

THEORETICAL PARTICLE PHYSICS

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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 ?
- ...





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

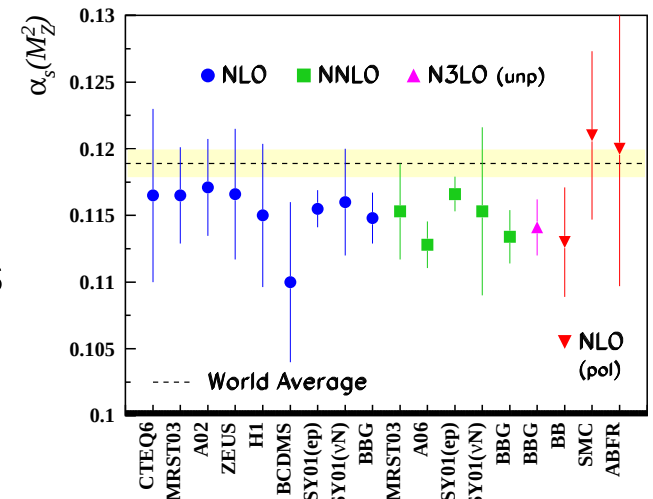
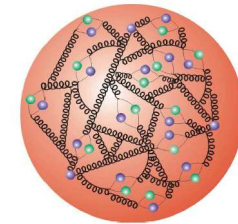
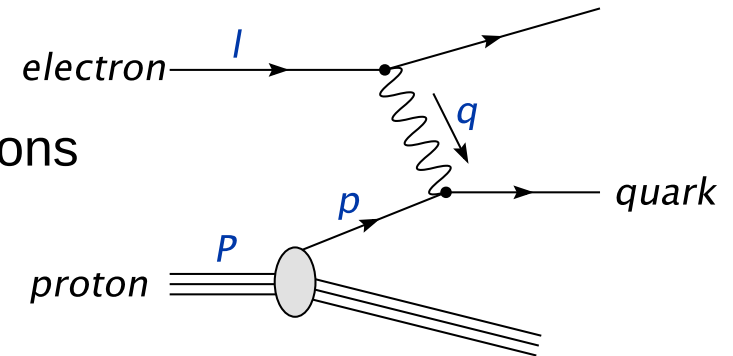
Recommendations of 2004

- 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

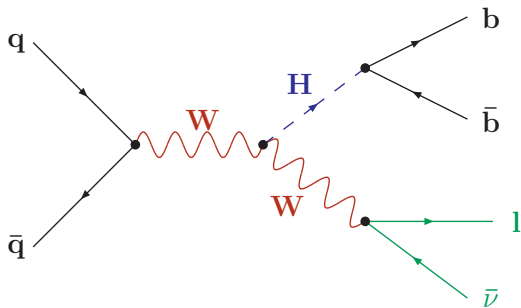
- Precision predictions for DIS structure functions
 - splitting functions
 - Wilson coefficients at 3 loops
- Parton distributions functions (PDFs) for the LHC
 - parton evolution with correlated errors
 - generalized PDFs ('3d imaging of proton')
 - essential ingredient for proton–proton collisions at TeV-scale
- Precision determination of α_s (1% uncertainty)
 - close collaboration for final HERA analysis
H1, ZEUS, HERMES
 - comparison with lattice results
ALPHA Coll., QCDSF Coll.



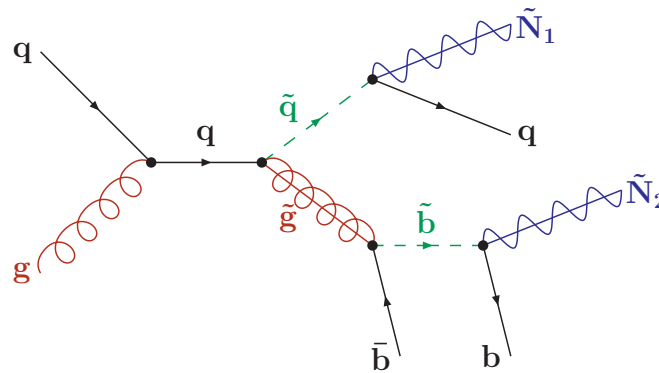
Collider Phenomenology (II)

Terascale Physics: LHC

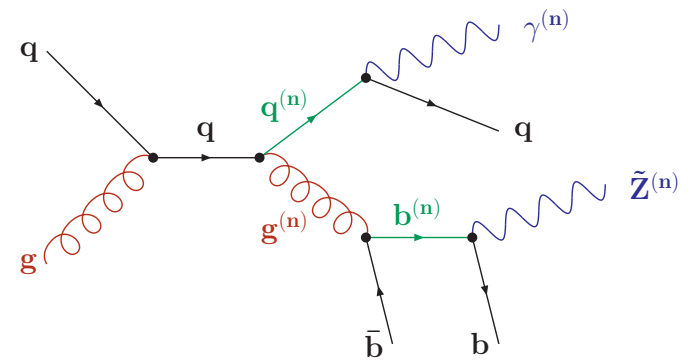
- Complexity of scattering processes at LHC is challenging
- New physics “look-alikes”
 - supersymmetry, Large Extra Dimensions, ...
 - missing energy in subsequent chain decays



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)

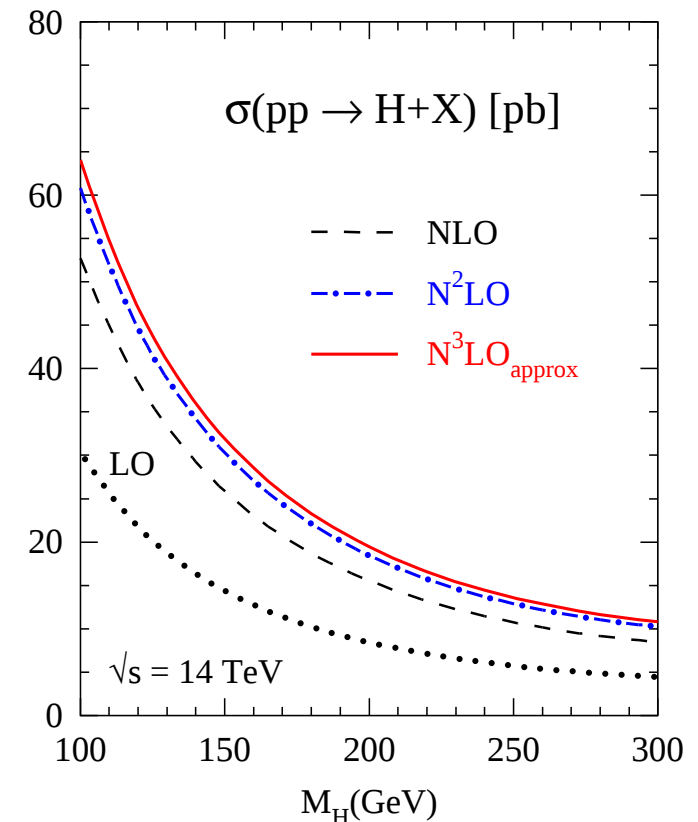


Large Extra Dimensions
 pair-production of
 excited KK-modes

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



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:

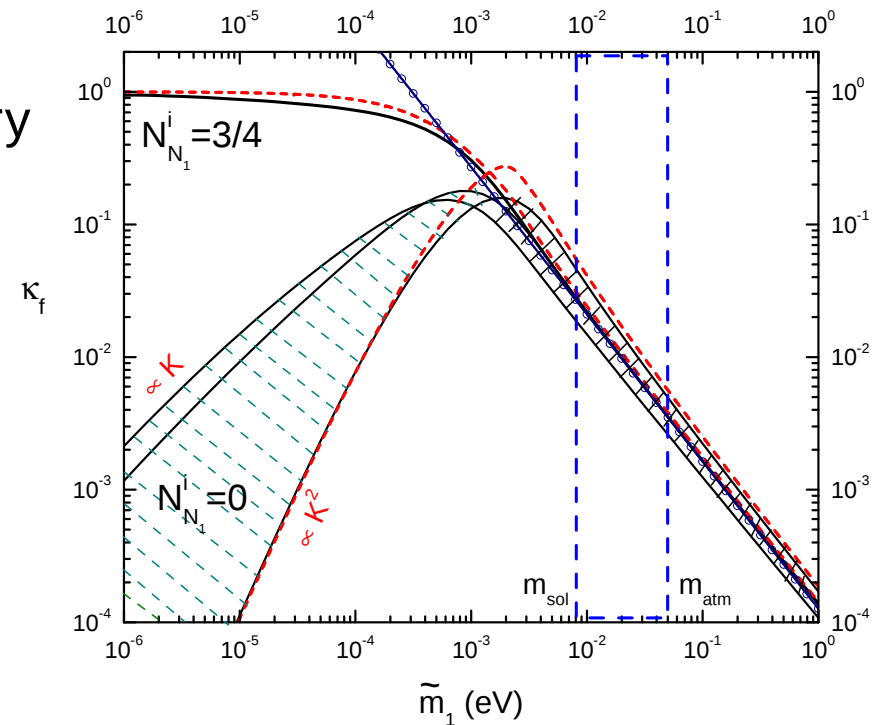
$$10^{-3} \text{ eV} < m_\nu < 0.1 \text{ eV}$$

early universe temperature:

$$T_B \sim M_1 > 10^9 \text{ GeV}$$

- Implications for Dark matter

- standard WIMPs inconsistent, decaying gravitinos ?



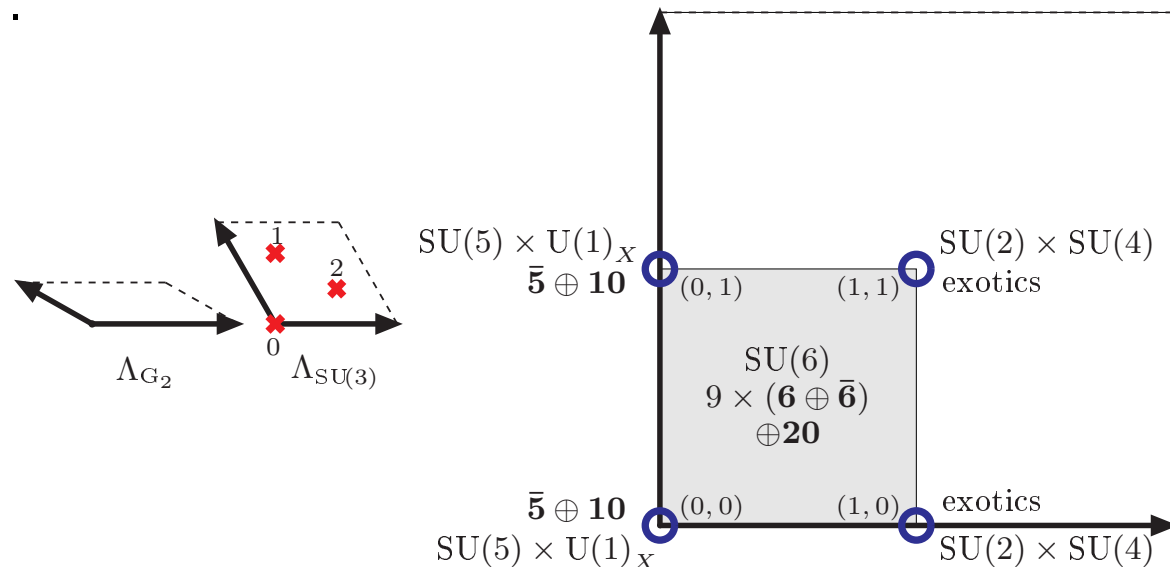
Cosmic rays

- 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, ...

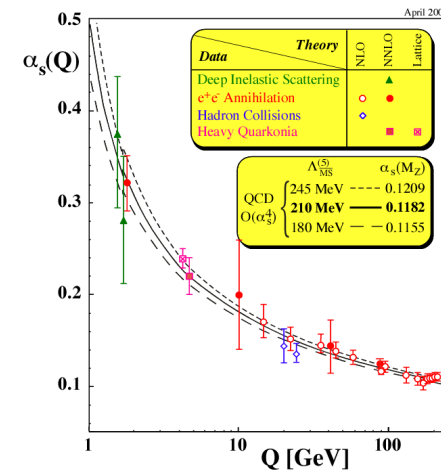
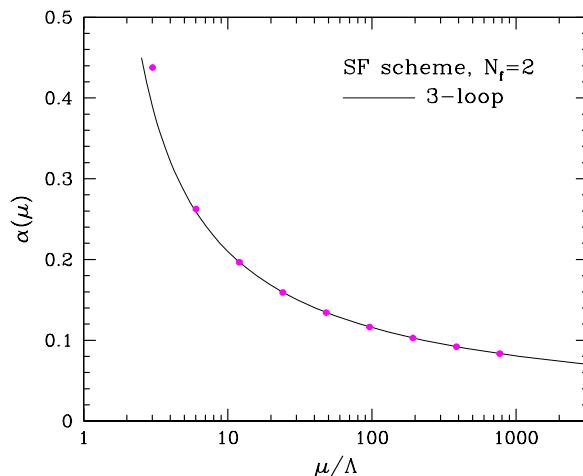


Lattice gauge theory

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

Example: Strong coupling α_s

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

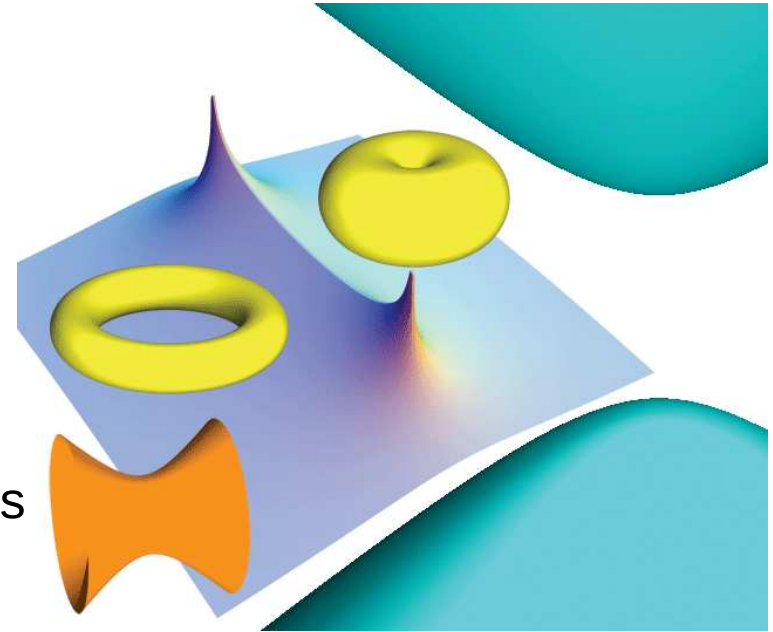


Future: strange and charm sea ...

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)

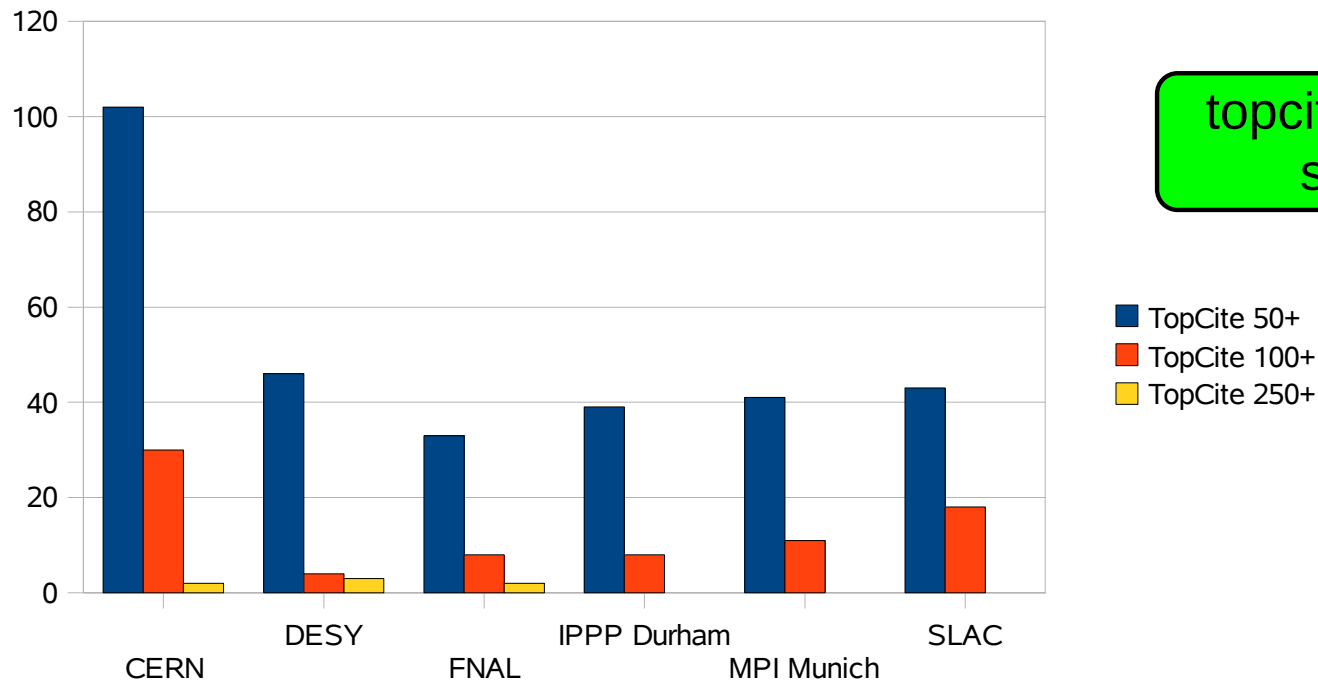


Monte Carlo

- 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



- 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 research
 - 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

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
 - 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)

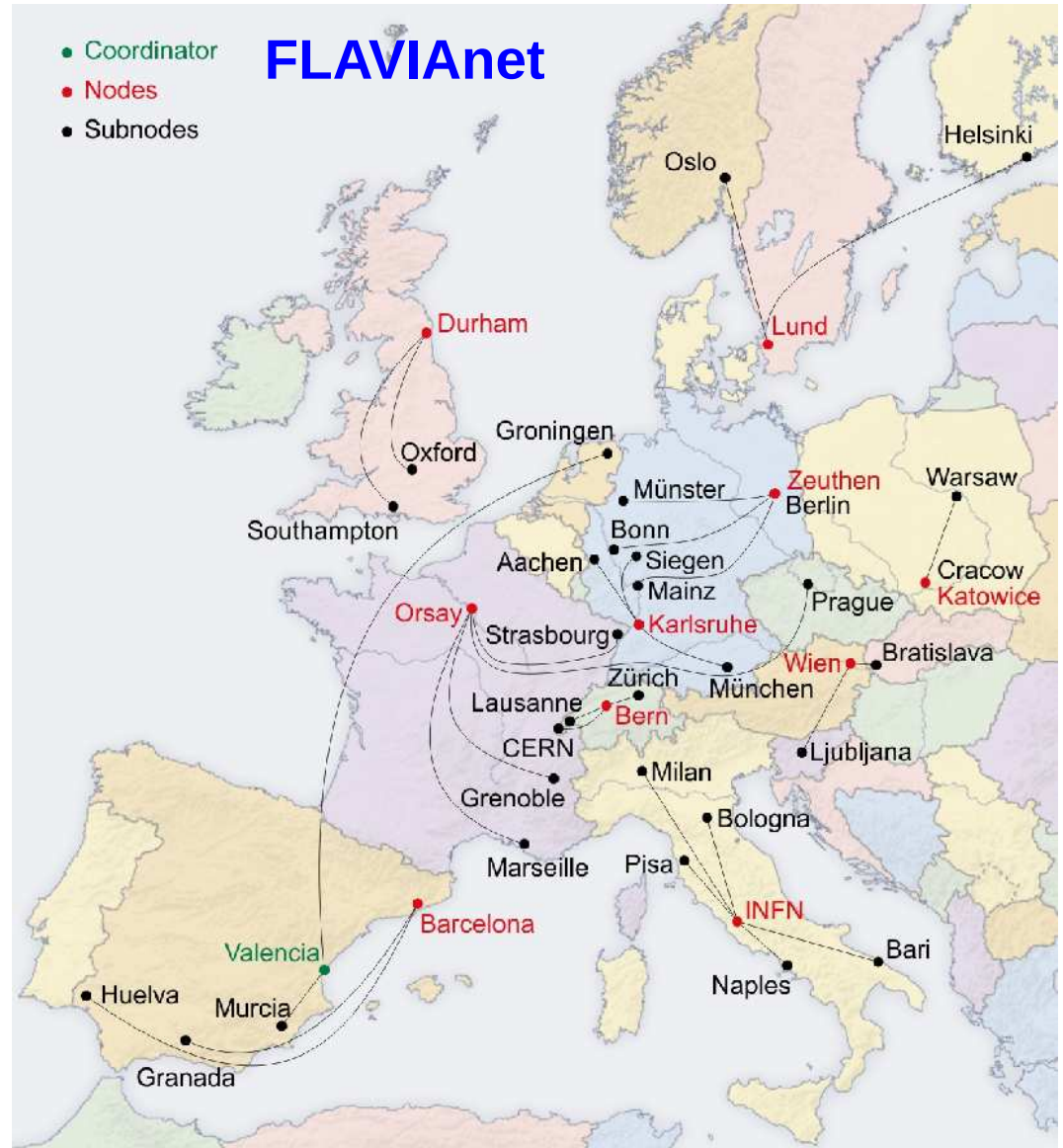
- Lattice ALPHA Coll., ETMC Coll. management from DESY
- Computer Algebra RISC

EU funding

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

Humboldt

- Alexander von Humboldt prizes



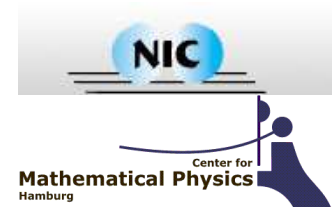
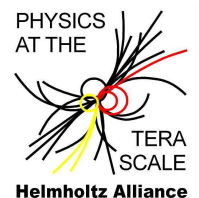
Summary

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 (→ **Bonus Award**)
 - John von Neumann institute for computing **NIC**
 - Center for Mathematical Physics **ZMP**

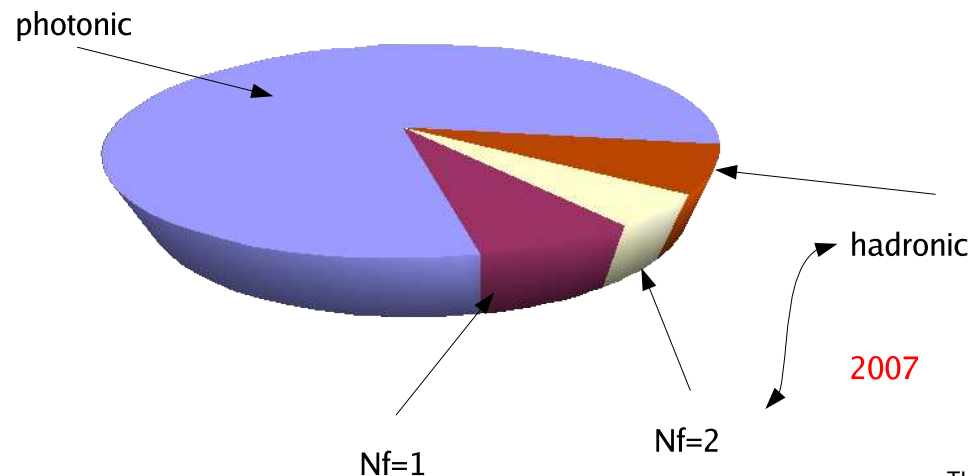
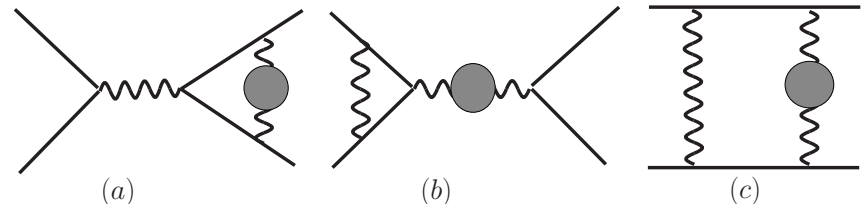


Extra Slides

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

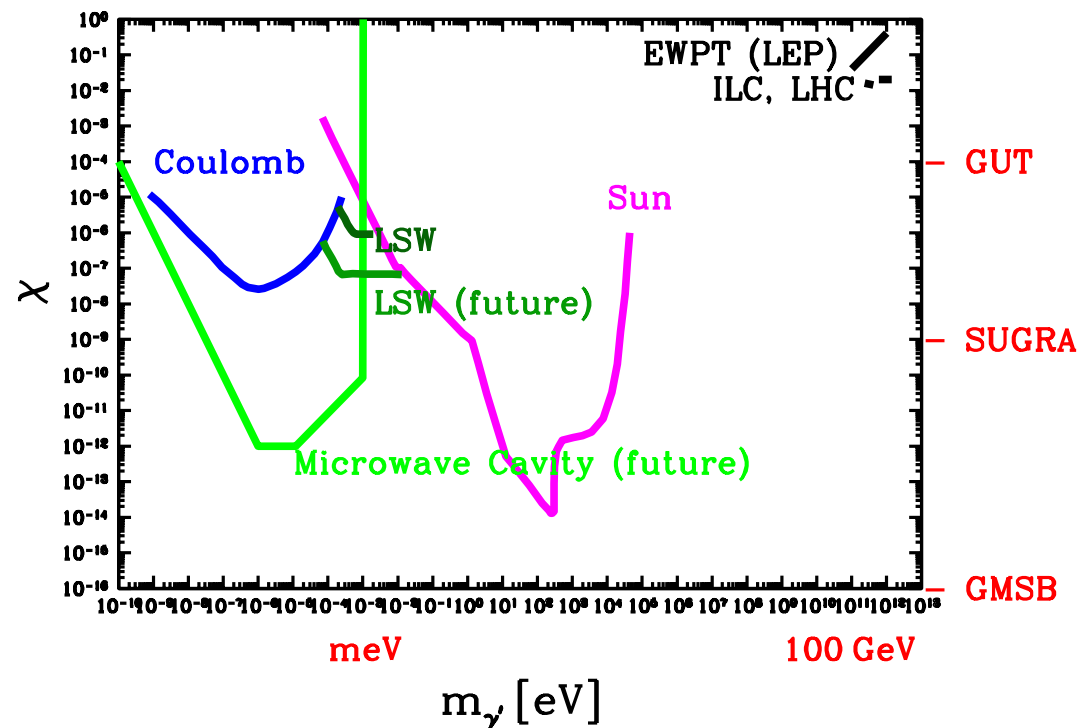
WISPs

- 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

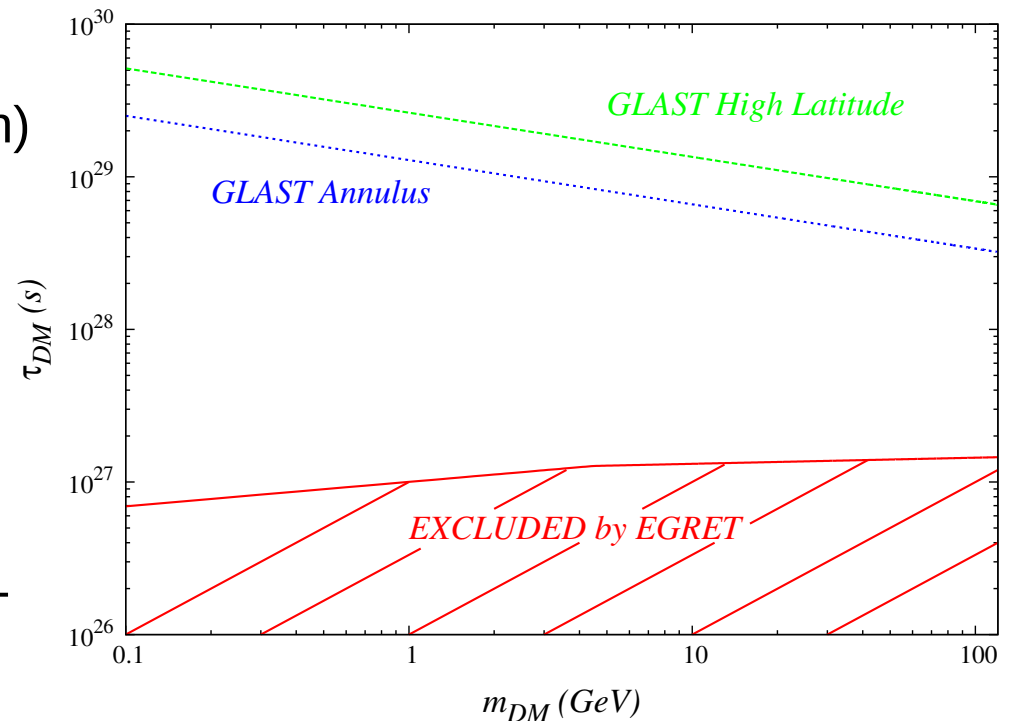


- Explore and shape worldwide experimental WISP opportunities **ALPS**

Particle Cosmology and Unification

Dark matter and cosmic ray anomalies

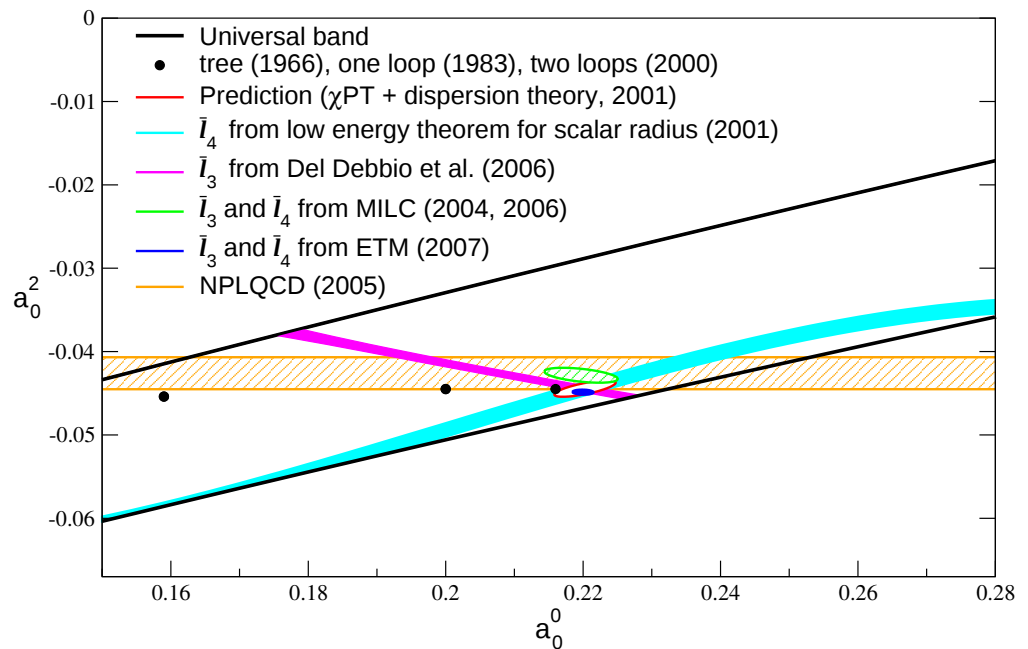
- Decaying gravitino dark matter:
consistent cosmology with leptogenesis, primordial nucleosynthesis
- Characteristic signatures
of cosmic ray
(different from WIMP annihilation)
- Consistent with
PAMELA positron anomaly
(ATIC anomaly problematic)
- Being tested by FERMI
 - significant extension of
sensitivity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



Lattice gauge theory

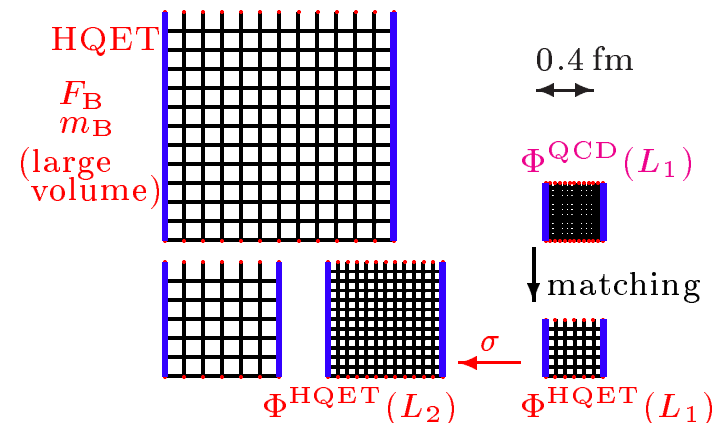
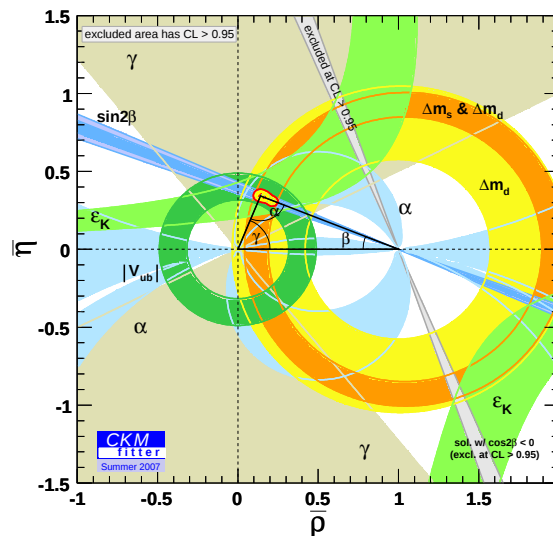
Verification of QCD

- in low energy, non-perturbative region e.g. $\pi\pi \rightarrow \pi\pi$ with unprecedented precision



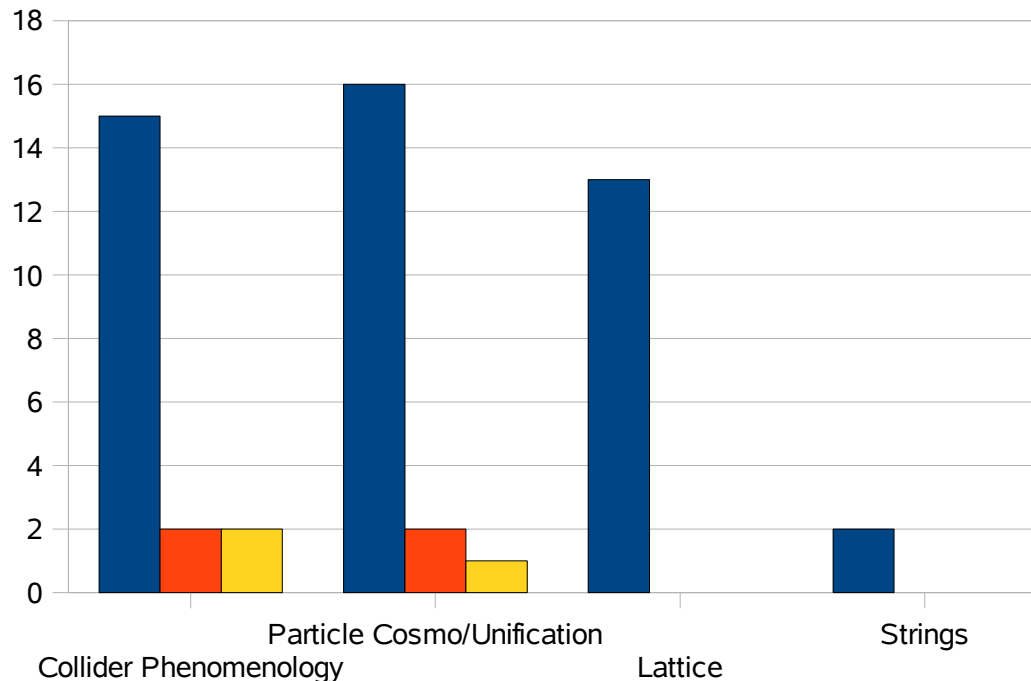
Flavour physics

- 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)