

THEORETICAL PARTICLE PHYSICS

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DESY



— *Review of Programme “Elementary Particle Physics”* — February 26, 2009, Hamburg

Main Research Topics

Collider Physics

- Physics at LHC, ILC and HERA; QCD and electroweak precision predictions for colliders; B -physics Ali, Blümlein, Diehl, Moch, Riemann + NN

Particle Cosmology and Unification

- Leptogenesis; Dark matter; Inflation, UHE cosmic rays; axions; Grand Unification; Extra dimensions Buchmüller, Covi, Ringwald

Lattice Gauge Theory

- Non-perturbative QCD dynamics; Heavy Quark Effective Theory; Dynamical fermions and algorithms Jansen, Simma, Sommer

String Theory

- AdS/CFT correspondence; Strongly coupled gauge theories (QCD); Non-compact curved backgrounds; Cosmology Schomerus, Teschner

Challenges

The Big Questions

- What is the origin of mass ?
- Are quarks and leptons elementary ?
- Are the known forces unified ?
- What is the origin of dark matter ?
- Why is there no more antimatter ?
- Do extra dimensions of space really exist ?
- ...

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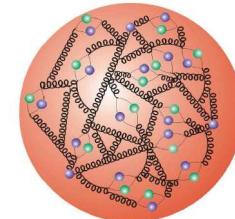
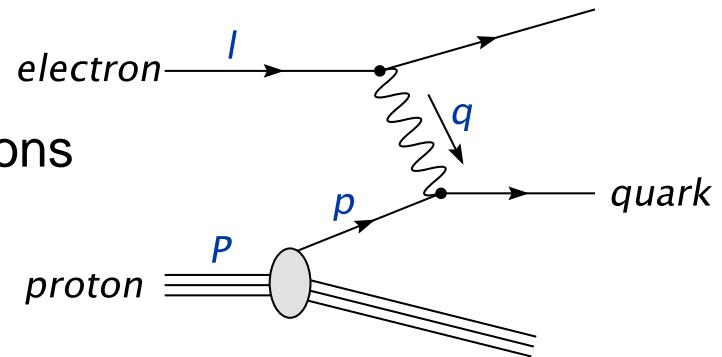




Collider Phenomenology (I)

Our assets: HERA

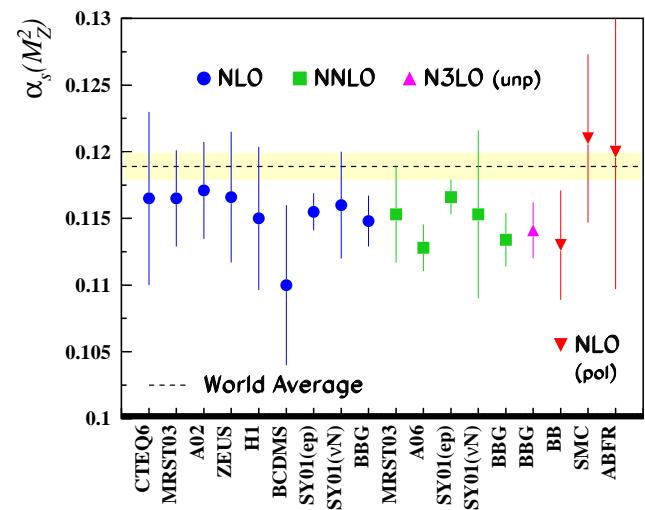
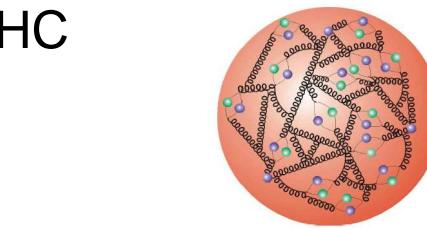
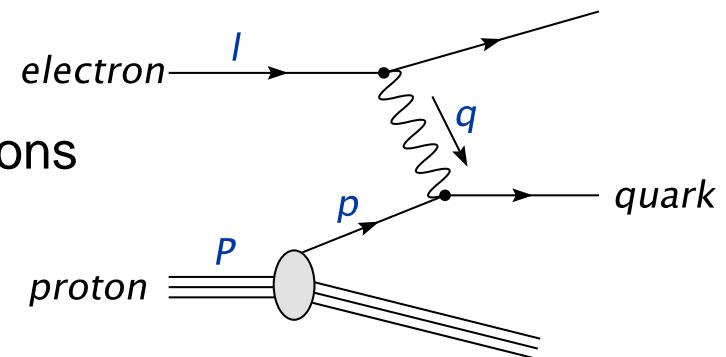
- Precision predictions for DIS structure functions
 - splitting functions
 - Wilson coefficients at 3 loops
- Parton distributions functions (PDFs) for the LHC
 - parton evolution with correlated errors
 - generalized PDFs ('3d imaging of proton')
 - essential ingredient
for proton–proton collisions at TeV-scale



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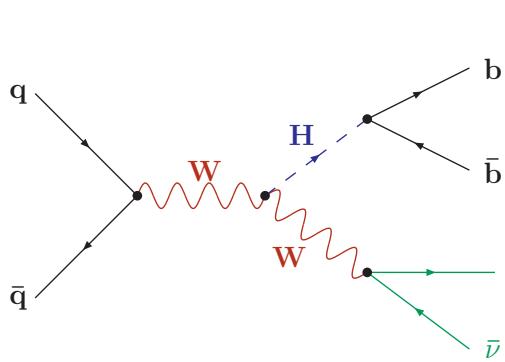
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- Parton distributions functions (PDFs) for the LHC
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 - generalized PDFs ('3d imaging of proton')
 - essential ingredient for proton–proton collisions at TeV-scale
- Precision determination of α_s (1% uncertainty)
 - close collaboration for final HERA analysis H1, ZEUS, HERMES
 - comparison with lattice results Alpha Coll., QCDSF Coll.



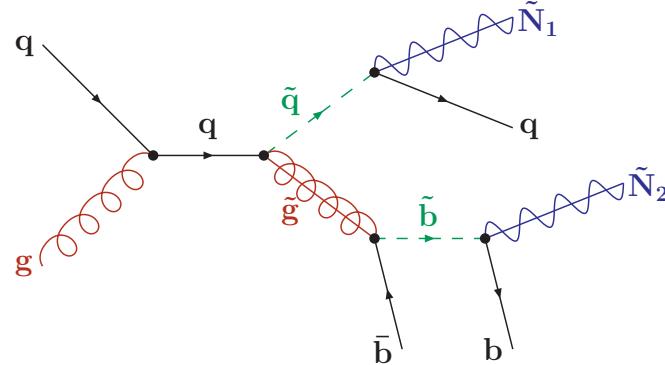
Collider Phenomenology (II)

Terascale Physics: LHC

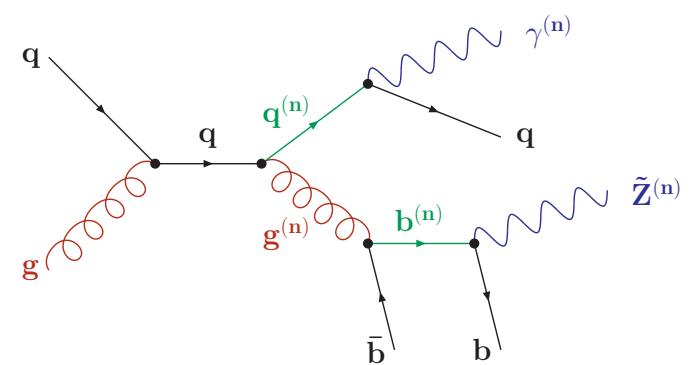
- Complexity of scattering processes at LHC is challenging
- New physics “look-alikes”
 - supersymmetry, Large Extra Dimensions, ...
 - missing energy in subsequent chain decays



Higgs-strahlung
 $q\bar{q} \rightarrow W(Z)H$
with $H \rightarrow b\bar{b}$



Supersymmetry
neutralino production $\tilde{N}_{1,2}^0$
(R -parity)

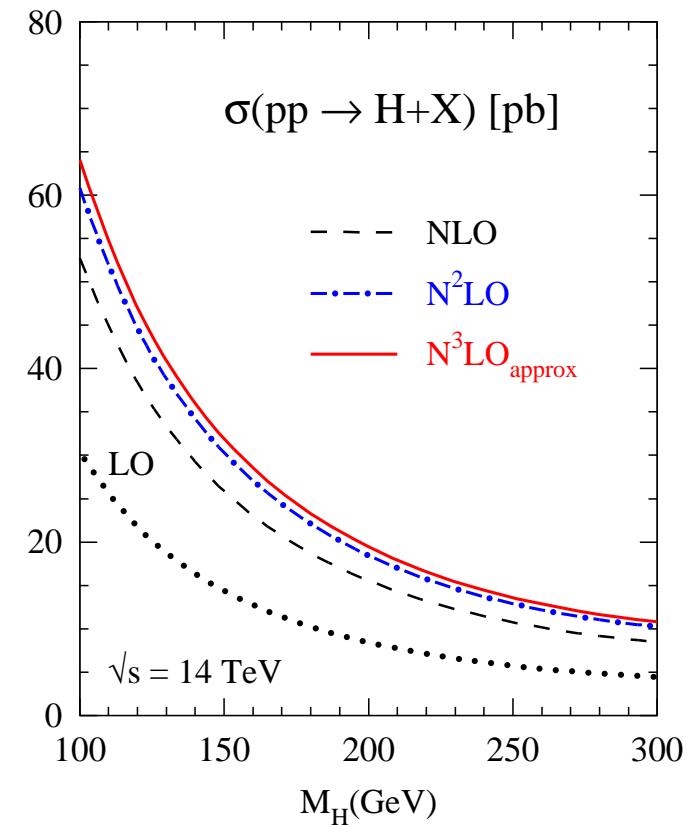


Large Extra Dimensions
pair-production of
excited KK-modes

Collider Phenomenology (II)

Terascale Physics: LHC

- Phenomenology for successful new physics searches [Analysis Center](#)
- High precision prediction for scattering processes in SM and beyond
 - e.g. Higgs boson production from gluon-gluon fusion
→ large QCD radiative corrections
 - large K -factors
cross section ratio $\text{NLO}/\text{LO} \sim \mathcal{O}(2)$

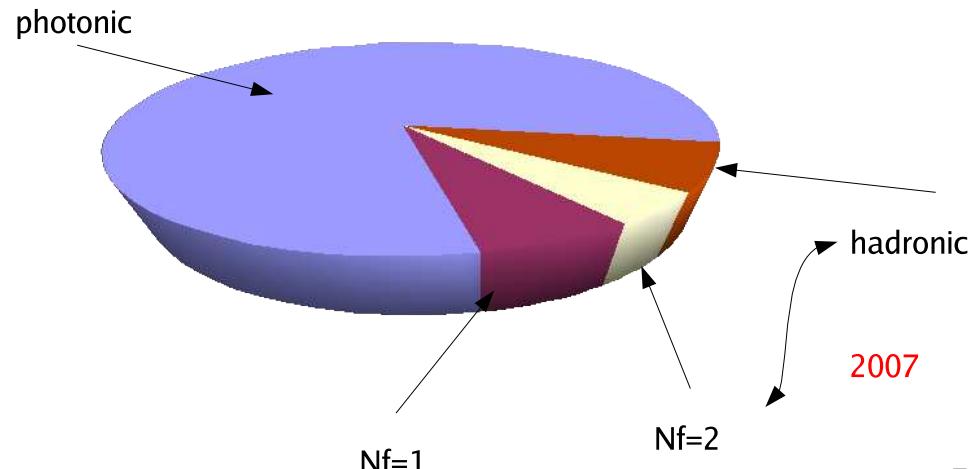
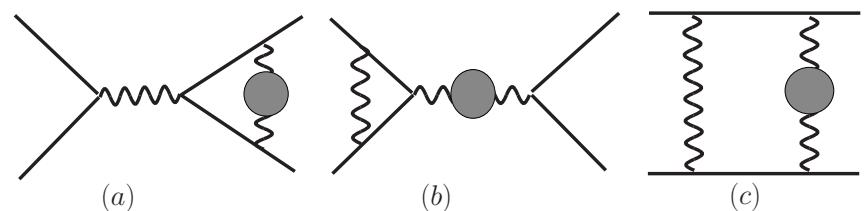


- Multi-leg processes at NLO ($2 \rightarrow 4$ current edge of technology)
- PDFs from HERA
- B -Physics at the LHC (rare decays, $|V_{CKM}|$, etc.)

Collider Phenomenology (III)

The Road ahead: ILC

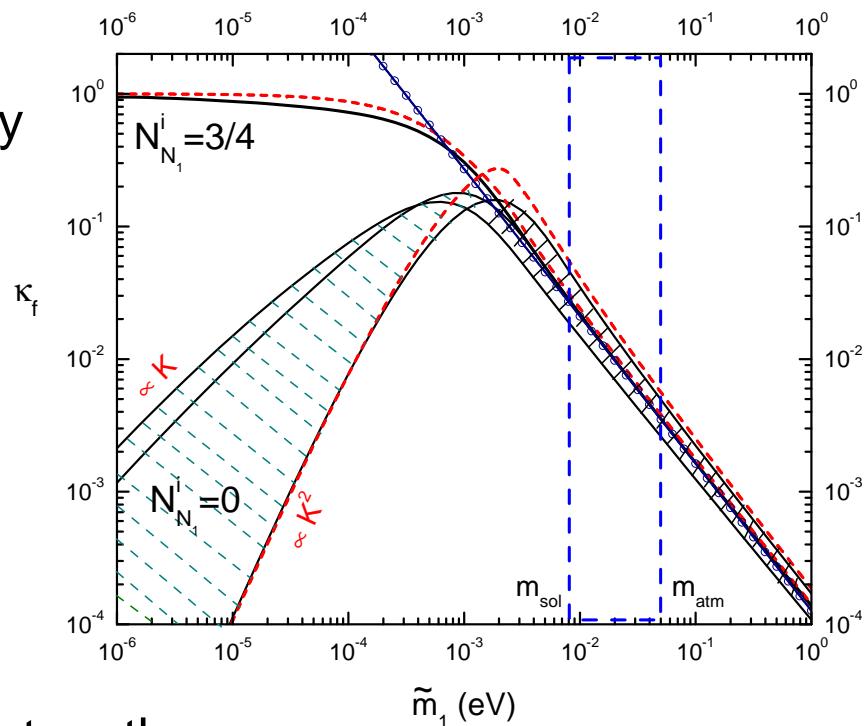
- Bhabha scattering to monitor luminosity: $\mathcal{L} = N_{Bhabha}/\sigma_{Bhabha}$
- Forward calorimeter (FCAL) project prepares detector element at very small angles (few degrees) for ILC and GigaZ with $\delta\mathcal{L}/\mathcal{L} \sim 10^{-4}$
- Precision theory for Bhabha scattering required
 - QED radiative corrections at 2 loops required
 - progress during last 2 years
- Theory prediction: error budget of various contributions



Particle Cosmology and Unification (I)

Matter-antimatter asymmetry

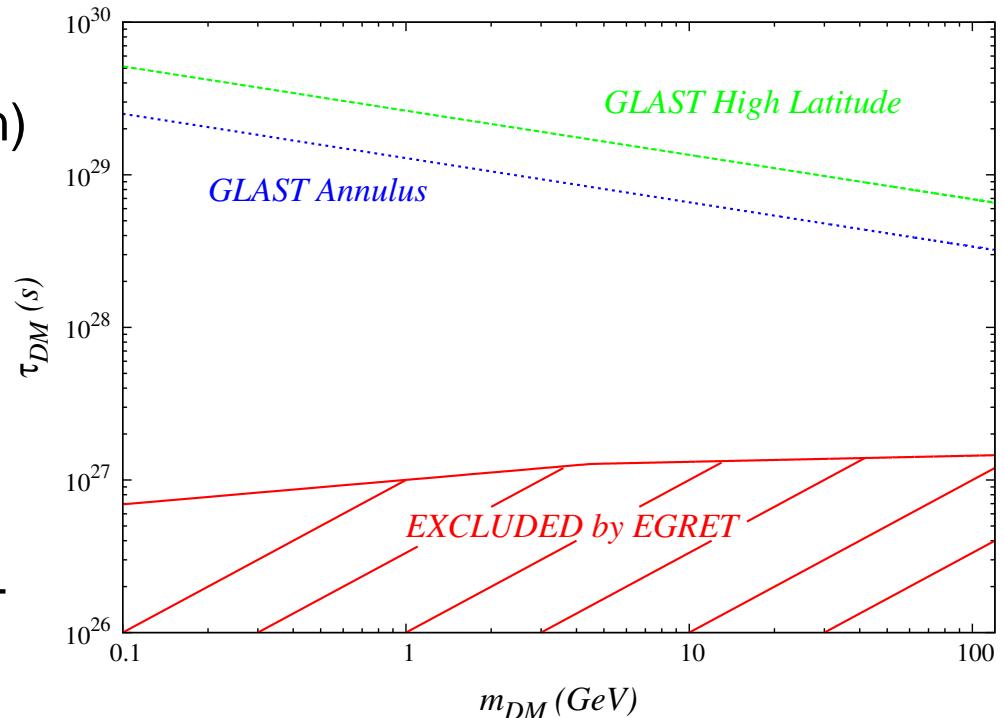
- Leptogenesis attractive theory for origin of matter
- Quantitative relation between neutrino masses and baryon asymmetry
 $\eta_B \simeq 0.01 \varepsilon_1 \kappa_f$
- Light neutrino mass window:
 $10^{-3} \text{ eV} < m_\nu < 0.1 \text{ eV}$
early universe temperature:
 $T_B \sim M_1 > 10^9 \text{ GeV}$
- Recent developments
 - lepton flavour dependence, full quantum theory
- Implications for Dark matter
 - standard WIMPs inconsistent, decaying gravitinos ?



Particle Cosmology and Unification (II)

Dark matter and cosmic ray anomalies

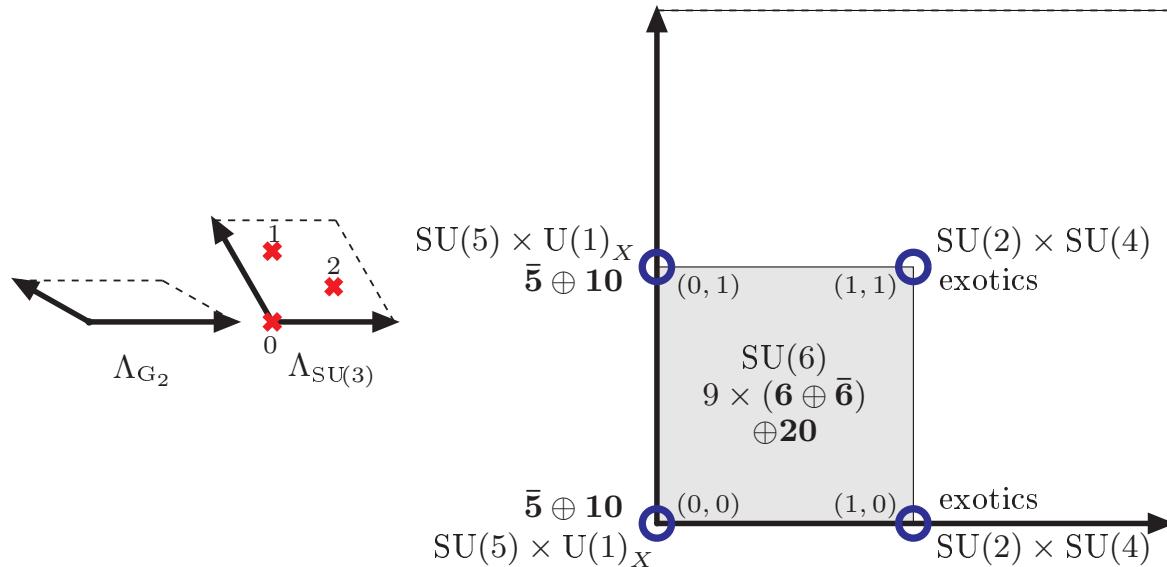
- Decaying gravitino dark matter:
consistent cosmology with leptogenesis, primordial nucleosynthesis
- Characteristic signatures
of cosmic ray
(different from WIMP annihilation)
- Consistent with
PAMELA positron anomaly
(ATIC anomaly problematic)
- Being tested by FERMI
 - significant extension of
sensitivity in mass and
lifetime compared to EGRET
- Can be falsified at LHC
 - specific decays of ‘long lived’ neutral/charged heavy particles



Particle Cosmology and Unification (III)

Local grand unification and the heterotic string

- Supersymmetric Standard Model can be embedded in Heterotic String via Georgi-Glashow unification at ‘fixed points’ in extra dimensions
 - compactification on anisotropic 6-dimensional ‘orbifold’
 - matter and Higgs: brane and bulk fields
- Consequences: gauge coupling unification, gauge-top unification, pattern of supersymmetry breaking, flavour dependence of proton decay,...



Lattice gauge theory (I)

Lattice challenge

- Fundamental parameters of QCD with full non-perturbative precision from low energy experimental input
 - e.g. $\alpha_s; m_u, \dots, m_b$ from baryon/meson masses, ...
- Input for high energy analysis of SM and beyond

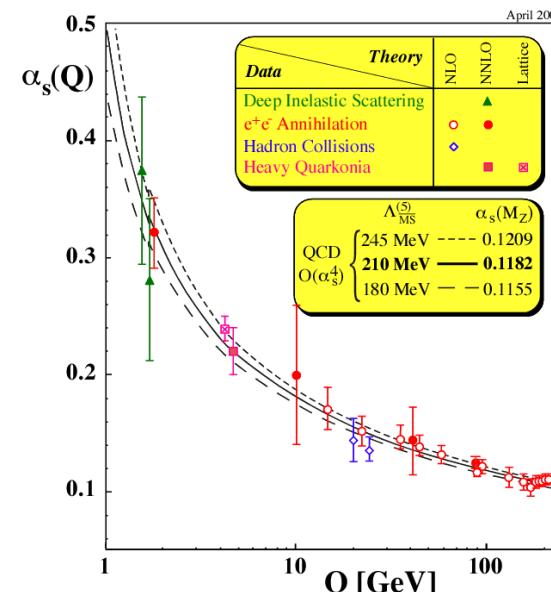
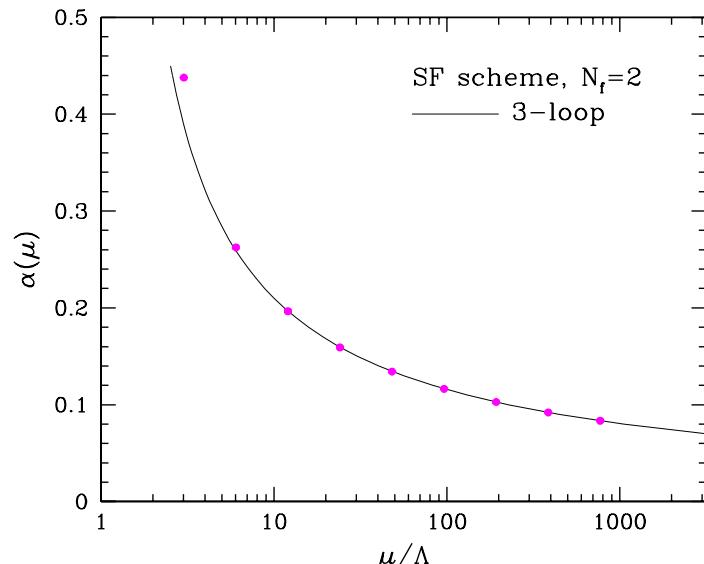
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Strong coupling constant α_s

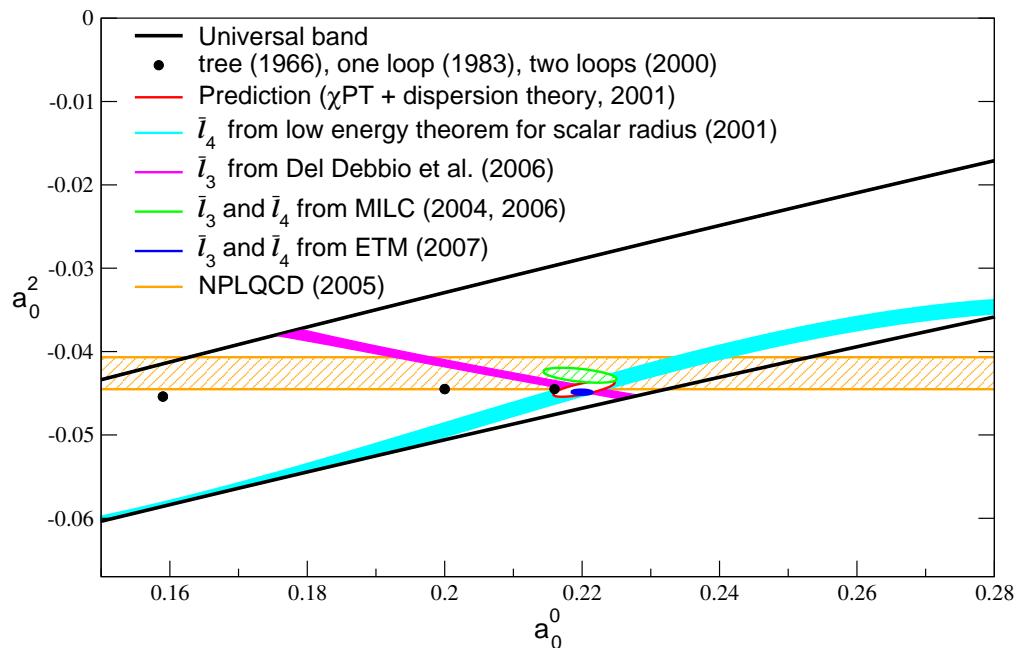
- Lattice gauge theory ($N_f = 2$) \longleftrightarrow experiment + perturbation theory



Lattice gauge theory (II)

QCD in the chiral limit

- Light dynamical quarks
- Precise numerical results for m_π and f_π
- Comparison with chiral perturbation theory
 - world record precision for π -scattering length



Other applications

- (generalized) PDFs: moments of parton distributions
- CKM phenomenology: B -physics on the lattice
- Effective theories, e.g. HQET: non-perturbative matching

String theory (I)

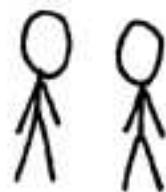
Local grand unification and the heterotic string

STRING THEORY SUMMARIZED:

I JUST HAD AN AWESOME IDEA.
SUPPOSE ALL MATTER AND ENERGY
IS MADE OF TINY, VIBRATING "STRINGS."

OKAY. WHAT WOULD
THAT IMPLY?

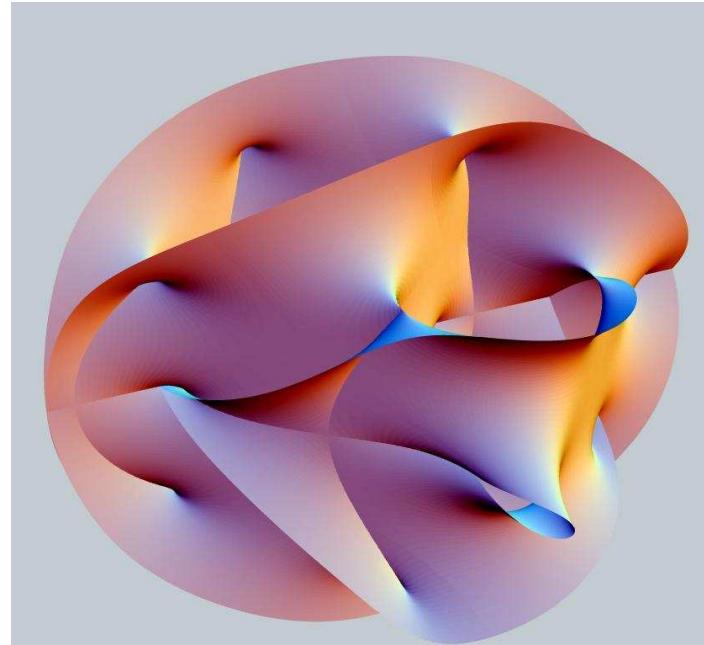
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String theory (II)

Strings for QCD

- AdS/CFT duality for non-abelian gauge theories
 - many SUSY gauge theories (w/o additional string vibrational modes!) from strings in special curved backgrounds
 - new handle on non-perturbative physics
- Quantization of string theory in relevant backgrounds



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Upshot

- Computation of anomalous dimensions for $N = 4$ SYM (from light cone quantization)
- Implications for high-energy limit of $N = 4$ SYM/QCD
 - relation between weak and strong coupling regime

Tools and Technology

Mathematics

- Phenomenology: multi-loop/leg problems require new technology
 - Mellin-Barnes, nested sums, unitarity approach, ...
- Strings: integrable systems, algebraic geometry, orbifolds, ...

Computing

- Phenomenology: Tools (AMBRE, XSummer, ...) in computer algebra systems (Form, Maple, Mathematica, ...)
- Lattice: topical center John von Neumann institute for computing (NIC) high performance computing; dedicated hardware (540 kEuro in 2010-2014)



Monte Carlo

- Phenomenology: long tradition of tools for experimental analyses HECTOR, ZFITTER, Prospino, Whizard, ...
- Monte Carlo tools for LHC: parton showering Analysis Center; Nagy + others

Collaborations of DESY Theory (I)

- Collaboration with universities corner stone of the scientific life at DESY

Helmholtz

- Helmholtz Alliance Physics at the Terascale (HA-101)
- YIG Computer algebra and higher orders in particle theory (VH-NG-105)
- Virtual Institute VIPAC for particle cosmology (VH-VI-106)
- NIC: John von Neumann institute for computing (DESY, FZJ, GSI)



Collaborations of DESY Theory (I)

DFG funding

- SFB Transregio 9:
Computational Particle Physics
(Karlsruhe, Aachen, Berlin, Zeuthen)
- SFB 676:
Particles, Strings and the Early Universe
(Hamburg)
- GK 602: Graduiertenkolleg
(Hamburg)
- GK 1504: Graduiertenkolleg
(Berlin, Dresden, Zeuthen)



Collaborations of DESY Theory (I)

- Center for Mathematical Physics (Hamburg, Theo. Physics and Mathematics Dept.)
- Lattice collaborations Alpha Coll., ETMC Coll.

Teaching

- Close collaboration with Universities in Berlin, Hamburg and Potsdam

Workshops and Schools

- DESY Theory Workshop
- Conference series “Loops and Legs”
- Lattice Practises
- School on Computer-Algebra
- School on Parton Distribution Functions



Collaborations of DESY Theory (II)

EU funding

- MCRTN HEPTOOLS:
Collider Phenomenology
- MCRTN FLAVIAnet:
Flavour Physics
- Marie Curie Excellence award

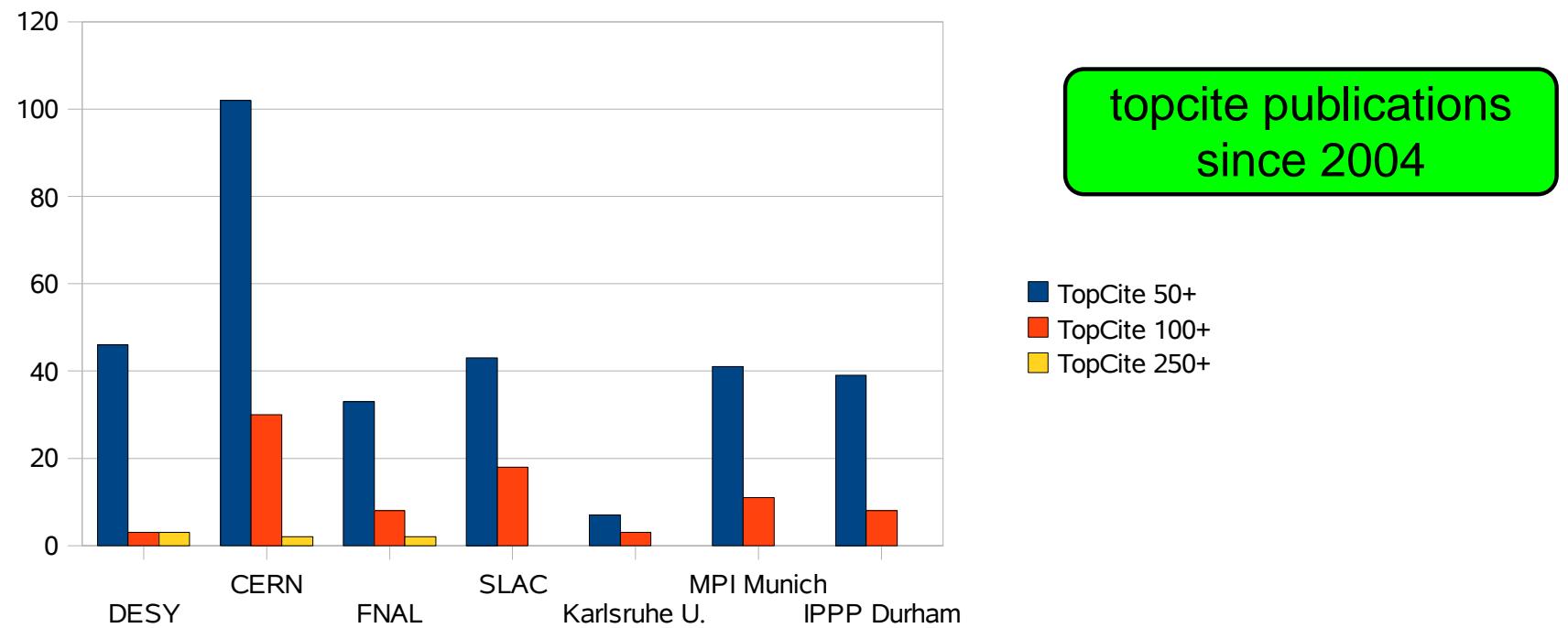
Humboldt

- Alexander von Humboldt prizes



Key features of DESY Theory (I)

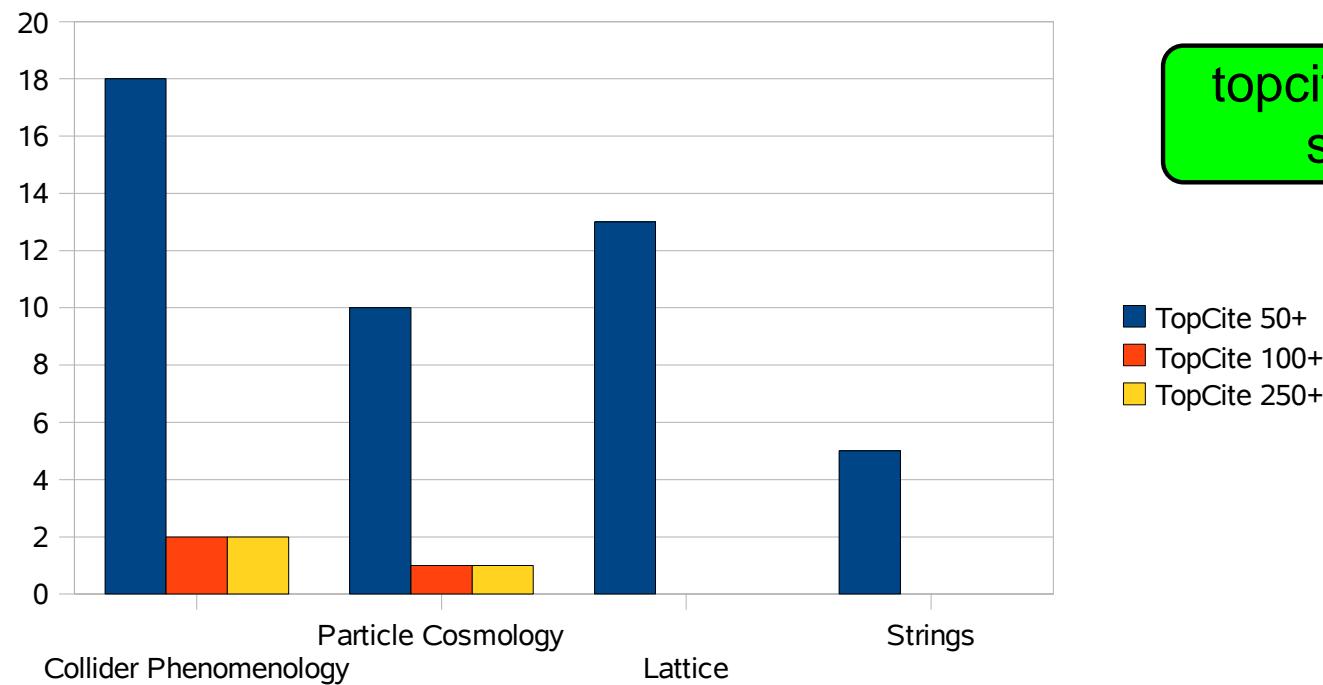
- Attractive spectrum of timely topics in high-energy physics
 - unique environment (academia, experiments, ...)
- Pillar of theoretical particle physics in Europe and beyond



- Research deeply rooted in experimental program
 - colliders (LHC, ILC, HERA & B -factories)
 - experimental astroparticle physics

Key features of DESY Theory (II)

- Research of DESY theory

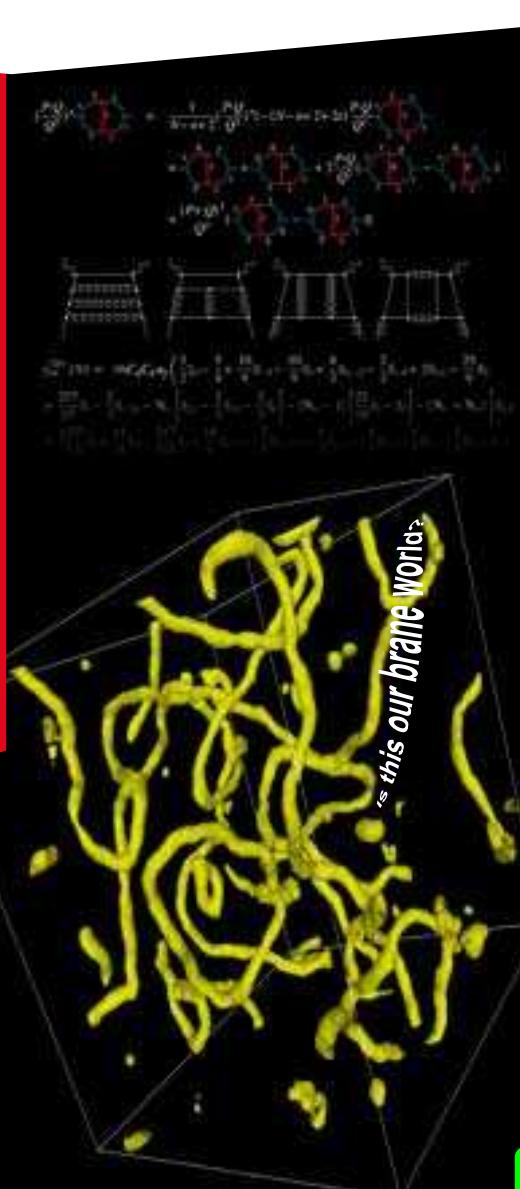
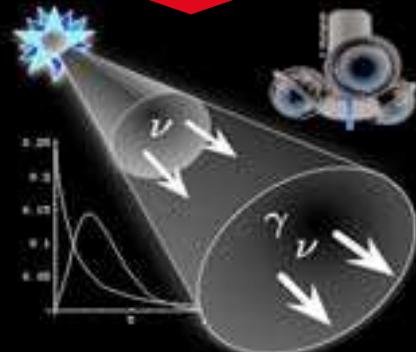


- Fellows with significant contributions to research
- All DESY staff members supervise PhD students
 - during past 5 years xx permanent positions in Europe filled with former graduate students

Theory

What exactly is the quantum behaviour of quarks and Higgs particles? Can we think of new theories that might explain the Standard Model itself? How should we include gravity in the quantum description of the world? Does dark matter consist of particles and if so, which ones? And, how could we possibly test such ideas, either in the laboratory, or by observing the universe?

Members of the theory group are thinking about questions like these. 'To think' means: devising new formulas or estimating predictions by using powerful computers. Together with our experimental colleagues we try to answer these questions.



Courtesy of Nikhef