THEORETICAL PARTICLE PHYSICS AT DESY

Wilfried Buchmüller, DESY

DESY PRC, November 2005, Open Session

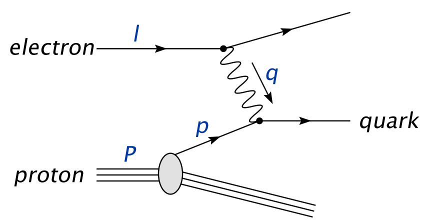
What is Theoretical High Energy Physics ?

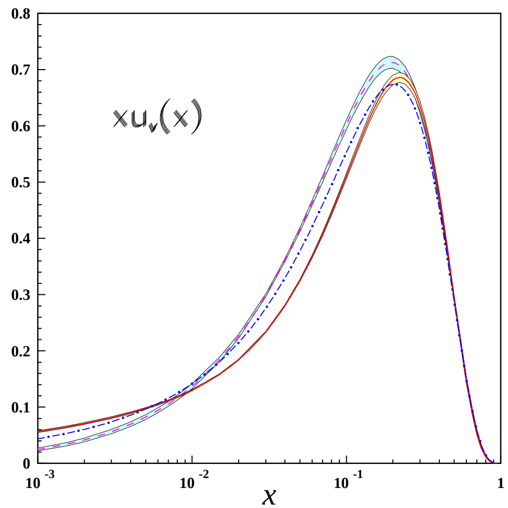
Some guidence is provided by the classification of the 'archive':

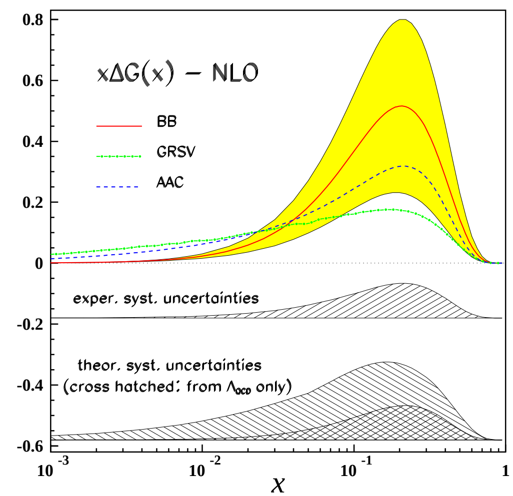
- hep-ph ('phenomenology')
  A. Gauge theories and collider physics: processes at HERA, Tevatron, LHC, ILC; radiative corrections (electroweak, SUSY), precision tests, QCD, B-physics,...
  [HH: Ali, Diehl, Kilian, Schrempp, Zerwas; Z: Blümlein, Moch, Riemann]
  B. Beyond the SM, Particle Cosmology and Astroparticle Physics: neutrino physics, grand unification, proton decay, high energy cosmic rays, model building, extra dimensions, leptogenesis,...
  [HH: Buchmüller, Covi, Hamaguchi, Ringwald]
- hep-lat (lattice gauge theories)
  [Z: Simma, Sommer; NIC: Jansen, Schierholz]
- hep-th ('theory')
  [HH: Schomerus, Teschner]

The DESY theory group always tried to cover the range from 'phenonomenology' to 'theory' in its activities; in the following the hep-ph activities will be illustrated with some representative examples, with emphasis on staff members; there are also important publications by postdocs and students.

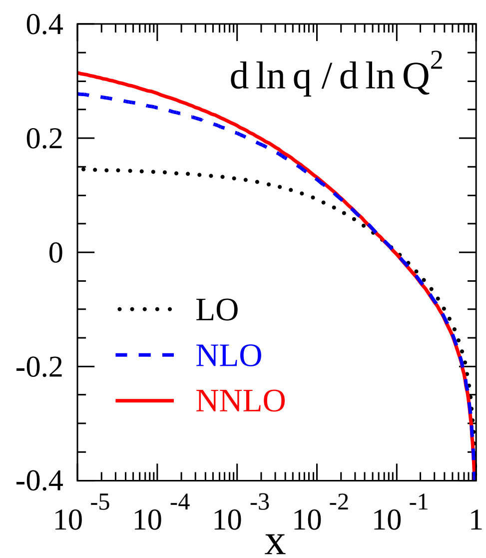
Deep-Inelastic Scattering at HERA: unpolarized and polarized







- Parton distributions with correlated errors (@ 2 and 3 loops)
- Precision calculations of anomalous dimensions and Wilson coefficients to 3 loops
- Precision determination of α_s (1% uncertainty) in close collaboration with H1, ZEUS, HERMES
- Detailed comparisons with Lattice results



[Blümlein, Moch]

HERA and LHC: Instantons ($\boldsymbol{I}$)

Basic non-perturbative aspect of QCD, yet direct expt'l evidence lacking. Characteristic, $\boldsymbol{I}$-induced processes, calculable within $\boldsymbol{I}$-perturbation theory.

- Hard scattering regime
  - **HERA** [Moch, Ringwald & Schrempp] $\Rightarrow$ 2 dedicated $\boldsymbol{I}$-search expts. (**H1, ZEUS**)
  - **LHC** [Petermann & Schrempp], in progress $\Rightarrow$ study of $\boldsymbol{I}$-discovery potential

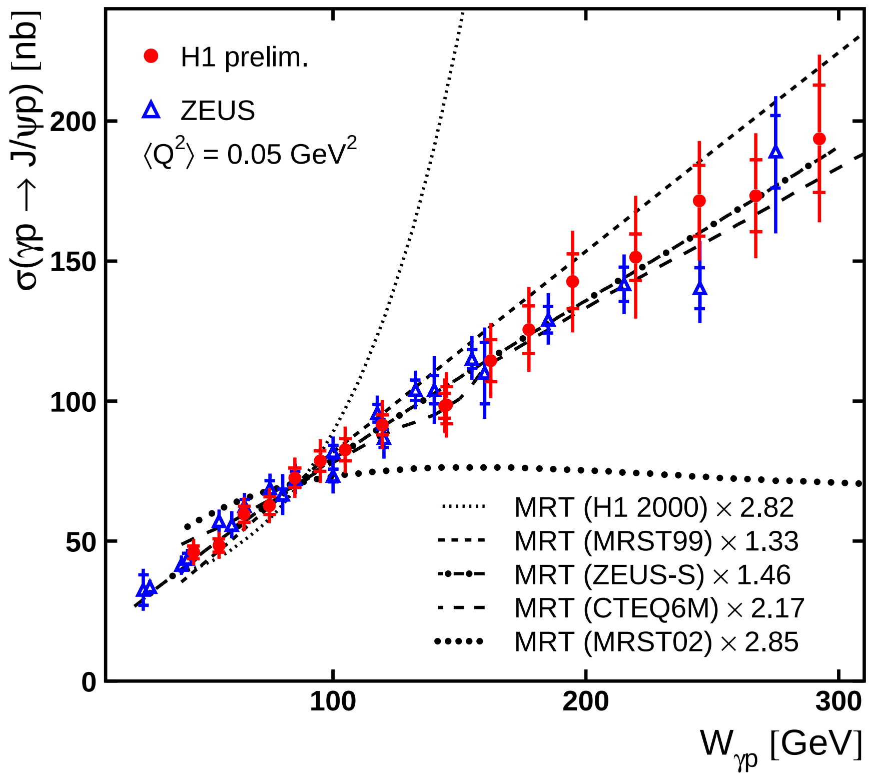
- Gluon saturation at small $x_{\rm Bj}$ [$\alpha_s(Q^2)$ still small]

  Expect: **many** non-perturbative gluons; multiplicity $\langle n_g \rangle \propto \frac{1}{\alpha_s}$; strong classical fields $\propto \frac{1}{\sqrt{\alpha_s}} \Rightarrow$ **Instantons!?** [Schrempp & Utermann]

Instanton-driven Saturation	$\Rightarrow$	Color Glass Condensate	$\Leftrightarrow$	QCD Sphaleron state
		Saturation scale	$\Leftrightarrow$	$\boldsymbol{I}$-size $\langle \rho \rangle \approx 0.5$ fm (lattice)

Exclusive Processes at HERA

theoretical framework for analysis: Generalized Parton Distributions
accessible in vector meson production, virtual Compton scattering, hard diffraction



- extend QCD factorization to exclusive final states
- information on proton structure:
  - spatial distribution of partons
  - orbital angular momentum carried by quarks
  - strong sensitivity to gluon distribution
- various measurements by H1, ZEUS, HERMES

H1 and ZEUS data on J/ψ production (theory: T. Teubner, DIS'05)
strong sensitivity to generalized gluon distribution

[Diehl]

Flavour Physics: Rare decays and CP violation

Experiment vs. SM ($b \to d\gamma$): Test of CKM unitarity, determination of $|V_{td}/V_{ts}|$

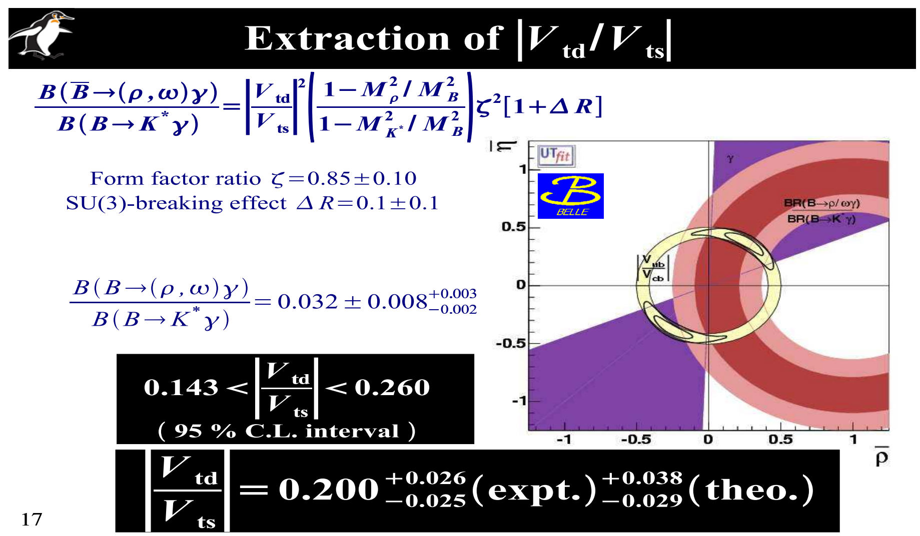
Theoretical Predictions:

$$\bar{\mathcal{B}}[B \to (\rho, \omega)\,\gamma] \quad = \quad (1.38 \pm 0.42) \times 10^{-6}$$

$$R[(\rho, \omega)/K^*] \equiv \frac{\bar{\mathcal{B}}[B \to (\rho, \omega)\,\gamma]}{\bar{\mathcal{B}}[B \to K^*\,\gamma]} = 0.033 \pm 0.010$$

BELLE

$$\bar{\mathcal{B}}_{\rm exp}[B \to (\rho, \omega)\,\gamma] = (1.34^{+0.34}_{-0.31}\ ({\rm stat})^{+0.14}_{-0.10}\ ({\rm syst})) \times 10^{-6}$$



[Ali, Lunghi, Parkhomenko]

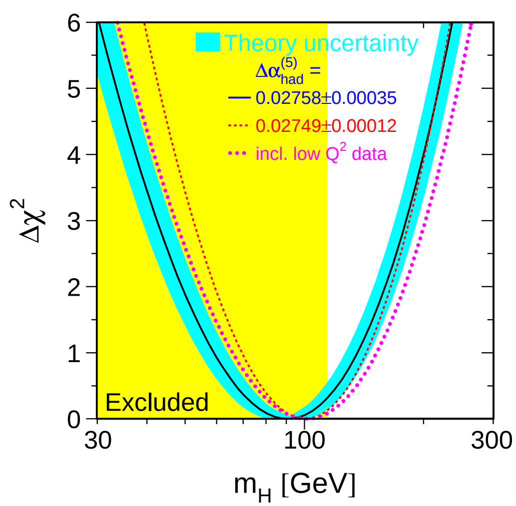
Electroweak Precision Predictions for LHC and ILC

♣ The m_{top} prediction for Tevatron

♣ The m_{Higgs} prediction for the LHC

See the "blue-band-plot"
made with ZFITTER (1985 – 2005)
7/2005: now with latest weak 2-loops
in close collaboration with experimentalists:
ZFITTER Support Group

http://www-zeuthen.desy.de/theory/research



♣ 10^{-4} luminosity measurement at ILC

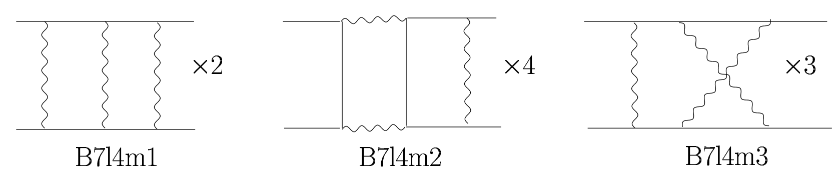
is possible with small angle Bhabha scattering
⟶ need for this:
massive 2-loop corrs. to Bhabha scattering
In order to complement the Bhabha Monte Carlos

First systematic evaluation of master integrals for massive 2-loop box diagrams

Non-trivial techniques:

– Solve systems of differential equations

– Use of n-dim. complex Mellin-Barnes representations



[Riemann]

② $\alpha_{\rm em}(s)$ in Precision Physics

Uncertainties of hadronic contributions to effective α are a problem for electroweak precision physics:

Precision physics limitations:

α , G_μ, M_Z **most precise input parameters**

$\Updownarrow$

partially non-perturbative relationship

precision predictions

$\sin^2\Theta_f, v_f, a_f, M_W, \Gamma_Z, \Gamma_W, \cdots$

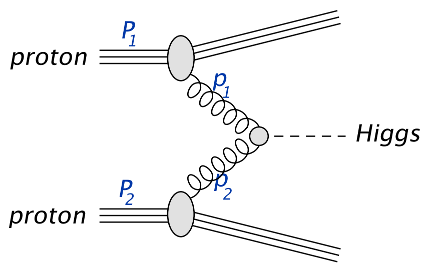
$\alpha(M_Z), G_\mu, M_Z$ **best effective input parameters for VB physics (Z,W) etc.**

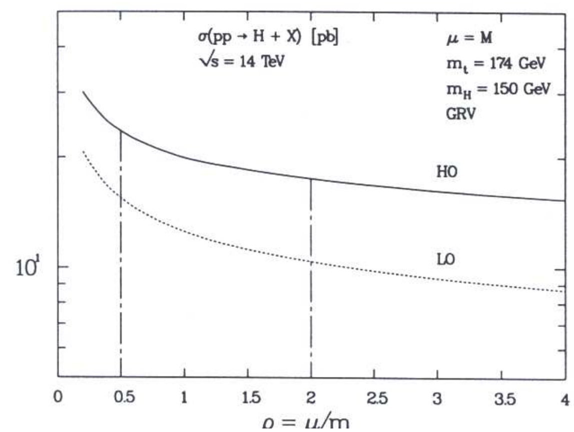
$$\frac{\delta\alpha}{\alpha} \sim 3.6 \times 10^{-9}$$
$$\frac{\delta G_\mu}{G_\mu} \sim 8.6 \times 10^{-6}$$
$$\frac{\delta M_Z}{M_Z} \sim 2.4 \times 10^{-5}$$
$$\frac{\delta\alpha(M_Z)}{\alpha(M_Z)} \sim 1.6 \div 6.8 \times 10^{-4} \quad \text{(present)}$$
$$\frac{\delta\alpha(M_Z)}{\alpha(M_Z)} \sim 5.3 \times 10^{-5} \quad \text{(TESLA requirement)}$$

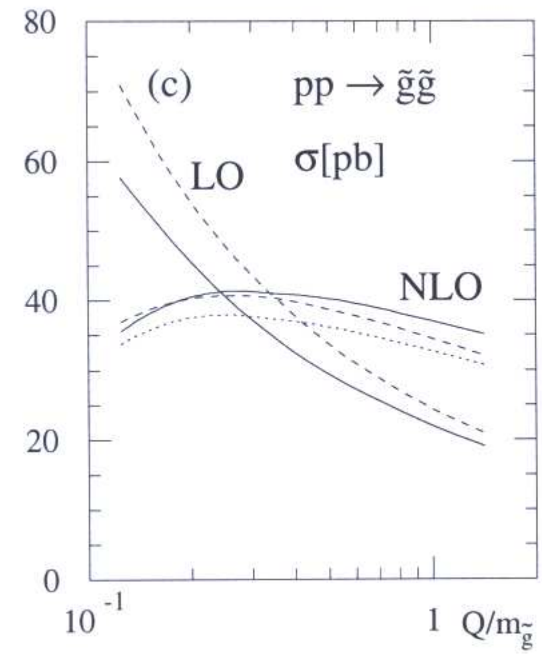
⇒ serious limiting factor for precision physics

[Jegerlehner]

Higgs and SUSY at LHC



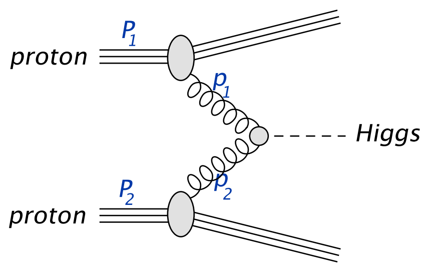


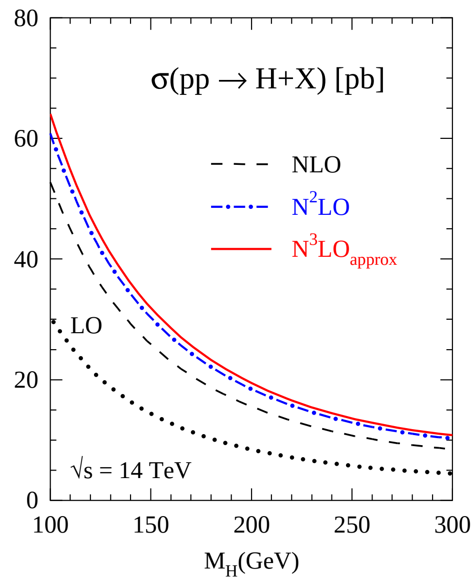


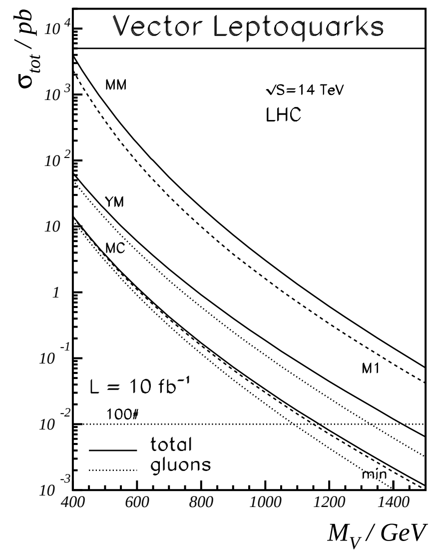
- Many production channels of Higgs bosons and SUSY particles based on gluon-gluon fusion $\longrightarrow$ large QCD radiative corrections
- Higgs bosons: SM and SUSY; $pp \longrightarrow H$ and ttH, etc; NLO/LO: cross section nearly doubled
- SUSY particles: $pp \longrightarrow \tilde{q}\tilde{q}, \tilde{g}\tilde{g}$ etc; cross section nearly doubled, prediction stabilized

[Plehn, Spira, Zerwas]

Predictions for the LHC: in the Standard Model and Beyond



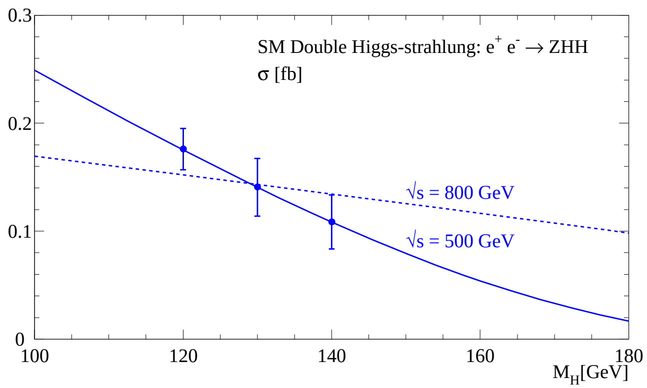


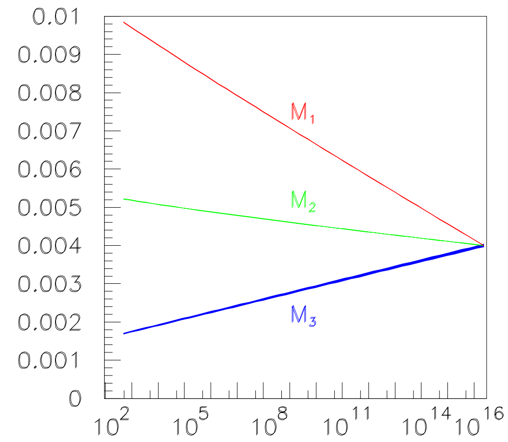


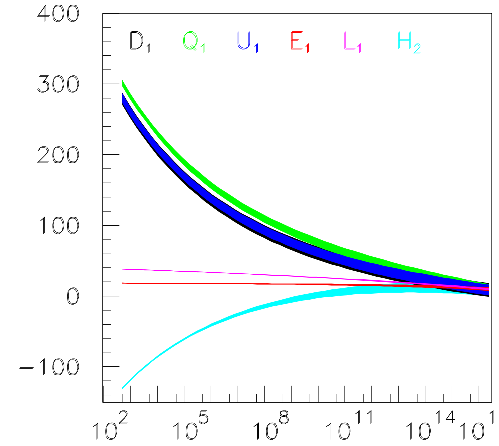
- Higgs Production: QCD corrections to total cross section at 3 loops
- Fast Mellin-based evolution codes for QCD matrix elements for inclusive LHC processes
- Transfer of DIS higher order technology to LHC physics
- Calculation of time-like processes with different mass scales
- Extension to physics beyond the Standard Model

[Blümlein, Moch]

Higgs and SUSY at LHC/ILC







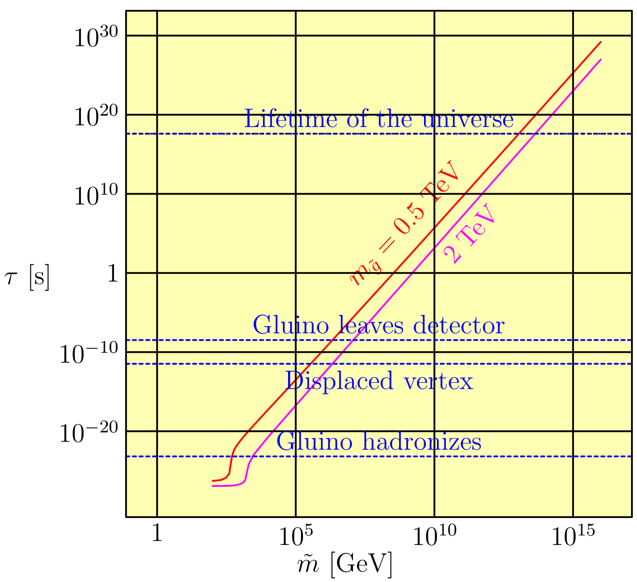
- Higgs at ILC: spin-parity and trilinear coupling, important for reconstruction of Higgs potential
- SUSY at LHC/ILC: sparticle masses/couplings, extrapolation to GUT/Planck scale
- Reconstruction of fundamental SUSY theory; identification of mechanism for supersymmetry breaking

[Kilian, Mühlleitner; Blair, Porod; Zerwas]

Split Supersymmetry at LHC/ILC

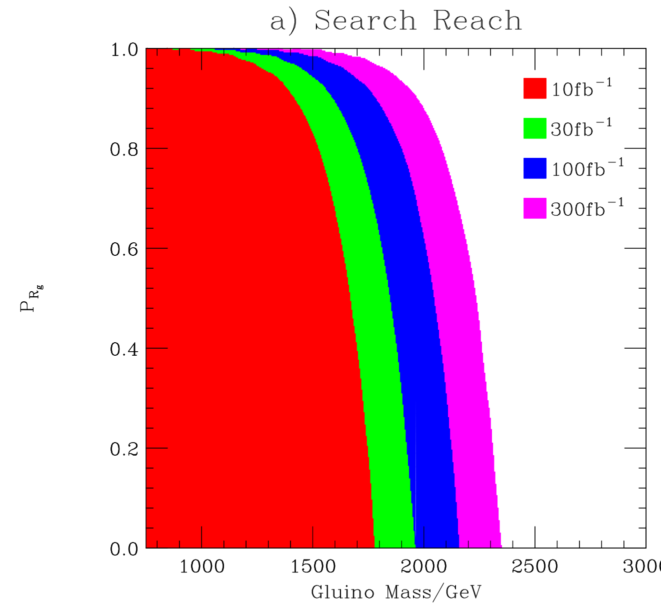
All scalars (except Higgs) superheavy = no flavor problem, but fine-tuning

Fine-tuning resolved by string-theory vacuum multiplicity?

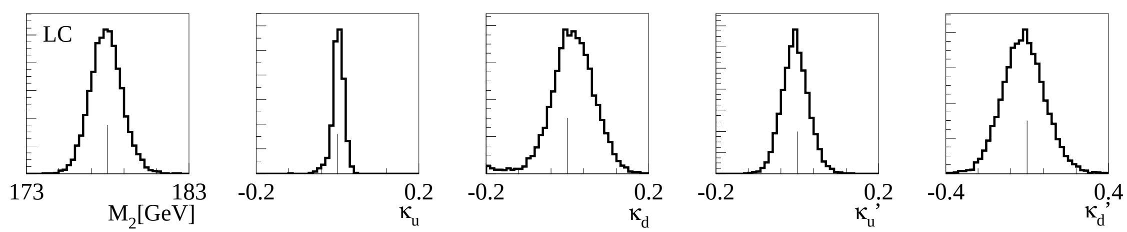


Phenomenology:

- Gluino is long-lived
- Gluino pairs at LHC: heavy stable hadrons
- Charginos/neutralinos at LHC and ILC
- Higgs boson with $m > 130\,\mathrm{GeV}$



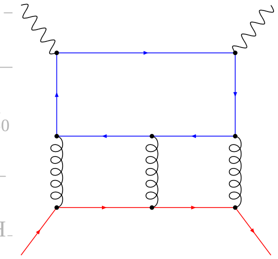
Establish high-scale supersymmetry: measure chargino/neutralino parameters at ILC



⇒ ILC: Anomalous Yukawa couplings can be measured with sufficient precision ($< 10\,\%$)

[Kilian, Plehn, Richardson, Schmidt]

Mathematical Challenges and Computer Algebra



The solution of multi-loop problems as needed by LHC, GigaZ, ILC faces us with serious technology challenges.

Feynman diagrams are no longer solved by conventional technology: Gbytes of integrals

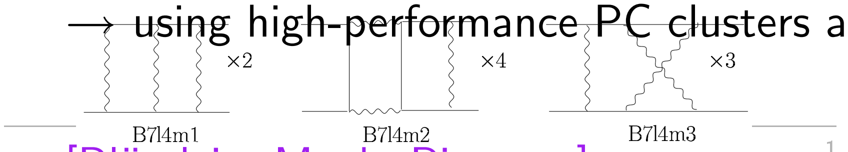
Need of:

- Mathematics of harmonic sums etc.
- Algorithmic solutions of complex problems like summation of nested series: XSUMMER program in FORM
- multi-dimensional Mellin-Barnes integrals – Maple, Mathematica
- Gröbner bases

Need: Development of innovative problem-solvers:

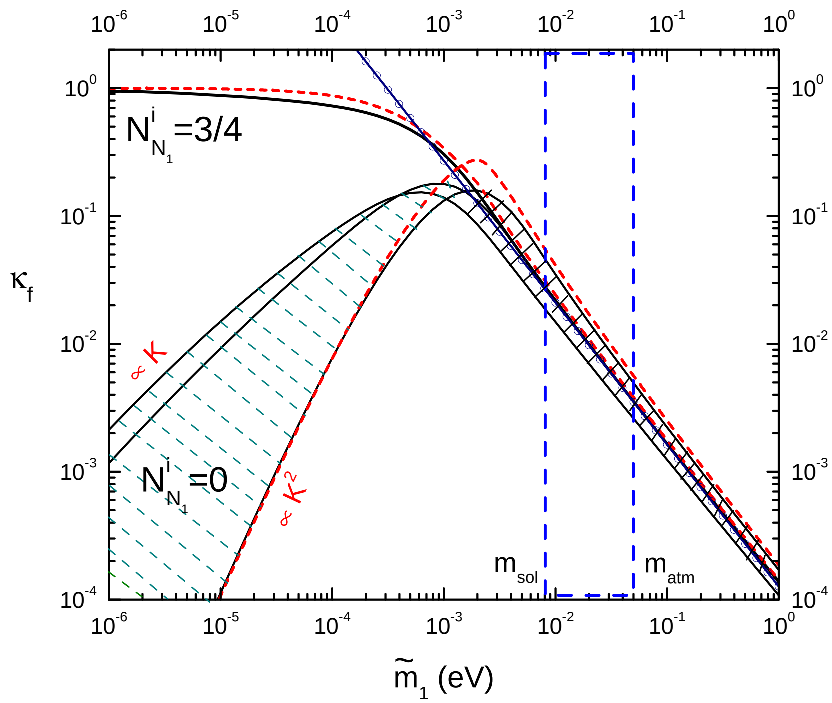
⟶ in cooperation with mathematicians

⟶ using high-performance PC clusters and efficient computer algebra systems



[Blümlein, Moch, Riemann]

Neutrino Masses and Baryon Asymmetry



- Leptogenesis: leading (?) theory for origin of matter (Fukugita, Yanagida; DESY '86).
- Non-equilibrium process: quantitative relation between neutrino masses and baryon asymmetry (CP asymmetry ε_1, efficiency factor κ_f):

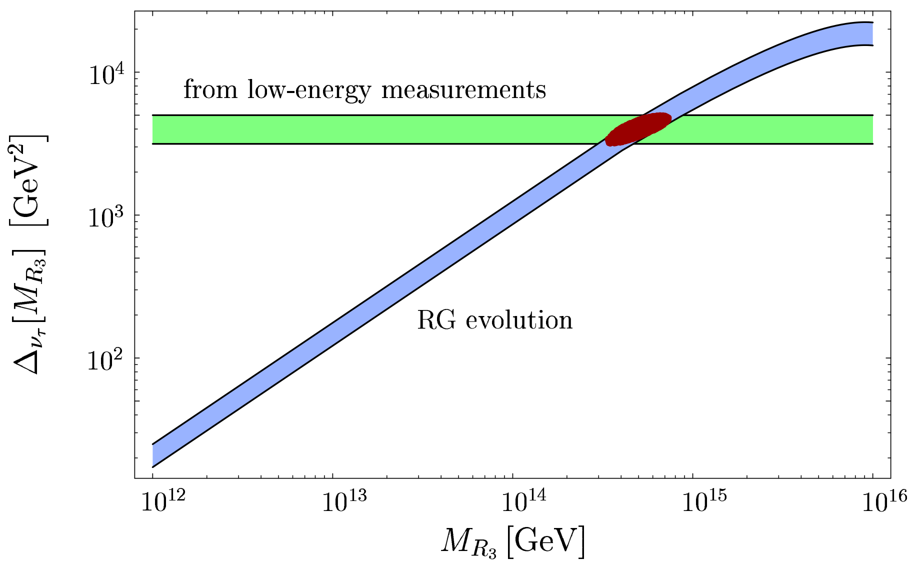
$$\eta_B \simeq 0.01\, \varepsilon_1\, \kappa_f .$$

Implications: light neutrino mass window, 10^{-3} eV $< m_{\nu_i} < 0.1$ eV, can be tested in laboratory experiments and cosmology; lower bound on the heavy neutrino mass and maximal temperature of the early universe, $T_B \sim M_1 > 10^9$ GeV $\rightarrow$ important implications for dark matter.

[WB, Di Bari, Plümacher]

Reconstruction of Heavy ν_R Mass Scale at the ILC

The reconstruction of the heavy neutrino mass scale is a theoretical/experimental challenge! For supersymmetric theories this may be possible in some regions of parameter space.

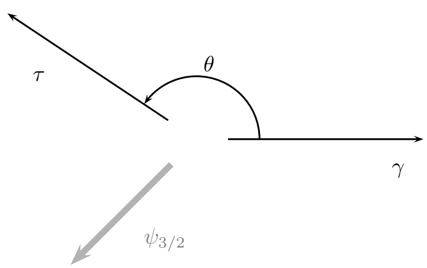


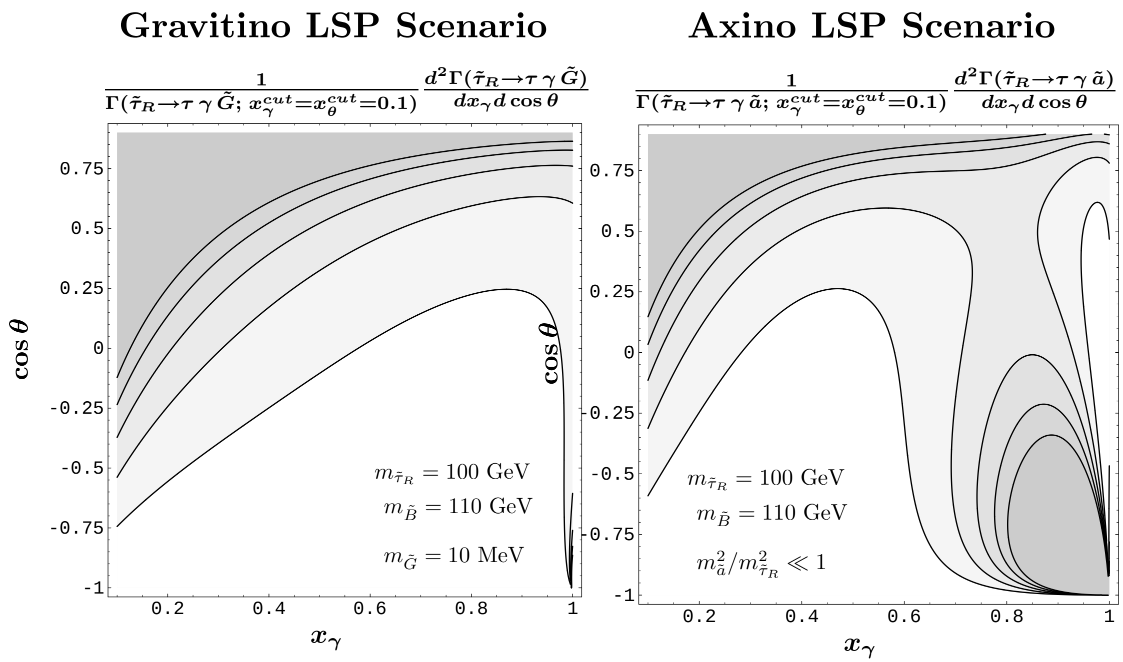
The mass differences between scalar tau-leptons and selectrons depend on the seesaw scale in supergravity SO(10) models. For light SUSY mass patterns, the mass differences can be accurately determined at ILC.

Compared with the SO(10) models, indirect evidence for the expected heavy neutrino mass scale can be obtained.

[Freitas, Porod, Zerwas]

Discovering the Gravitino at the LHC/ILC



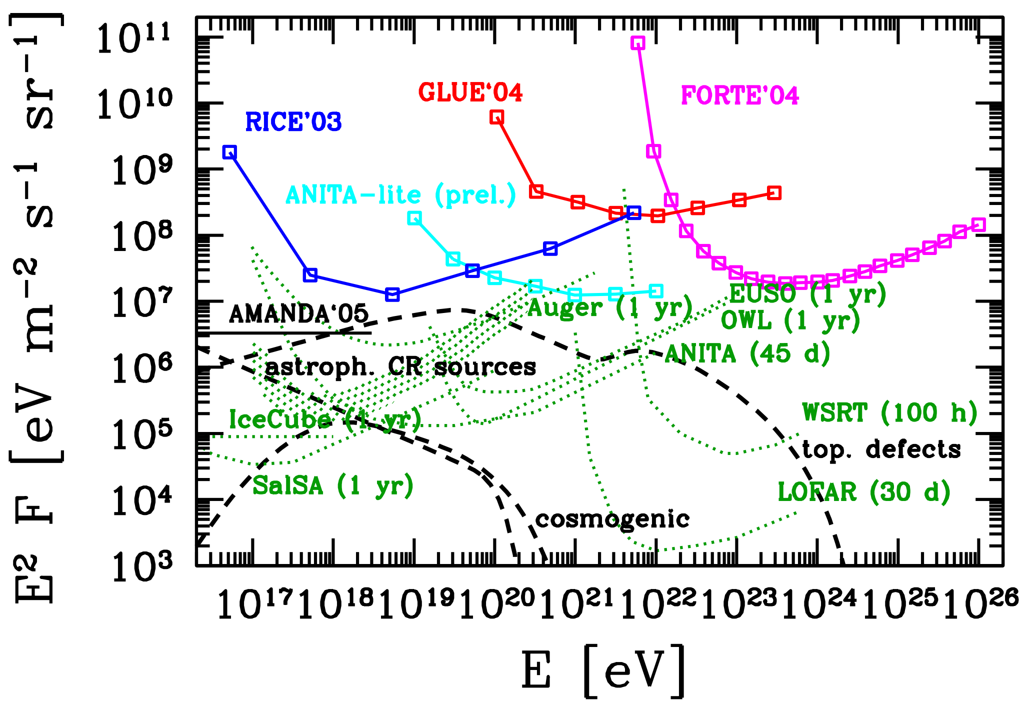


- The large temperature required by leptogenesis favours a gravitino LSP which can be the dominant component of dark matter.
- For a large range of parameters a quasi-stable scalar-tau is the NLSP; its lifetime yields a microscopic determination Newton's constant.
- From the 3-body decay $\tilde{\tau}\to\tau+\tilde{G}+\gamma$ one can determine the gravitino spin, s=3/2, ('Gedankenexperiment').

[Brandenburg, Covi, Hamaguchi, Roskowski, Steffen]

Extremely Energetic Cosmic Neutrinos

Many observatories running (AMANDA,...) or under construction (IceCube,...)
Already now stringent constraints on high energy neutrino flux with significant discovery potential in the next decade; strong impact on astrophysics, particle physics and cosmology



- astrophysics:
  processes associated with acceleration of cosmic rays
- particle physics:
  $\sigma_{\nu N}$ far beyond the reach of HERA and LHC; study beyond SM contributions
- cosmology:
  big bang relics (topological defects, relic neutrinos,...)

[Ahlers, Ringwald, Weiler, Wong]

Summary of the hep-ph activities:

- Broad research activities related to the colliders HERA, LHC/ILC, QCD, electroweak theory and B-physics, Higgs and SUSY with implications for cosmology
- Sophisticated 'tools' have been/are being developed which will be crucial for the physics analysis at LHC/ILC
- Research in Astroparticle Physics is closely related to AMANDA/IceCube
- Physics beyond the SM (neutrinos, supersymmetry, GUTs...) tries to bridge the gap between the SM and string theory
- Particle Cosmology is focussed on applications of particle physics to the physics of the early universe, with implications for collider physics

General Strategy

- close connection with experimental program: HERA, LHC/ILC, IceCube
- center for theoretical particle physics in Germany and beyond

major changes in recent past reflect development of particle physics and changes at (German) universities:

- Zeuthen: expansion of astroparticle physics (exp), support for strong QCD lattice group (NIC)
- Hamburg: lattice group ends, string group starts; more activity in particle cosmology (Virtual Institute)

HGF Evaluation in 2003: 'The building-up/strengthening of groups in 'String Theory' and 'Particle Cosmology' is strongly supported'

Additional funding from HGF, DFG, EU,...

- HGF-Nachwuchsgruppe VH-NG-004: QCD in exklusiven Prozessen bei HERA
- HGF-Nachwuchsgruppe VH-NG-005: Universelle Ereignisgeneratoren für zukünftige Lepton-Collider
- HGF-Nachwuchsgruppe VH-NG-006: Particle physics and cosmology: beyond the two standard models
- HGF-Nachwuchsgruppe VH-NG-105: Computer algebra and higher orders in particle theory
- HGF-Virtuelles Institut VH-VI-106: Particle Cosmology (VIPAC, coordination DESY)
- HGF-Virtuelles Institut VH-VI-032: Hochenergiestrahlungen aus dem Kosmos (VIHKOS)
- HELEN: High Energy Physics Latinamerican-European Network (Coordination DESY: F. Schrempp)
- European Network for Theoretical Astroparticle Physics ENTApP
- SFB Transregio-9: Computational Particle Physics (Karlsruhe, Berlin, Aachen, Zeuthen/NIC)
- SFB: Particles, Strings and the Early Universe (positive pre-evaluation; evaluation of full application January 2006; coordination Hamburg University)

Collaboration with (German) Universities

corner stone of the scientific life at DESY, includes:

- the close collaboration with the Universities in Berlin, Potsdam and Hamburg
- frequent joint workshops on collider physics (HERA, LHC and ILC)
- the new Center for Mathematical Physics with the II. Institute of Theoretical Physics and Department of Mathematics (Hamburg)
- Virtual Institute on Particle Cosmology with Univ. Bonn, Heidelberg, Munich
- HGF-Nachwuchsgruppen with Univ. Karlsruhe, Padua, Regensburg, Würzburg
- the annual Theory Workshop in Hamburg, organized jointly with German universities
- the conference series Loops and Legs in QFT, organized by the Zeuthen group
- the Computer-Algebra School, organized by Zeuthen/German Universities and MPG
- all DESY staff members supervise graduate students. During the past 4 years, 10 permanent positions in particle theory were filled in Europe with former graduate students from Hamburg, including 6 professorships at German Universities

the continuous flow of excellent graduate students from (German) Universities is decisive for the scientific life and the success of the DESY theory group...