Theoretical Particle Physics at DESY

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Research Topics

- higher orders in perturbation theory
- precision calculations on the lattice
- small-x, non-pert. QCD
- astrophysics, cosmology
- physics beyond the Standard Model

Zeuthen

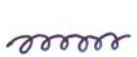
Hamburg

Combination of Standard-Model (SM) precision physics, qualitative problems within the SM, and exploration of new concepts and ideas outside the SM

Higher orders in perturbation theory

- tests of SM and constraints on (or discovery of) new physics
- precise determination of SM parameters (for understanding of deeper structure)

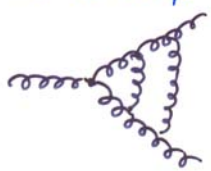
the problem: (e.g. QCD)



$= -i g_{\mu\nu} / (k^2 + i\varepsilon)$

$= -g_s \{ (k-p)_\sigma g_{\mu\nu} + (p-q)_\mu g_{\nu\sigma} + (q-k)_\nu g_{\mu\sigma} \}$

already at 2-loop, immensely complicated:

e.g.  $\sim 6^5 \sim 6000$ terms

and $\gg \exp(N)$ diagrams at N-loop

tech. aspects: multi-loop ; multi-leg

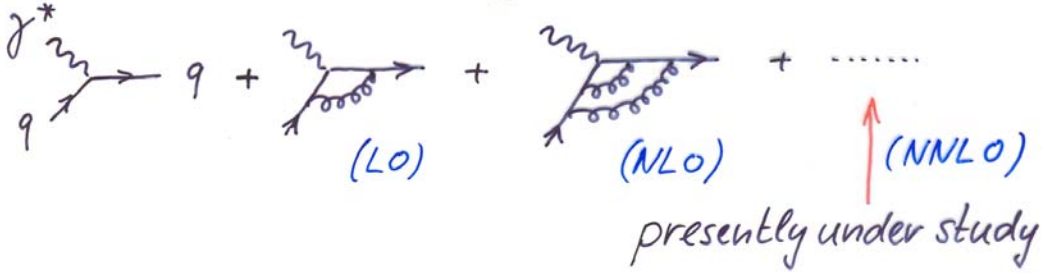
exp. aspects: QCD, Electroweak, QED, chiral pert. theory

recent important contrib. to $(g-2)_{muon}$

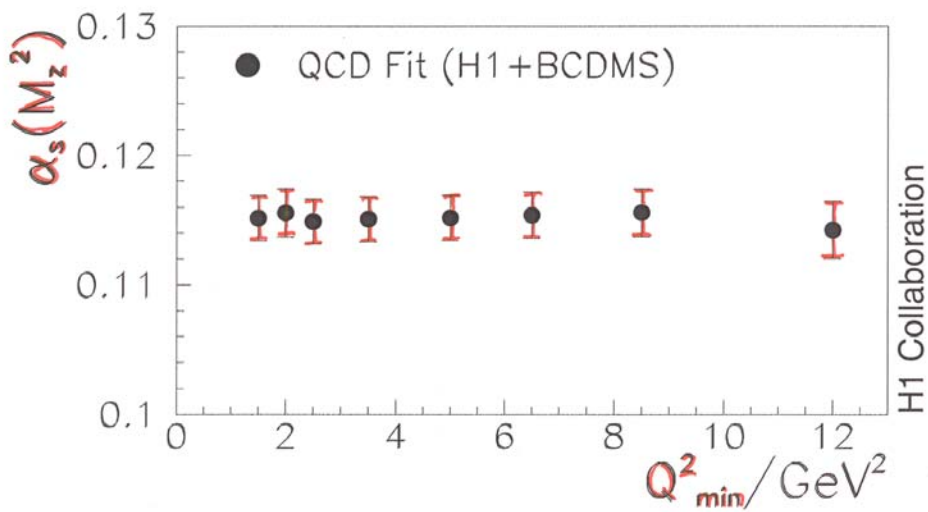
Precision measurement of α_s at HERA

deep inelastic scattering – $F_2(x, Q^2)$

α_s enters via Q^2-dependence



- needed since theory error dominates α_s-determ. (potential for world leadership)
- advanced computer algebra
- highly developed math. methods for analyt. integr.

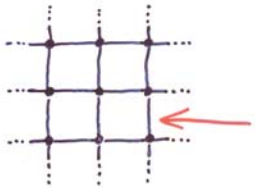


Precision calculations in lattice QFT

QCD: SU_3 gauge theory

$$\alpha_s(Q^2) \sim \frac{1}{\ln(Q^2/\Lambda^2)} \quad ; \quad \Lambda \sim 0.2\,\text{GeV}$$

scale of non-perturb. physics



$$U = \exp\left(i\int_{x_1}^{x_2} A\,dx\right)$$

most fundamental problem: light fermions

reason:

$$\int D\psi \exp\left[\int \bar{\psi}\gamma^\mu(\partial_\mu - iA_\mu)\psi\right] \sim \det\left[\gamma^\mu(\partial_\mu - iA_\mu)\right]$$

non-local!

at present:

- first steps towards realistic dynamical fermions
- use of lattice-version of chiral symmetry

relevance

- first-principles treatment of non-pert. QCD
- precision in light & heavy quark physics (CP-violation, quark masses)
- structure functions ; high-T ; SUSY models
- α_s

α_s on the lattice

need: $\alpha_s(M_Z)$ (very short distances – cannot be directly obtained)

method:
- lattice fixes α_s at large distances (e.g. K-decay)
- lattice extrapolation to small distances
- translation into $\alpha_s(M_Z)_{\overline{MS}}$ (perturb.)

→ highly non-trivial test of QCD
→ α_s needed for all precision calculations
→ α_s ($+\alpha_1$ & α_2) needed for unified models

Perturbative & lattice calculations are a long-term, large-scale effort

- SFB Transregio
- EU networks
- "DFG-Forschergruppe"
- LATFOR
- J. v. Neumann-Institute of Computing (NIC)
- Collab. with universities (Berlin, Leipzig, Hamburg ...)

Small-x and non-perturbative QCD

fundamental problem:

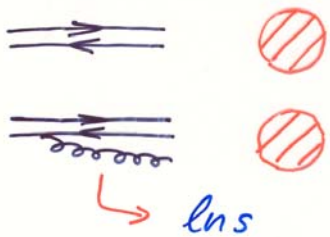
How do hadronic cross-sect.s behave at $s \to \infty$?

naive: $\sigma \sim$ const.

bound: $\sigma \lesssim \ln^2 s$

experiment: slow rise

perturbation theory:



but: true limit $s \to \infty$ is non-perturbative

ideas:
- high gluon densities
- importance of QCD instantons

non-perturb. gauge field config.

at HERA:

$(x \sim \frac{Q^2}{s})$

perfect setting for study
of the above fundamental question!

Astrophysics & Cosmology

- **Leptogenesis**

  (matter-antimatter asymm. $\leftrightarrow$ neutrino masses)

- **Inflation**

  (models with direct impact on some of the unexpected findings of WMAP)

- **Ultra-high-energy cosmic rays** (UHECR)

  - some events with $E \gtrsim 10^{20}$ eV observed (?)
  - problem: inelastic scattering off γ's from CMB becomes possible above that energy

  $\Rightarrow$ 'short' mean free path

  but no 'nearby' sources known

  $\Rightarrow$ possible way out: neutrinos as 'primaries'

  $\Rightarrow$ need large ν-matter cross-sect. at large energies

  ... electroweak instantons ? ...

Beyond the Standard Model

- SM very successful up to ~ 100 GeV
- strong constraints on physics up to ~ 1 TeV
  (precision calculations!)

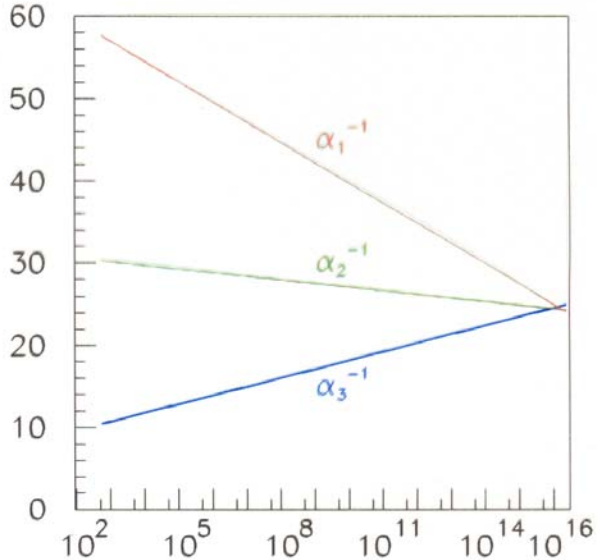
- light Higgs!
  ⇒ (technical) hierarchy problem
  ⇒ SUSY – best known solution
  (boson-fermion symm.)
- SUSY-discovery possible at LHC,
  but prec. measurements need linear collider
  ↓
  important for many reasons,
  in particular: Grand Unification

$\alpha_1, \alpha_2, \alpha_3$
$m_{q,i}$
M_1, M_2, M_3
(gaugino masses)

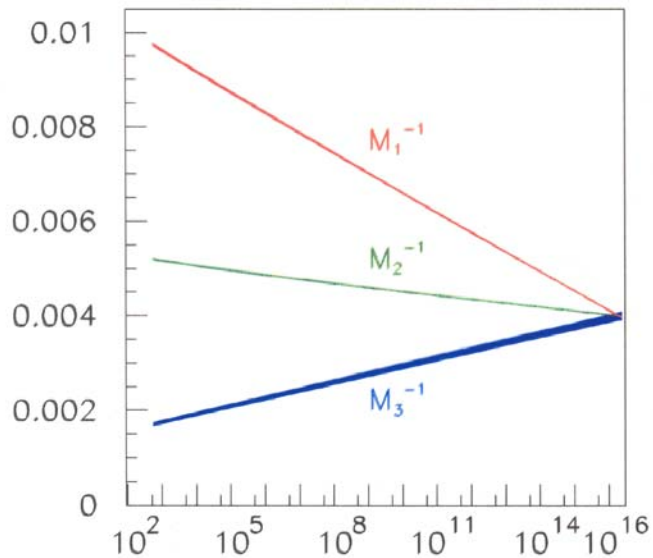
$\Big\}$ extrapolation $\longrightarrow M_{GUT} \sim 10^{16}$ GeV

Parameters in MSSM

gauge couplings α_i^{-1}



gaugino masses M_i^{-1} (GeV^{-1})



Standard Model (SM) "data"

- gauge symmetry: $SU_3 \times SU_2 \times U_1$
- 3 matter generations of

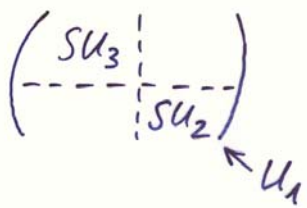
$$(3,2)_{1/3} + (\bar{3},1)_{-4/3} + (\bar{3},1)_{2/3} + (1,2)_{-1} + (1,1)_{2}$$

$$Q \qquad u \qquad d \qquad L \qquad e$$

- Higgs: $(1,2)_{-1}$

SU_5 unification

$SU_5 \supset SU_3 \times SU_2 \times U_1$



crucial observation:

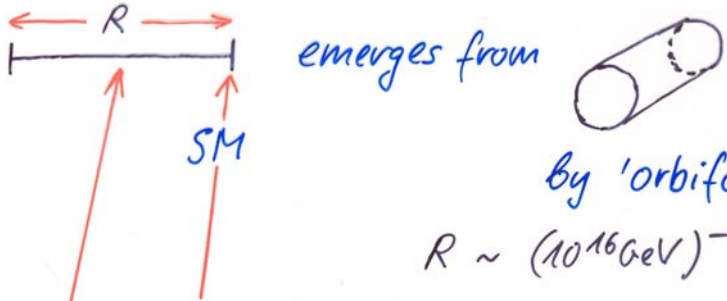
- $\bar{5} + 10$ of SU_5 = one SM matter generation

problems:

- Higgs only as doublet
- proton decay not seen

Orbifold GUTs

use idea of extra dimensions at scale 10^{16} GeV



emerges from

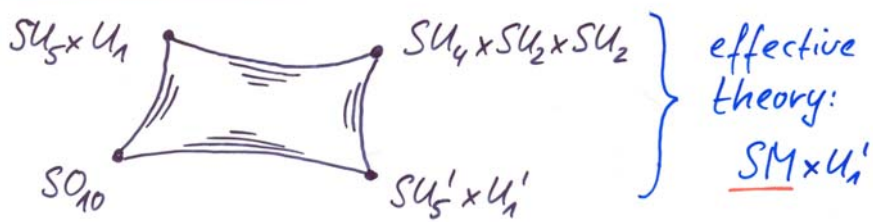
by 'orbifolding'

$R \sim (10^{16}\,\text{GeV})^{-1}$

Higgs doublet,
matter without proton decay

gauge fields
with coupling-unification (SU_5)

similarly for SO_{10} : (2 extra dimensions)



future: good chances for understanding

- 3 generations
- Yukawa couplings as gauge couplings

....

Summary

- very diverse program, addressing many fundamental questions
- variety of links, strong mutual dependence of different fields
- includes, in particular,
  - precision physics for HERA and other (present & future) experiments (both in Standard Model and Beyond)
  - exploration of exciting new ideas and concepts