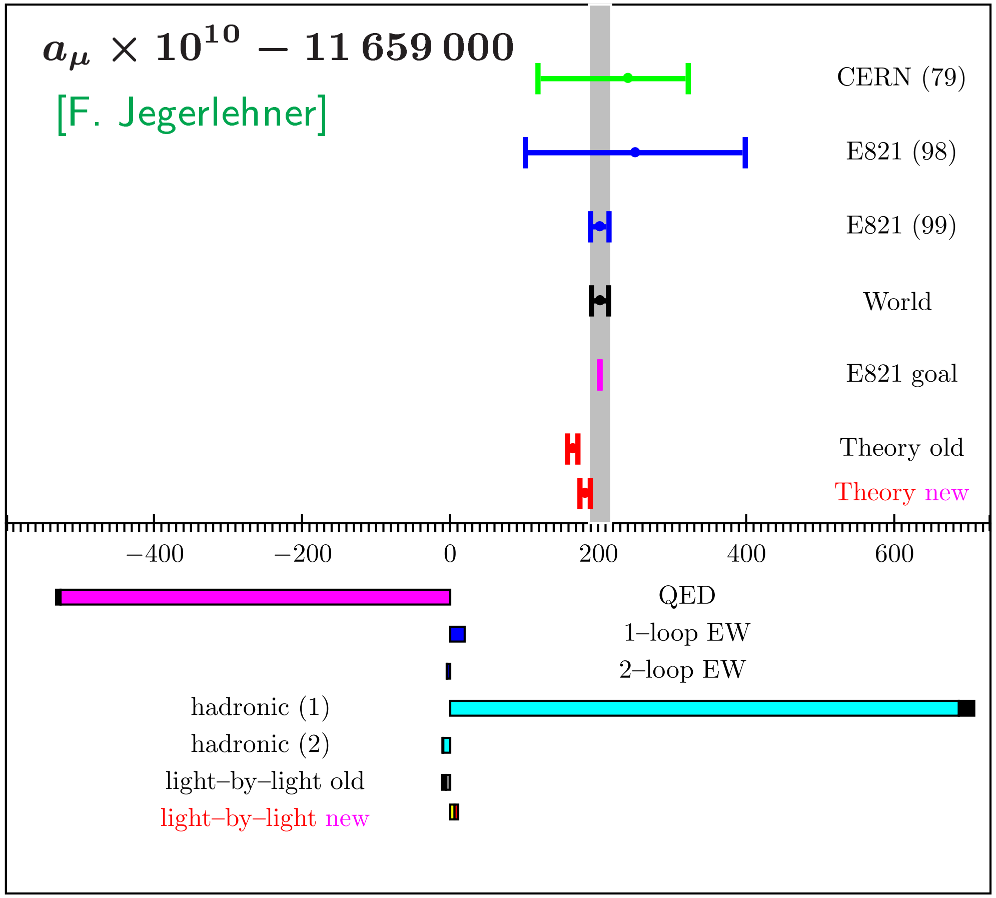
Theoretically possible

$M_H < 199\ \text{GeV at } 95\%$

Anomalous magnetic moments challenging the Standard Model

Electron: **Triumph of quantum field theory**: $a_{e^-}^{\text{exp}} = 0.001\,159\,652\,188\,4\,(43)$ **11 digits!**

predicted correctly by theory!! (4 loops QED)



Muon: **Very precise recent measurement**

$\Rightarrow a_\mu^{\text{exp}} = 0.001\,116\,592\,023\,(151)$

$\Rightarrow$ **Theory discrepancy in the last 3 digits**

Physics beyond the Standard Model?

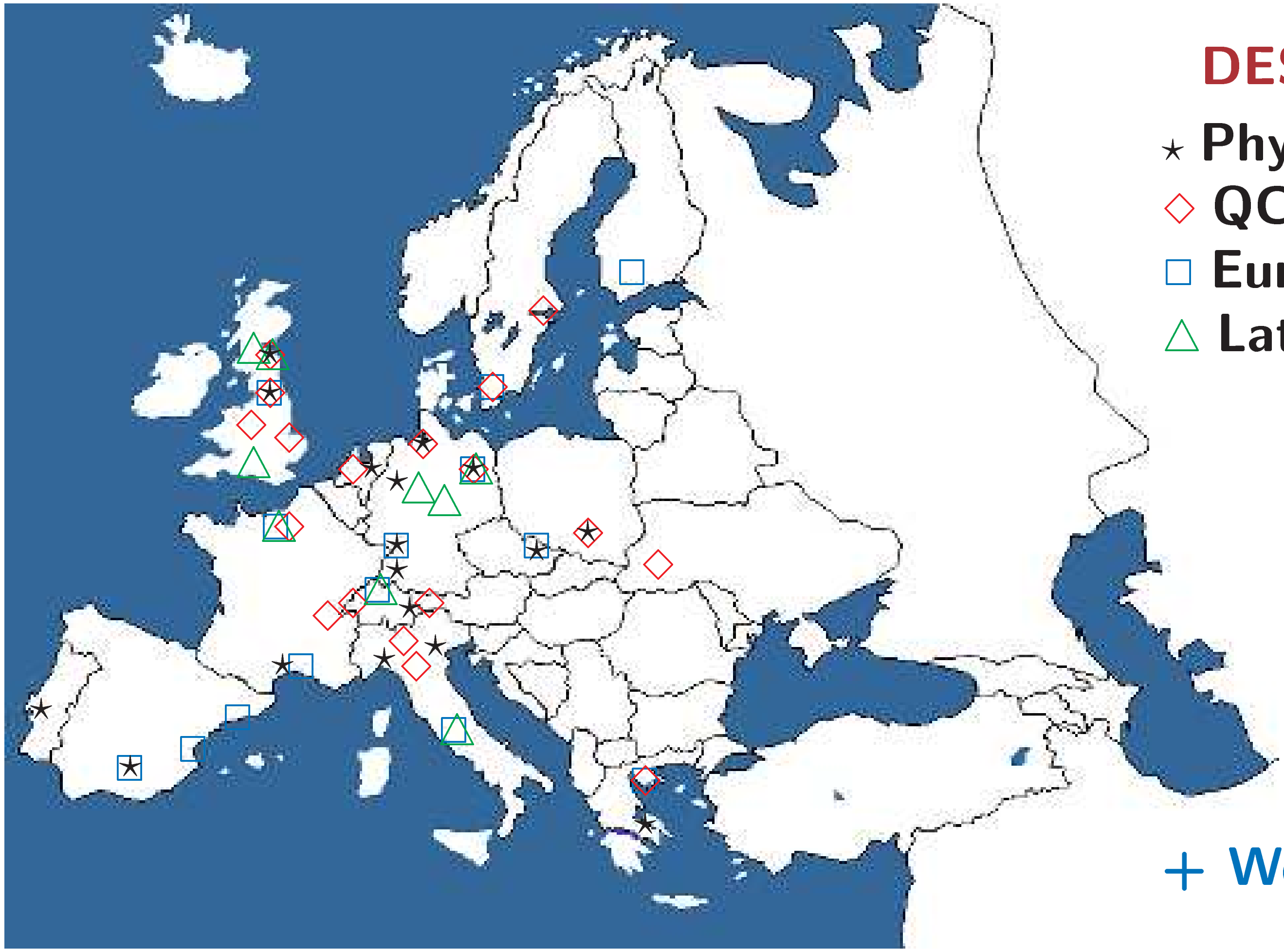
International Cooperation

Research Training Networks

Research Training Networks funded through the European Commission's 5th Framework *Improving Human Potential* programme, with the aim to:

"*support training and mobility of researchers from virtually all scientific fields throughout Europe.*"

▷ Transnational collaborations, Workshops, Graduate and Postdoctoral positions . . .



DESY Zeuthen participates in

- ⋆ **Physics at Colliders**
- ◇ **QCD and Proton's Structure**
- □ **Eurodaphne: Physics at DaΦne**
- △ **Lattice QCD**

Net	Coordinator	Sites
⋆	Granada	17
◇	Durham	18
□	Frascati	16
△	Glasgow	11

+ Worldwide Collaborations

Conclusions

Standard Model

correct down to 10^{-16} cm

BUT

find the Higgs particle (or something else)!

incorporate gravity!

...

explore smaller distances (higher energies)!

Supersymmetry? Extra dimensions?

High Energy Physics

Precision machinery

every piece matters

Raffiniert ist der Herrgott aber boshaft ist er nicht

A. Einstein