THEORETICAL PARTICLE PHYSICS

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DESY

HELMHOLTZ GEMEINSCHAFT

DESY

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

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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BSM theory landscape (Murayama)

Status Quo

Current Issues in Theoretical Particle Physics

- Start-up of LHC
  - very complex data
  - background and signals of new physics must be disentangled
  - new physics needs to be interpreted
    (origin of mass, supersymmetry, extra dimensions, . . .)
- Interface with cosmology
  - intriguing new window to particle physics (dark matter, . . .)
- Non-perturbative approach to gauge theory
  - theory of strong interaction: QCD (e.g. α_s, . . .)

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

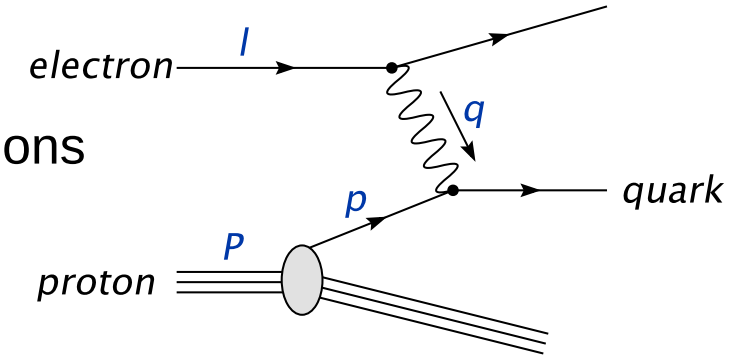
Past Program Evaluation

Recommendations of 2004

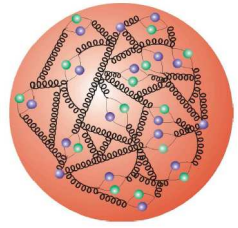
- Evaluation of Theoretical Physics
  - strong support for *“an impressive spectrum in close contact with experiments to pure theory”*
  - *“building-up/strengthening of group in String theory and Particle Cosmology should be supported”*
- Successful start of string theory group in 2006

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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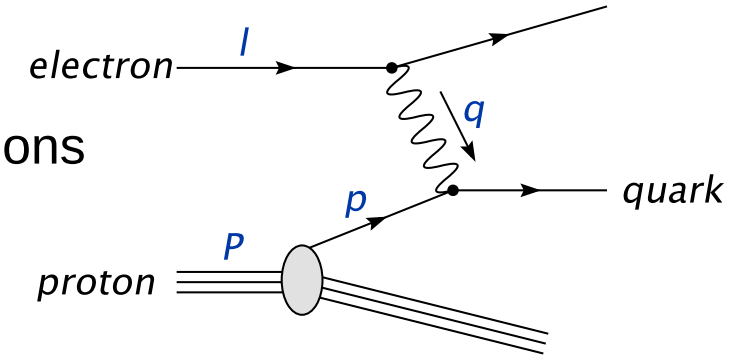

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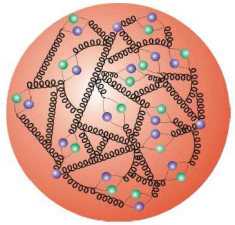

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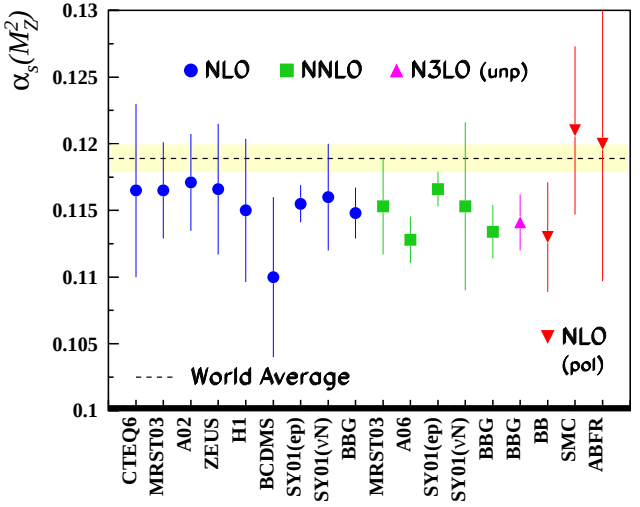
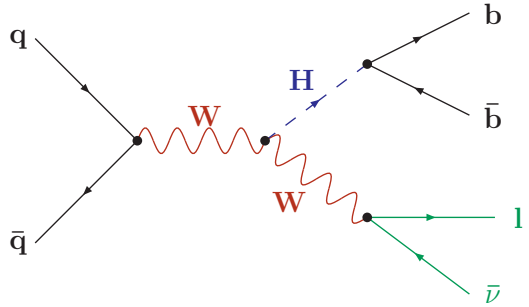


- Precision determination of α_s (1% uncertainty)
  - close collaboration for final HERA analysis
    H1, ZEUS, HERMES
  - comparison with lattice results
    ALPHA Coll., QCDSF Coll.

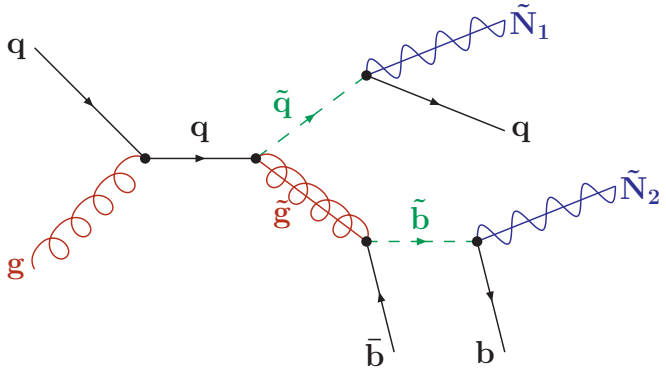
Collider Phenomenology (II)

Terascale Physics: LHC

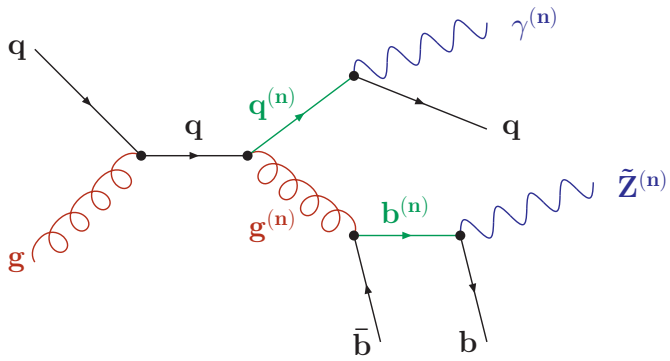
- Complexity of scattering processes at LHC is challenging
- New physics “look-alikes”
  - supersymmetry, Large Extra Dimensions, . . .
  - missing energy in subsequent chain decays



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



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

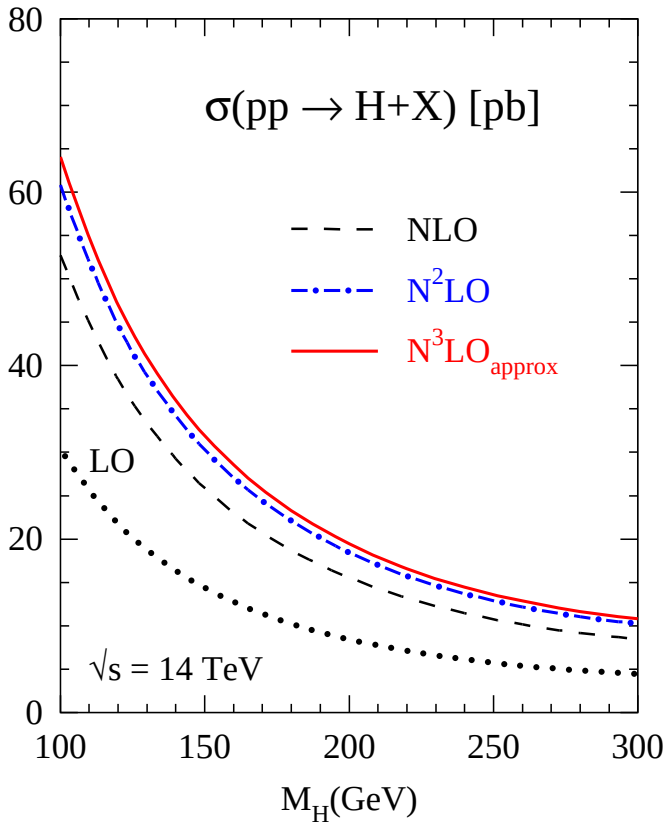


Large Extra Dimensions
pair-production of
excited KK-modes

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
  - QCD: large K-factors cross section ratio NLO/LO $\sim \mathcal{O}(2)$
- B-Physics (rare decays, $|V_{CKM}|$, etc.)



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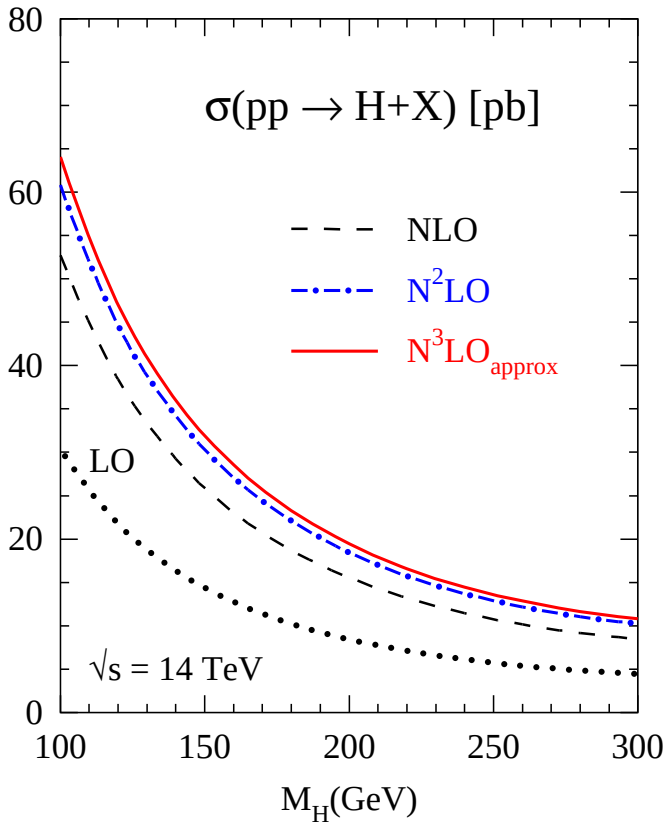


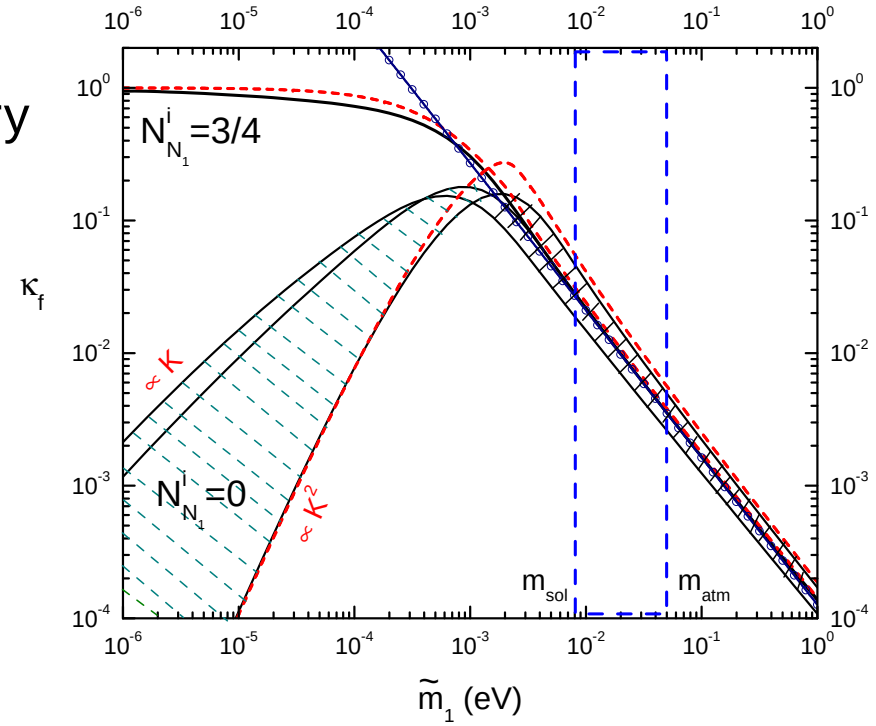
Road ahead: ILC

- High precision theory required, e.g. Bhabha scattering
  - monitor luminosity (forward calorimeter): $\mathcal{L} = N_{Bhabha}/\sigma_{Bhabha}$

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:
  $T_B \sim M_1 > 10^9\ \text{GeV}$
- Implications for Dark matter
  - standard WIMPs inconsistent, decaying gravitinos ?



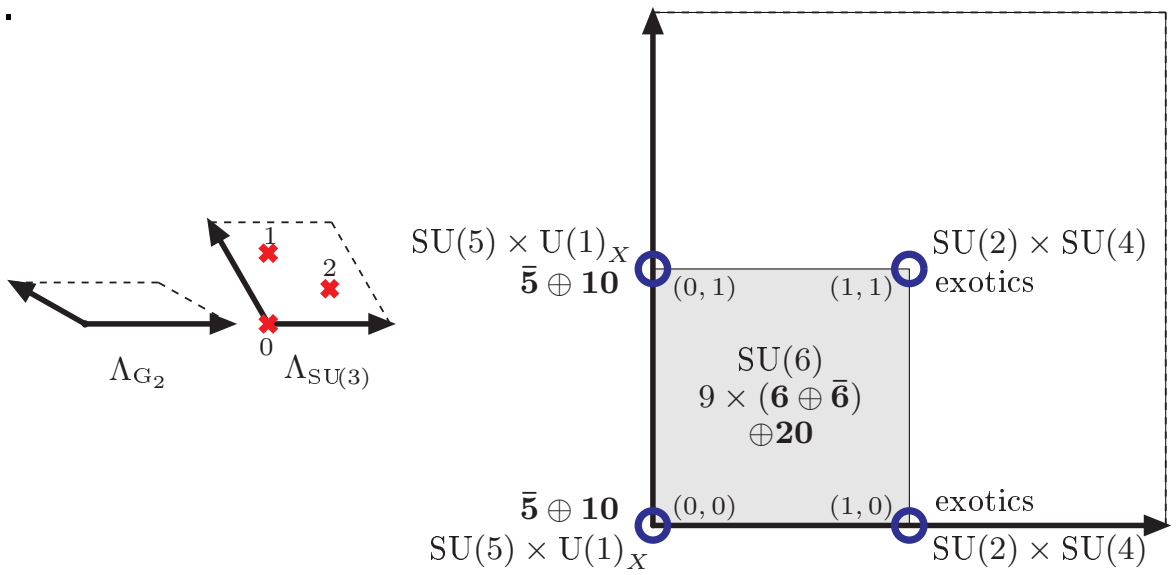
Cosmic rays

- New information from satellite experiments (PAMELA, FERMI, . . .)
  (e.g. interpretation through decaying gravitino dark matter)

Particle Cosmology and Unification (II)

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

- Low energy, non-perturbative, dynamics of QCD, structure functions
- Fundamental parameters $\alpha_s; m_u, ..., m_b$ from hadron masses, ...
  $\longrightarrow$ input for high energy analysis of SM and beyond
- Precision flavour physics $\longrightarrow$ high intensity frontier
- Higgs-mass bounds in chirally invariant Yukawa model

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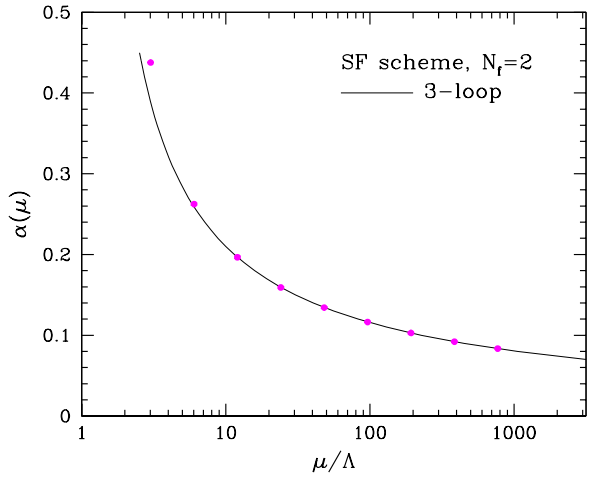
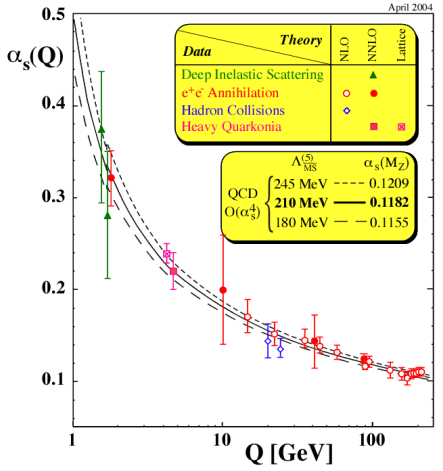
Example: Strong coupling α_s

- Lattice gauge theory ($N_{\rm f} = 2$) $\longleftrightarrow$ experiment + perturbation theory



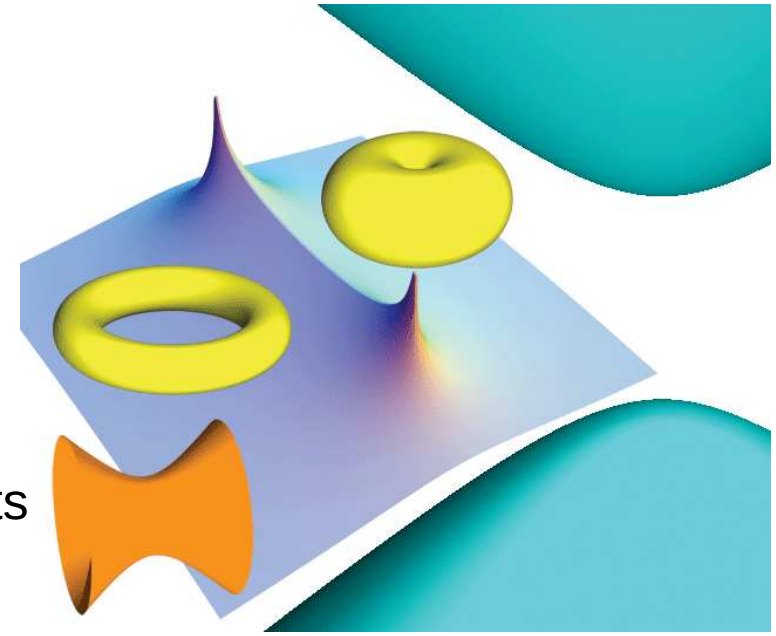


Future: strange and charm sea ...

String theory

Supersymmetric gauge theories

- Many SUSY gauge theories
  (w/o additional string vibrational modes!)
  described through string theory
  in curved backgrounds
  - AdS/CFT correspondence
  - new handle on non-perturbative aspects
    of (non-abelian) gauge theories



Tasks and achievements

- Consequences of integrability in string and gauge theory
  - quantization of string theory in relevant AdS backgrounds
  - computation of all-loop anomalous dimensions in $N = 4$ SYM,
    gauge theory correlation functions, gluon scattering amplitudes
- Application of gauge string duality to QCD
  - integrability in high energy limit and study of dual theories

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

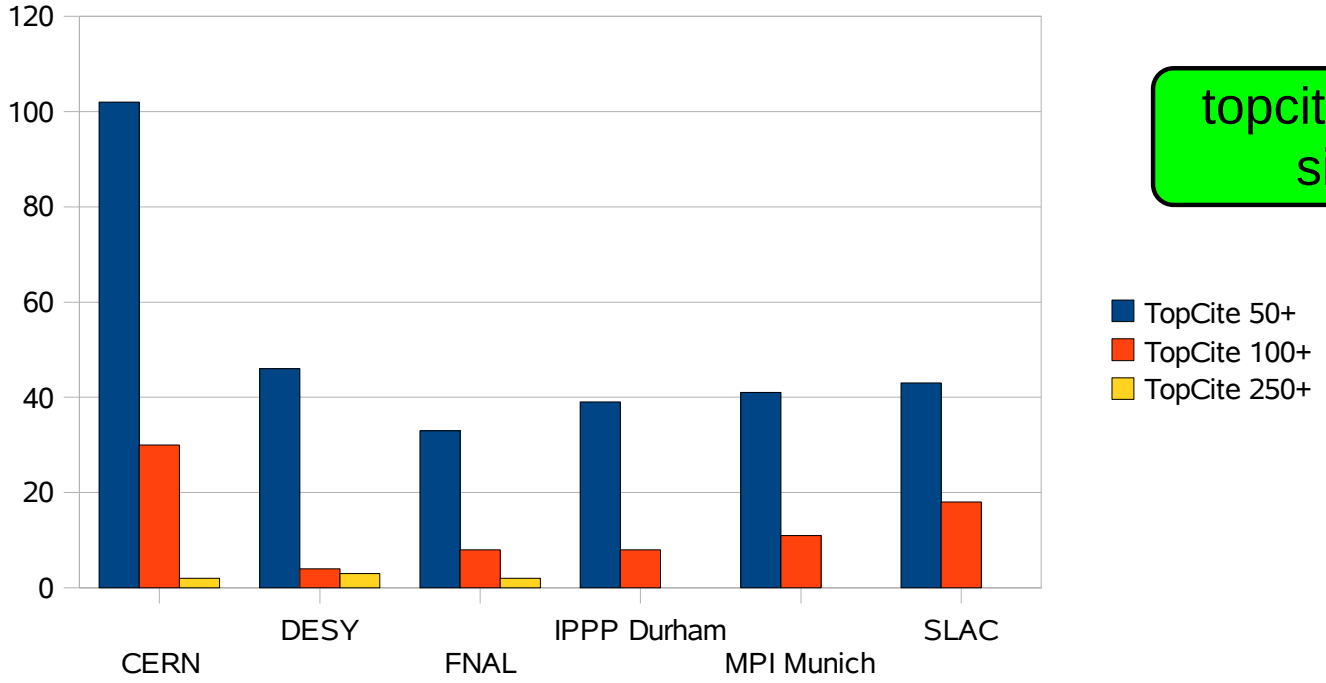
- Phenomenology: Tools (AMBRE, XSummer, . . .) in computer algebra systems (Form, Maple, Mathematica, ...)
- Lattice: topical center John von Neumann institute for computing (NIC) high performance computing; dedicated hardware (540 kEuro in 2010-2014)

Monte Carlo

- Phenomenology: long tradition of tools for experimental analyses HECTOR, ZFITTER, Prospino, Whizard, CASCADE, . . .
- Monte Carlo tools for LHC: parton shower, underlying event, NLO+parton shower Analysis Center

Key features of DESY Theory (I)

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



topcite publications since 2004

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

Key features of DESY Theory (II)

Collaboration with universities

- Corner stone of broad research program
  - all DESY staff members supervise PhD students and graduate students contribute significantly to reseach
  - teaching at Universities in Berlin, Hamburg and Potsdam
- Hamburg site
  - DESY theory and University in one building
  - common research: Collider Physics, Particle Cosmology, Strings
  - Center for Mathematical Physics ZMP
    (Hamburg, Theo. Physics and Mathematics Dept.)
- Zeuthen site
  - the center for particle theory in eastern part of Germany
    (Berlin, Dresden, Potsdam)
  - common research: Collider Physics, Lattice

Key features of DESY Theory (III)

Workshops and Schools

- Support for particle physics in Germany, Europe, . . .
  - DESY Theory Workshop
  - Conference series “Loops and Legs”
  - Lattice Practises
  - School on Computer-Algebra
  - School on Parton Distribution Functions

Key features of DESY Theory (III)

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  - School on Parton Distribution Functions

Long term impact

- Professors in Particle Theory (German universities, MPI’s and DESY)
  - 14 moved from DESY to university and/or did PhD at DESY
  - in addition, 15 former DESY fellows
- Upshot
  - about 50% of theorists at German universities have ’DESY history’

DESY fellowship program

Talent management

- DESY theory positions prestigious
  - total PostDoc applications $\mathcal{O}(250)$ per year
  - worldwide competition for 6 fellowships (+ third party funds)
- Large turnover in manpower
  - 50% new members in group every two years
- Chances for young researchers
  - high visibility: international recognition/collaboration (e.g. IMPU)
  - significant contributions embedded in broad theory activity
- e.g. PostDoc statistics (Hamburg) 1996-2005 and current activities
  - 93% (68 of 73) research in theoretical particle physics
    $\longrightarrow$ 26% Germany; 67% abroad, mostly Europe, also US, Japan
- Training of future professors and research staff

Collaborations of DESY Theory (I)

Helmholtz

- Helmholtz Alliance
  Physics at the Terascale (HA-101)
- YIG
  Particle physics and cosmology:
  beyond the two standard models
  (VH-NG-006)
  Computer algebra and higher orders
  in particle theory (VH-NG-105)
- Virtual Institute
  VIPAC for particle cosmology
  (VH-VI-106)
- John von Neumann institute
  for computing NIC
  (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 (II)

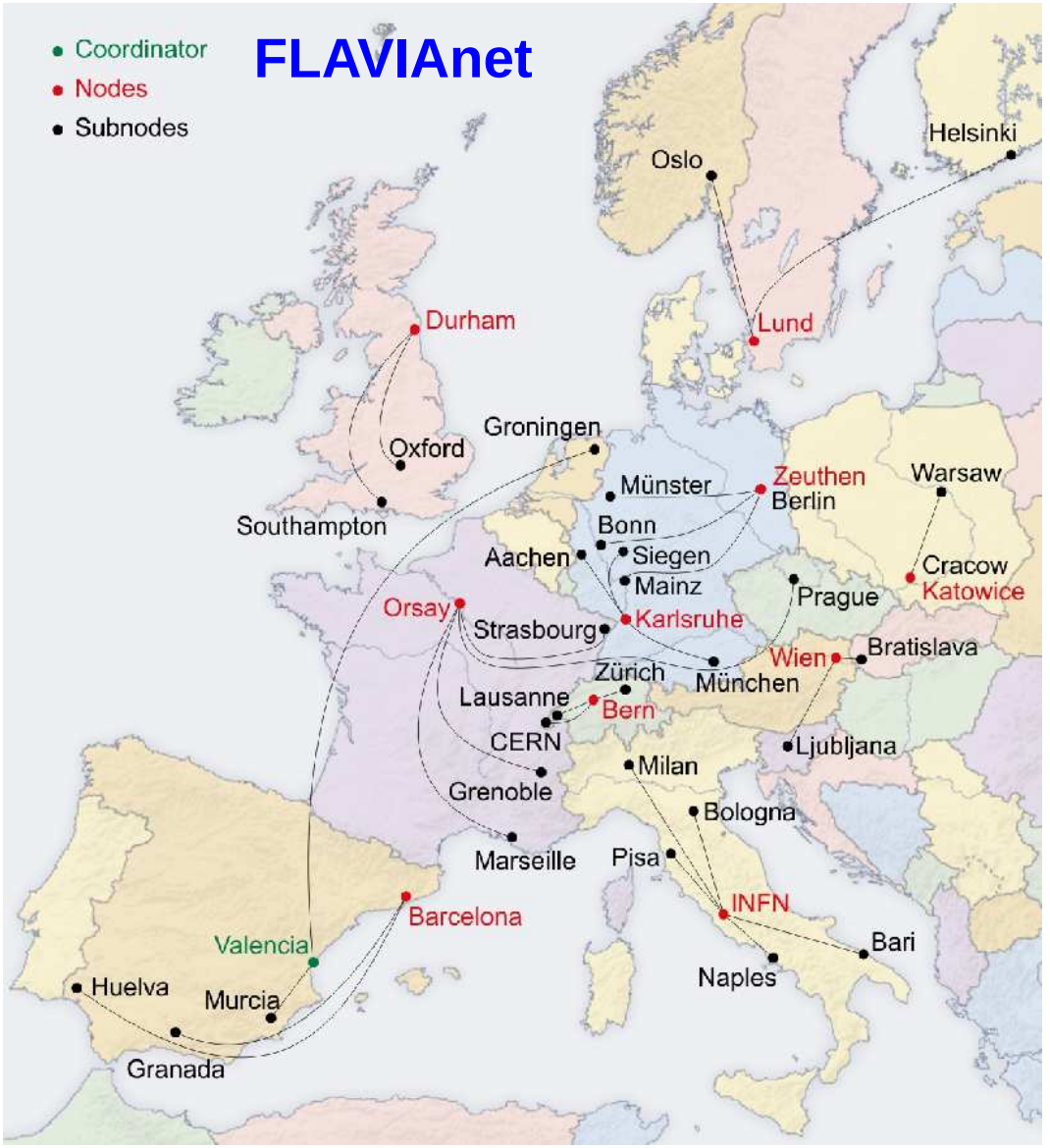
- Lattice ALPHA Coll., ETMC Coll. management from DESY
- Computer Algebra RISC

EU funding

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

Humboldt

- Alexander von Humboldt prizes



Summary

DESY theory

- Unique center for Theoretical Particle Physics
  - full spectrum: Collider Physics, Particle Cosmology, Lattice and Strings
  - complementarity in topics between Hamburg/Zeuthen
  - close collaboration with universities at both sites
- Highly successful program for PhD students and DESY Fellowships

Key strategic items

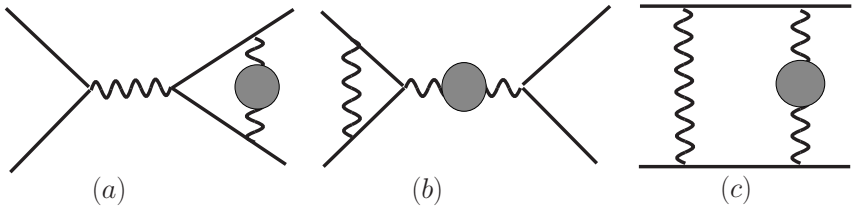
- Strengthen Collider Phenomenology with leading role in Helmholtz Alliance Analysis Center
- Maintain/develop topical centers
  - Particle Cosmology ($\longrightarrow$ Bonus Award)
  - John von Neumann institute for computing NIC
  - Center for Mathematical Physics ZMP

Extra Slides

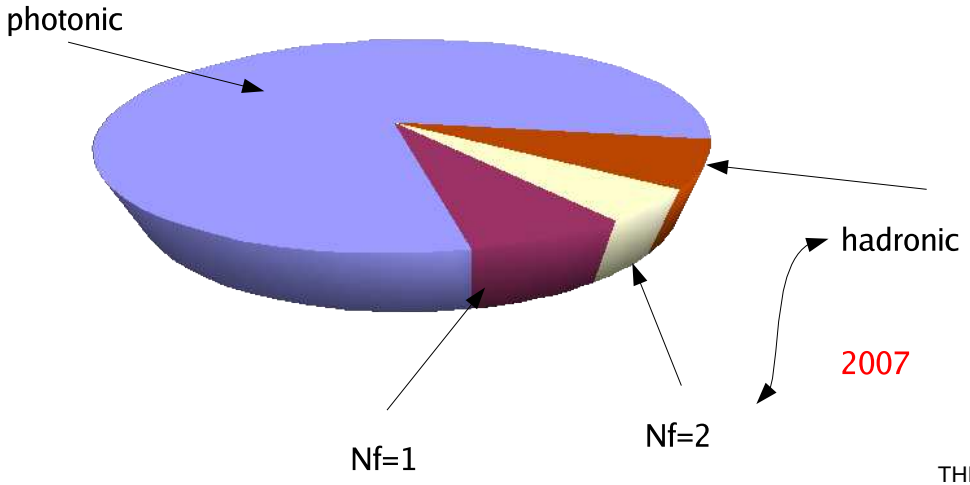
Collider Phenomenology

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



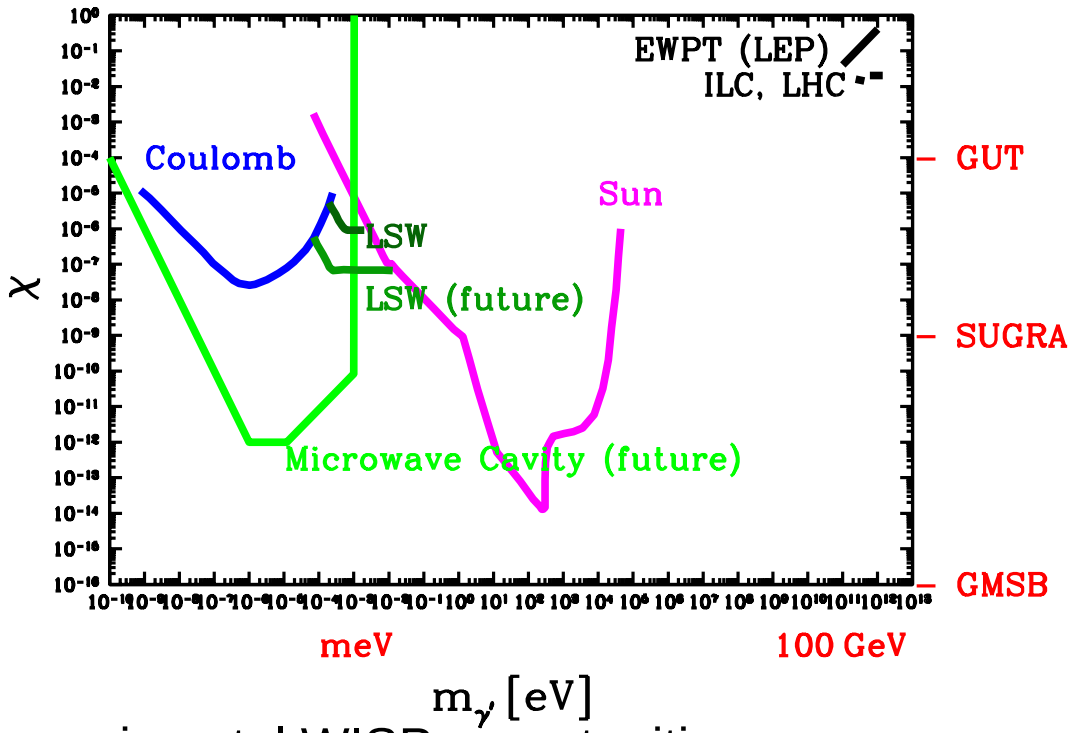
- Theory prediction: error budget of various contributions



Particle Cosmology and Unification

WISPs

- Well-motivated extensions of SM predict Weakly Interacting Sub-eV Particles: axions, hidden sector $U(1)$ bosons (γ'), ...
- Theory and phenomenology actively pursued and including
  - string model building
  - astroparticle physics and cosmology
  - experimental proposals
- Physics Case for Low Energy Frontier of Fundamental Physics

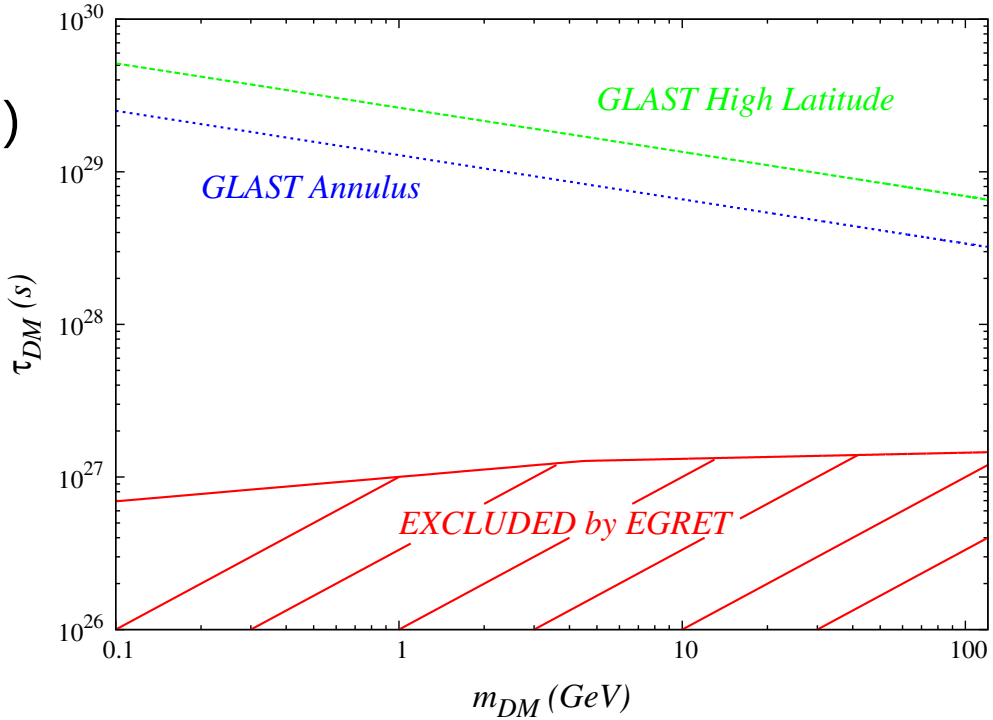


- Explore and shape worldwide experimental WISP opportunities ALPS

Particle Cosmology and Unification

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 testet 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

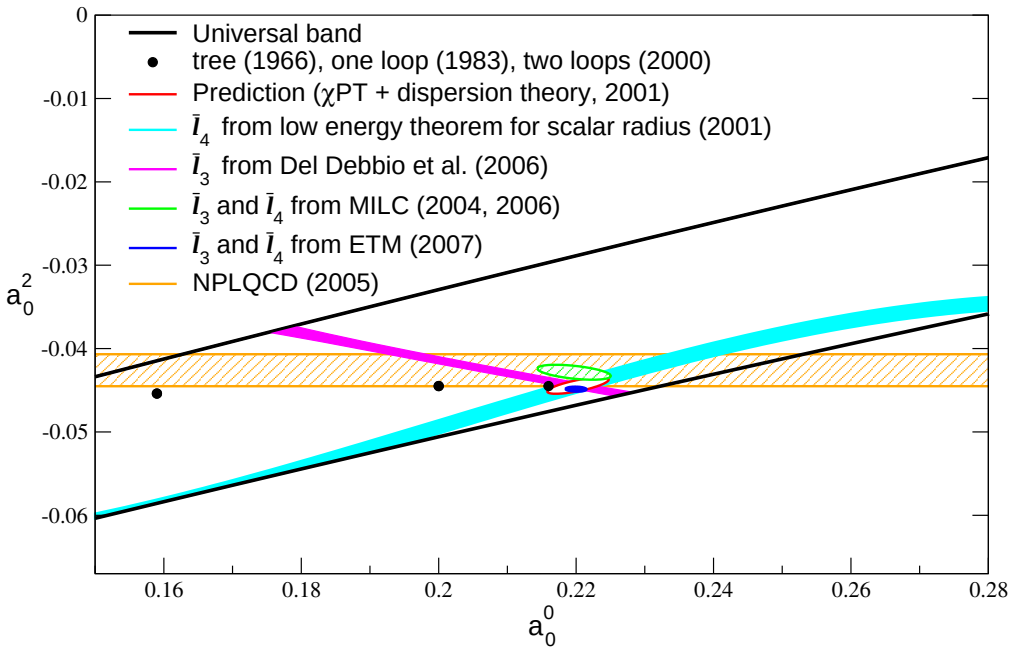


Lattice gauge theory

Verification of QCD

- in low energy, non-perturbative region e.g. $\pi\,\pi \;\longrightarrow\; \pi\,\pi$

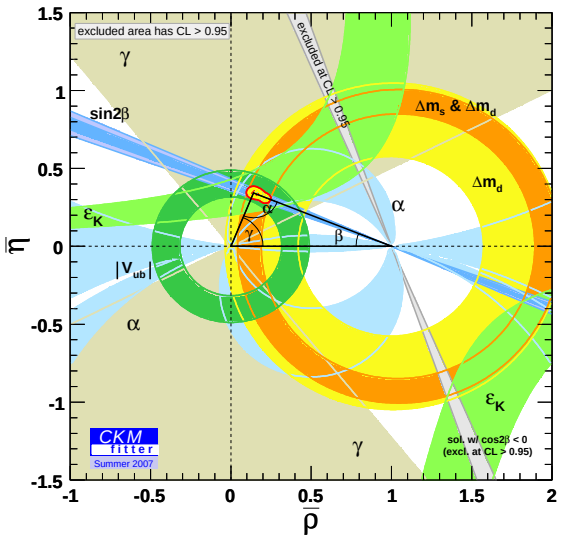
  with unprecedented precision

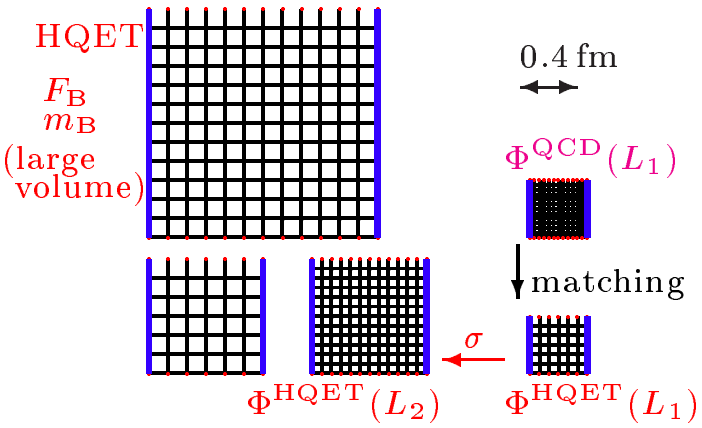


Flavour physics

- non-perturbative QCD "background" in B -physics

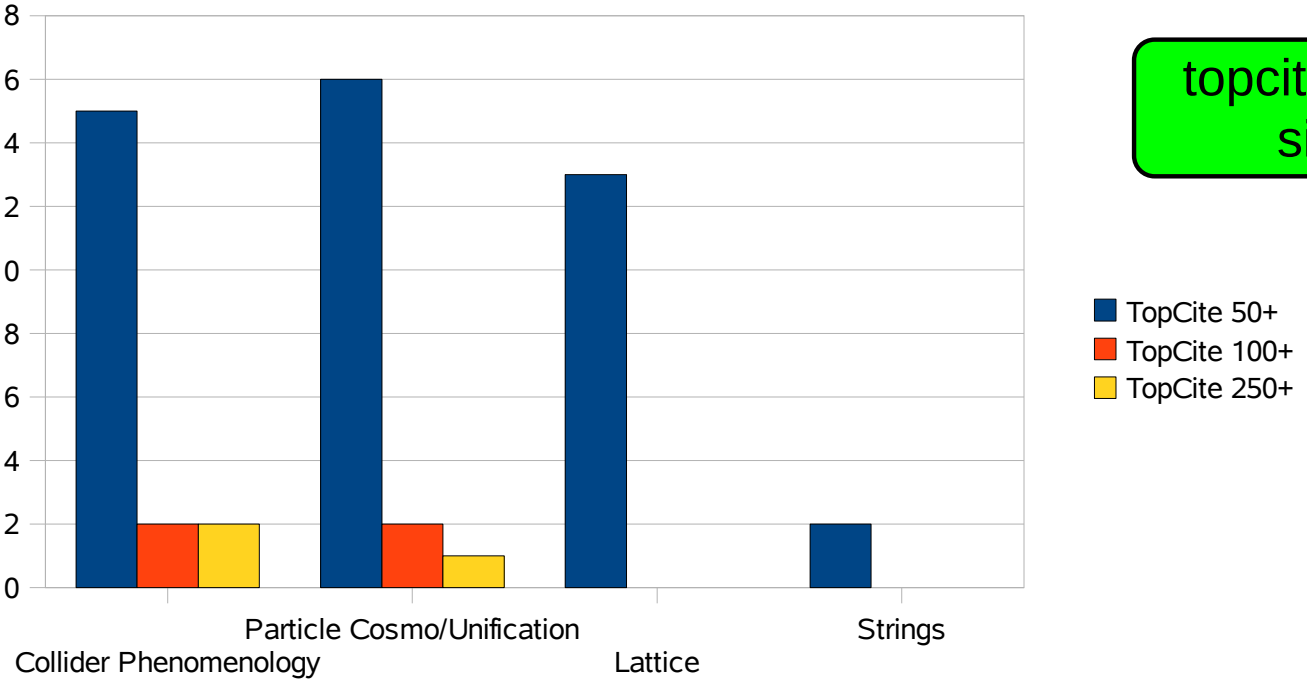
  Non-perturbative HQET





Key features of DESY Theory

- Research of DESY theory



topcite publications since 2004

- Selection criteria for citation counts
  - focus on individual contributions
  - no RPP, no workshop procs (HERA-LHC, Les Houches, etc.)
- Bins according to working groups (+ guests)