THEORETICAL PARTICLE PHYSICS IN KARLSRUHE

I. The Team

II. Research in Theoretical Particle Physics

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Karlsruhe Institute of Technology

I. THE TEAM

theoretical particle physics $\longleftrightarrow$ astro-particle physics

$\nwarrow\!\searrow$ $\swarrow\!\nearrow$

experimental particle physics

historically: $\begin{cases} \text{research center KA} \\ \text{university KA} \end{cases}$

now: KIT $=$ campus north $+$ campus south

astro-particle physics

AUGER Blümer $+ \dots$

AMS de Boer

(Kascade-Grande, Lopes, Edelweiss)

$\Rightarrow$ talks by Gattone and Engel, ...

experimental particle physics and astro-particle physics

- 7 professors
- 10 leading scientists
- 30 scientists
- 60 PhD students

(+ administration + technicians)

experimental particle physics

CDF at FNAL

Thomas Müller

KATRIN at Karlsruhe

Guido Drexlin

BELLE, BELLE II at KEK (Japan)

Michael Feindt,...

CMS at CERN

Thomas Müller, Günther Quast, Ulrich Husemann

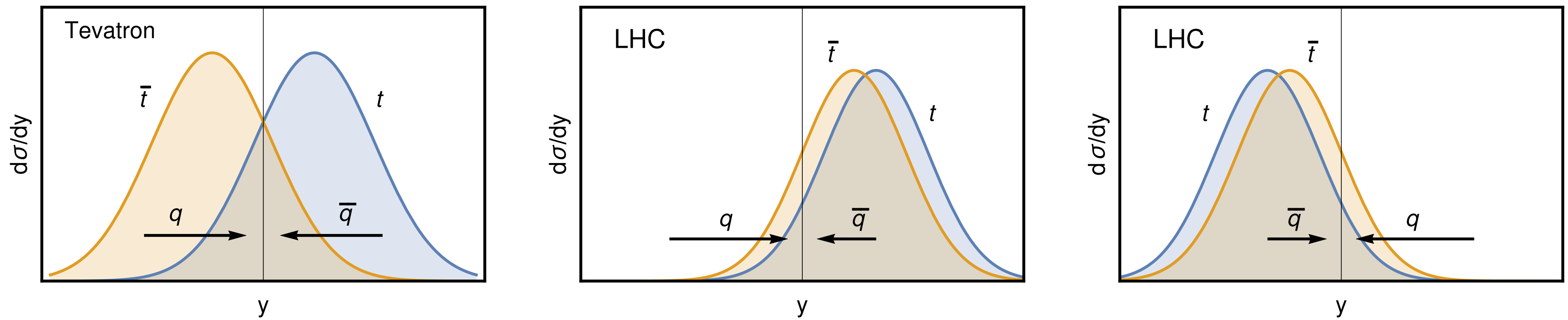
CDF at FNAL

Example:

properties of top quark

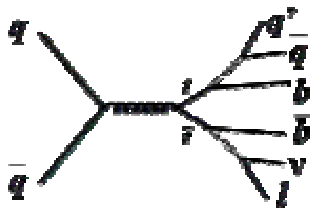
e.g. top quark asymmetry

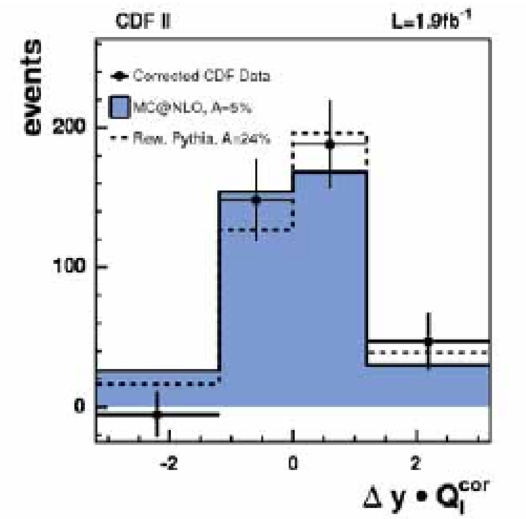
(predicted 1999 by JK + Rodrigo)

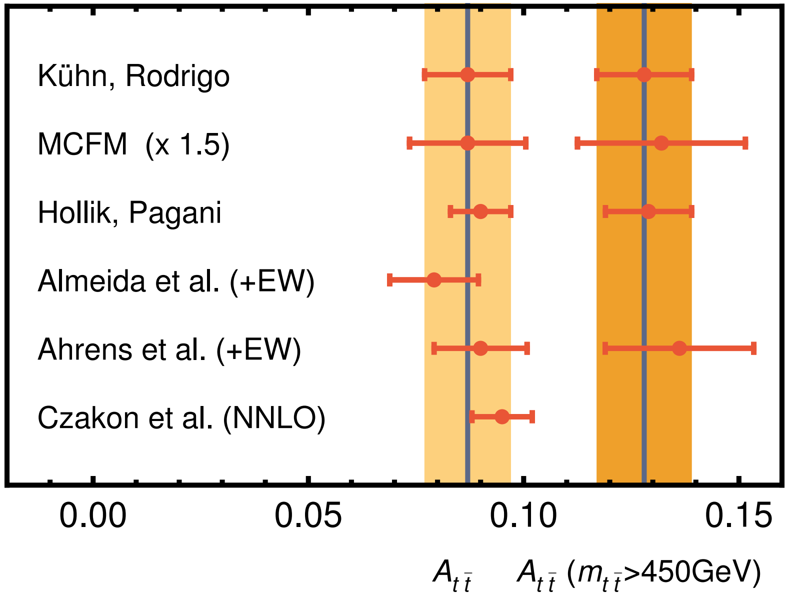


Not to scale partonic rapidity distributions of top and antitop quarks at the Tevatron (left) and the LHC (centre, right).

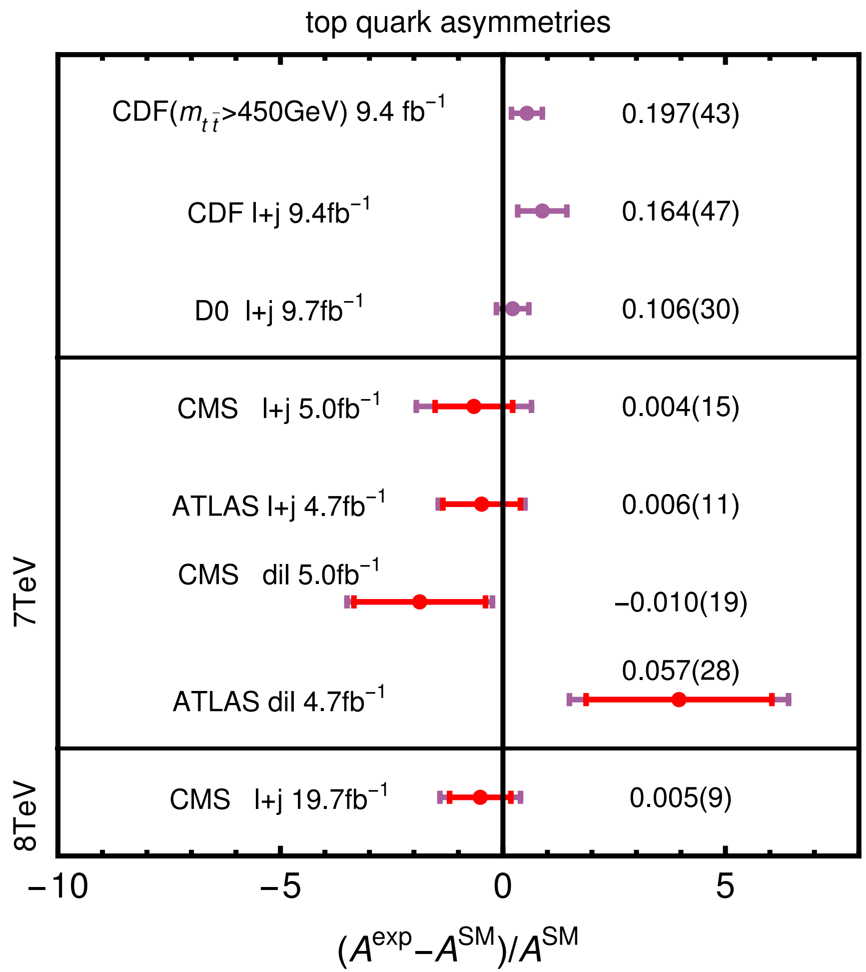
charge asymmetry







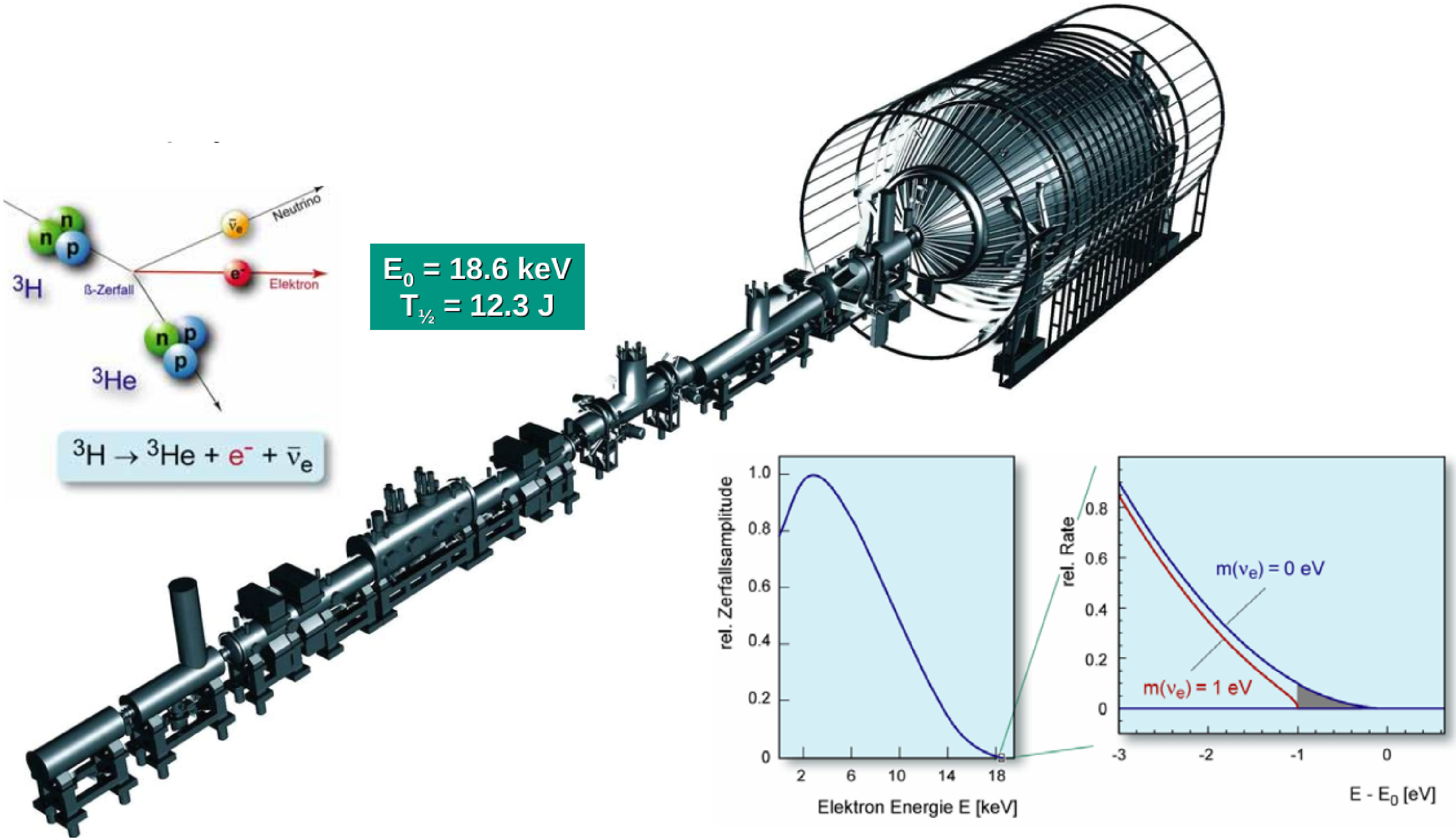
theoretical predictions at the Tevatron in the $t\bar{t}$ rest-frame



experimental measurements in comparison with theoretical predictions

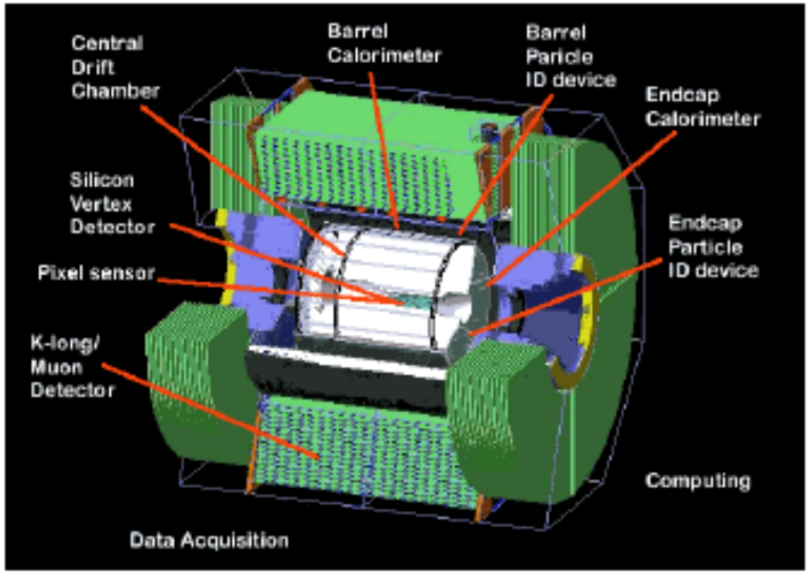
KATRIN

$E_0 = 18.6$ keV
$T_{½} = 12.3$ J



- Electron-positron collisions at the Y-4s resonance
- KIT joins in April 2008
- Int. luminosity 2009: 1000 fb^{-1}
- KIT employees: 15
- Plan: Belle data analysis till 2016
- Construction of SuperKEKB till 2016
- Data taking till 2020: 50 ab^{-1}

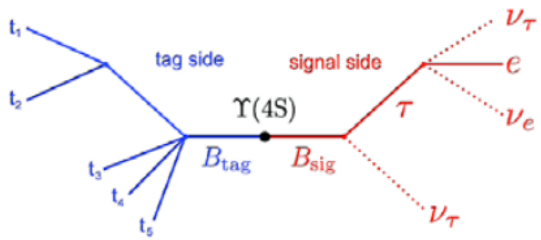
- New reconstruction of Belle data
- Search for exotic hadrons
- Precision measurements of B-decays
- Developments for the pixel tracker
- Computing and software development
- Tracking



Examples for Karlsruhe analyses

B-meson oscillation and CP-violation

- measurement of direct and indirect CP-violation in $B^0 \to D^{(*)}D^{(*)}$ and $B^0 \to \phi K^*$
- planning of the search for new physics via
- precision measurements of CP-violation in the B^0-system (since 2014)



Spectroscopy

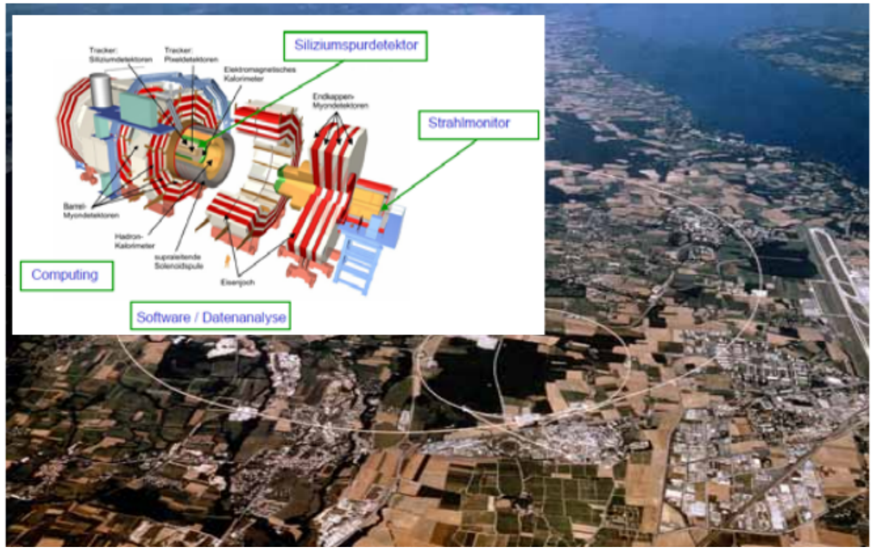
- search for the Y(4140)
- discovery of new particles

Rare decays and the CKM-matrix

- measurement of the branching ratio and the kinematics of $B \to D^{(*)}\tau\nu$
- search for $B \to K\nu\nu$
- search for very rare decays ...

CMS

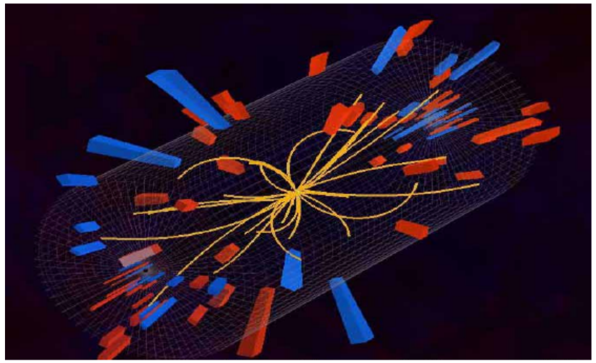
Main Karlsruhe Collider Experiment (~ 70 members)



- QCD
- forward physics
- top quark physics
- search for the Higgs boson
- search for BSM physics

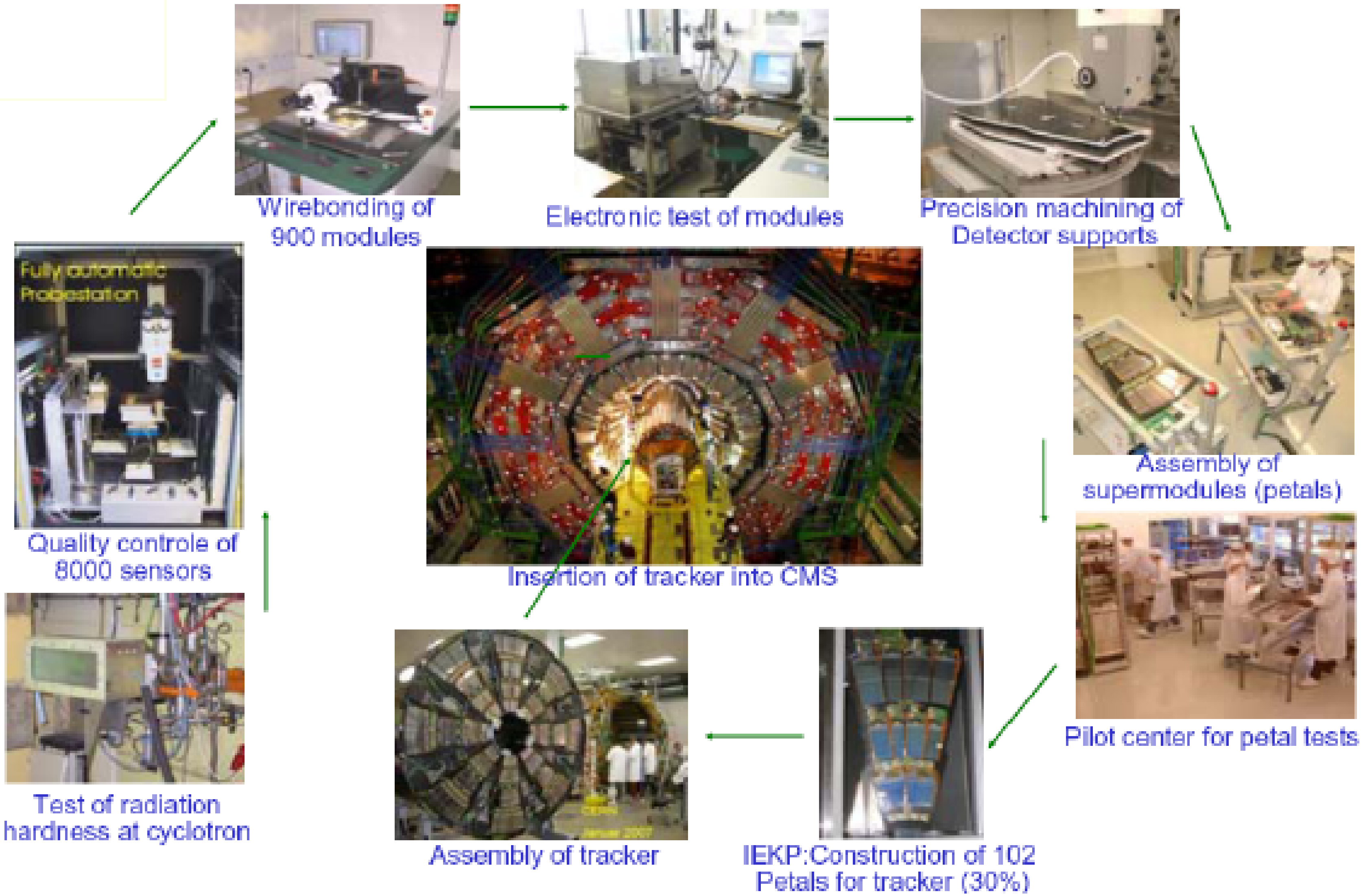
LHC program:
proton-antiproton collisions at 7, 8, 13 TeV
luminosity up to $10^{34}/\mathrm{cm}^2$

2016: Upgrade phase I (pixel detector)
2021: Upgrade phase II for SLHC (tracking)



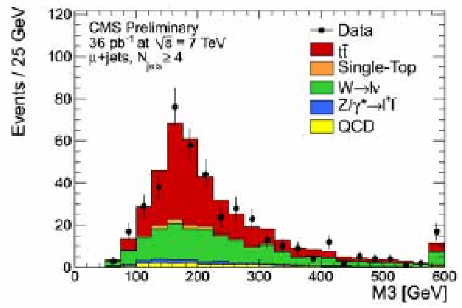
7 TeV collision

Construction of the silicon detector at KIT



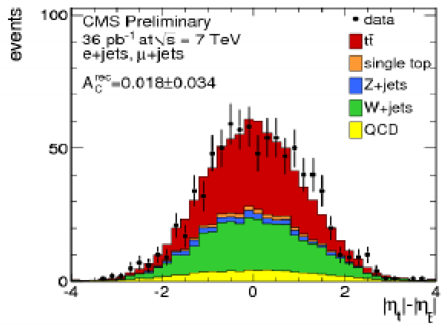
Important examples for analyses at KIT

$t\bar{t}$ cross section



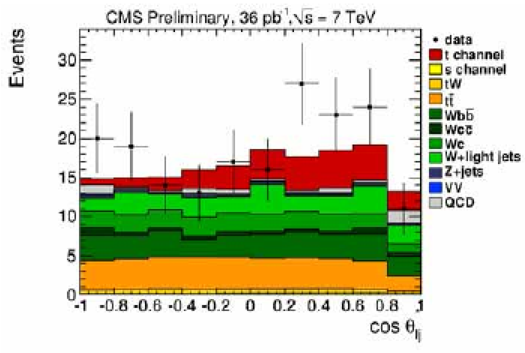
$$\sigma_{t\bar{t}} = 173^{+39}_{-32}(\text{stat+syst}) \pm 7(\text{lumi})\ \text{pb}$$

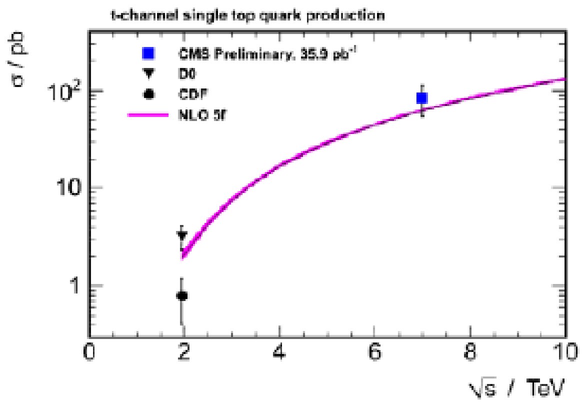
top quark asymmetry



$$A_C = 0.060 \pm 0.134(\text{stat}) \pm 0.026(\text{syst})$$

single top





II. Research in Theoretical Particle Physics

institute for theoretical physics
institute for theoretical particle physics

- 6(+2) professors: Melnikov, Zeppenfeld, Klinkhamer, Nierste, Steinhauser, Mühlleitner, (Kühn, Schwetz-Mangold)

- 3 leading scientists (permanent positions): Blanke, Chetyrkin, Gieseke

- 14 scientists (temporary positions)

- 20 PhD students

Four important external support lines
(about 30% theory, 70% experiment)

Karlsruhe School of Elementary Particle and Astroparticle Physics:
Science and Technology (KSETA)
(elementary particle physics, astroparticle physics, advanced technologies; about 100-120 PhD students; XX paid PhD positions)

Karlsruhe Research Training Group (Graduiertenkolleg):
"Particle Physics at highest energy and precision"
(theoretical and experimental particle physics, about 10-15 paid PhD positions)

additional PhD funding: state of Baden-Württemberg
(Landesgraduiertenförderung)
($\sim$ 15 PhD positions)

Sonderforschungsbereich/Transregio
“Computational Particle Physics” 2002-2004
(jointly with Aachen, Berlin, Zeuthen: 10 positions for Karlsruhe;
new project in preparation)

numerous smaller projects

Theoretical Particle Physics

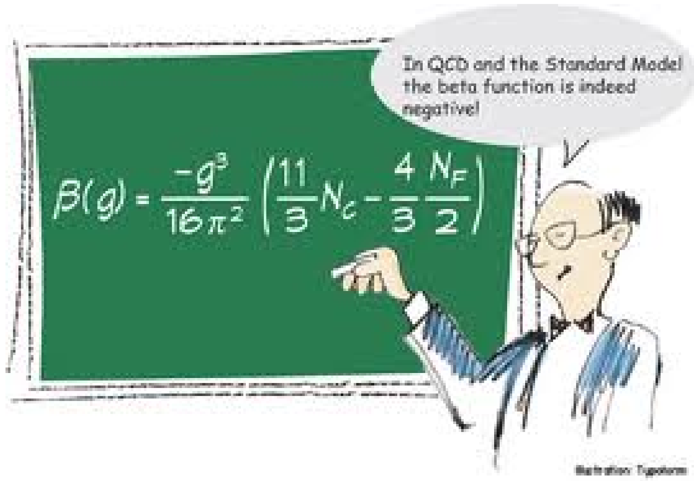
The research topics that we pursue are mostly of a broad phenomenological nature and have many connections to the experimental particle physics program.

The role of theoretical research in high-energy physics is, in general,

1. to ask the right questions;
2. to motivate experimental work;
3. to search for connections between different phenomena;
4. to provide the theoretical support for realizing physics goals of experiments;
5. to develop theoretical tools that are needed to address future challenges of the field.

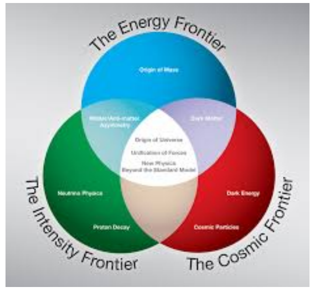
Most of these things we do in Karlsruhe.

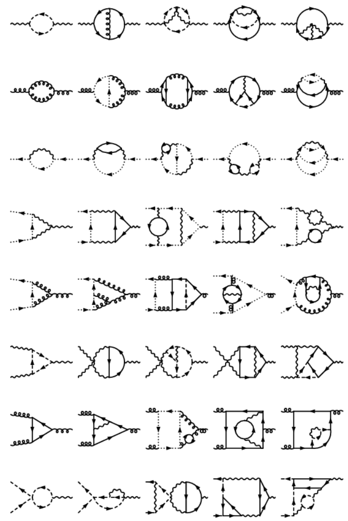
Particle Physics at KIT is a place where different expertise is available. This naturally leads to complementary approaches to solving physics problems and offers students an opportunity to deal with physics problems in their entirety, without being subject to narrow specialization boundaries.

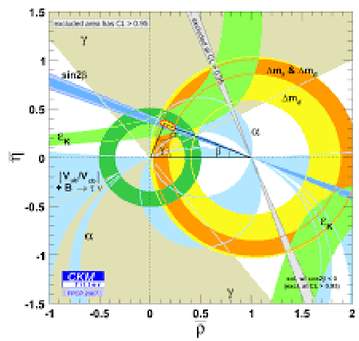


Theory research pursued at KIT

1. Physics at the LHC (hadron collider physics)
   Blanke, Gieseke, Kühn, Mühlleitner, Melnikov, Nierste, Steinhauser, Zeppenfeld
2. Higgs boson physics
   Mühlleitner, Melnikov, Nierste, Steinhauser, Zeppenfeld
3. Perturbative QCD
   Gieseke, Kühn, Melnikov, Steinhauser, Zeppenfeld
4. Flavor physics and CP violation
   Blanke, Nierste, Steinhauser
5. Physics beyond the Standard Model (SUSY phenomenology)
   Blanke, Mühlleitner, Nierste, Steinhauser, Zeppenfeld
6. Theoretical methods for perturbative QFTs
   Kühn, Melnikov, Steinhauser, Zeppenfeld
7. Computational particle physics
   Gieseke, Kühn, Melnikov, Steinhauser, Zeppenfeld
8. Multiloop calculations and precision physics
   Chetyrkin, Kühn, Steinhauser
9. Structure of space-time
   Klinkhamer







Theory research pursued at KIT

Topic	# of Ph.D students involved in a research on a given topic (finished and ongoing thesis)
Physics at the LHC	8
Higgs	7
pQCD	6
Flavor/CP	4
BSM	6
Theoretical methods in pQFT	4
Computational particle physics	3
Multiloop Calculations	2
Structure of space-time	2

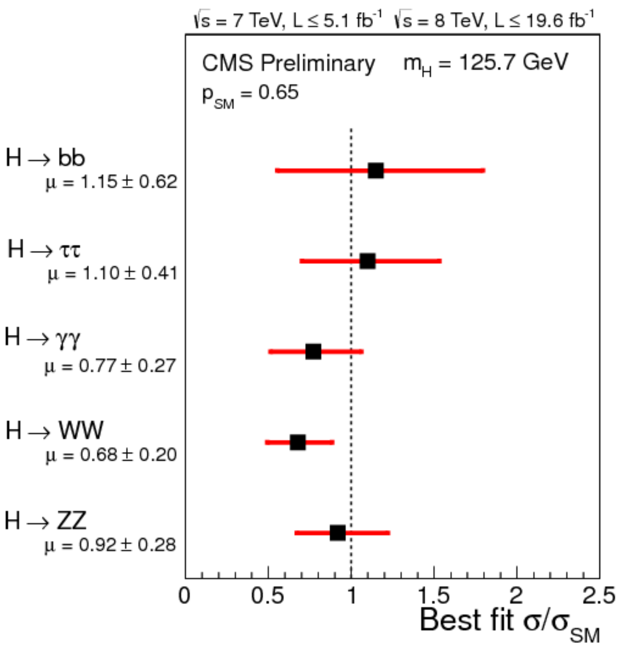
Disclaimer: some theses fit into more than one topic; they are then counted several times in the right column. The total number of students surveyed here is 22.

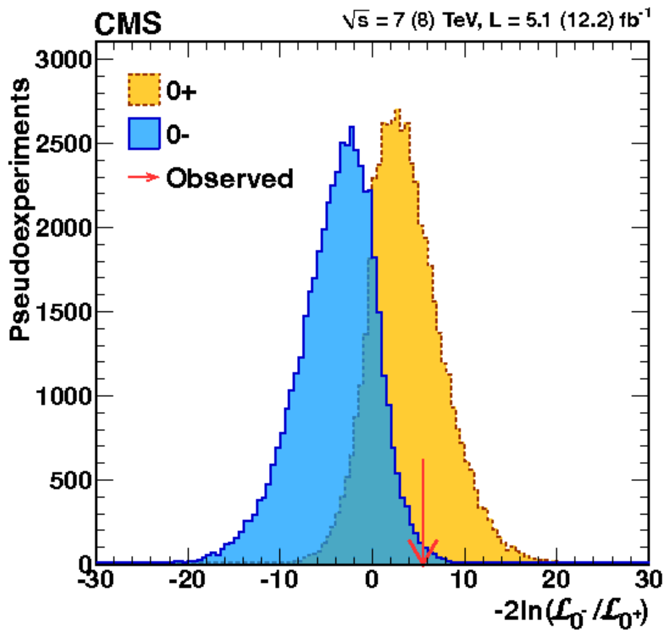
Physics of the Higgs boson

The past two and half years in particle physics were strongly influenced by the discovery of the Higgs boson, the most important particle of the Standard Model.

Experimental studies of this particle, guided by theoretical considerations, and assisted by the development of proper theoretical tools, led to an understanding that the discovered particle is very similar to the Higgs boson of the Standard Model.

The goal for the near future is to develop strategies to look for small deviations between measured and predicted SM couplings, put even tighter constraints on possible exotic quantum numbers of the Higgs boson, search for additional decay channels of the Higgs particle and look for additional (heavier?) Higgs bosons.





Physics of the Higgs boson

Researchers at KIT are well-positioned to play an important role in this endeavor since our research on Higgs boson focuses on all aspects of Higgs boson physics including

1. development of a proper framework for discussing non-SM contributions to Higgs physics – effective field theories for the Higgs sector (Mühlleitner et al.) ;

2. determination of the Higgs boson quantum numbers (Mühlleitner et al.)

3. predictions of the Higgs boson signals at the LHC to the highest possible precision (Steinhauser, Melnikov etc.) ;

4. improved theoretical predictions for backgrounds to the Higgs boson signals at the LHC (Zeppenfeld, Melnikov) ;

5. Higgs pair production at the LHC and the measurement of triple-Higgs coupling (Mühlleitner, Steinhauser, Melnikov) ;

6. Implications of the Higgs discovery for the big picture such as vacuum stability and precision EW fits (Nierste, Zoller) .

Higgs pair production

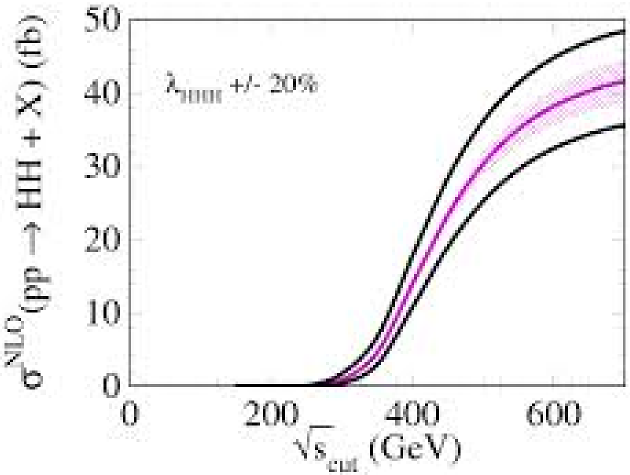
Production of Higgs pairs at the LHC is an important process which can be used to determine the triple Higgs boson coupling. However, it is difficult to do that experimentally (large backgrounds) and theoretically (difficult to predict the rate with high enough precision).

Studies of Higgs pair production performed within the Research Training Group encompass many different aspects of this process:

1. Higgs pair production in extensions of the SM (Nierste, Baglio, Eberhardt, Wiebusch)

2. Critical appraisal of the Higgs self-coupling measurement (Mühlleitner, Baglio, Gröber)

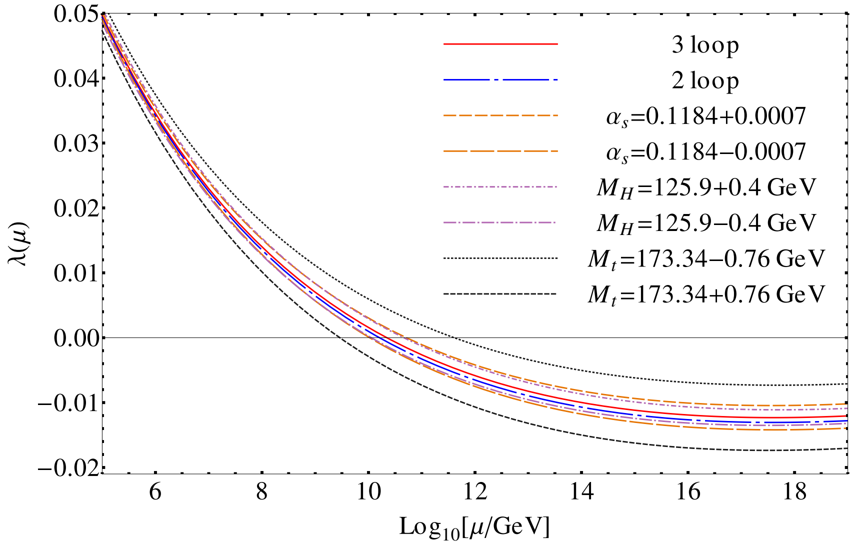
3. Top quark mass suppressed effects in HH production at higher orders in QCD (Steinhauser, Hoff, Grigo etc.)

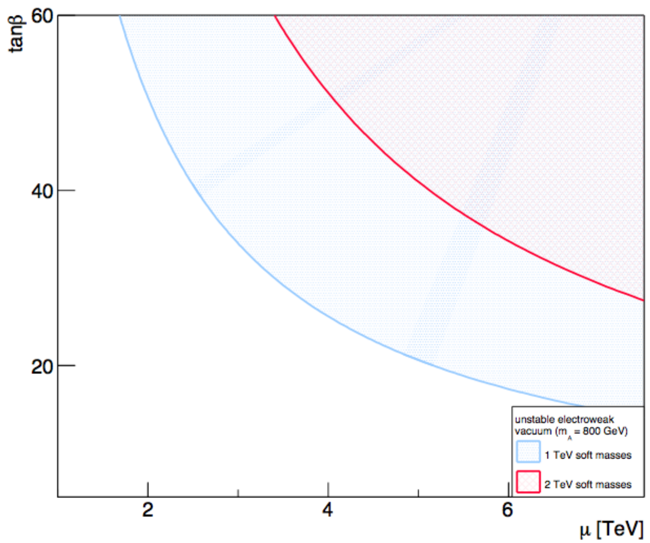


The vacuum stability of the Standard Model

The discovery of the Higgs boson and the measurement of its mass completely fixes all the parameters of the Standard Model and allows us to determine the Higgs potential V(h). Since the Higgs potential may have a different profile when higher-order radiative corrections are considered, it is interesting to ask if our electroweak vacuum is a true vacuum?

Calculation of V(h) requires extrapolation to large values of the Higgs field; this can be done using renormalization group evolution equations for Higgs-top Yukawa couplings and the Higgs quartic coupling.





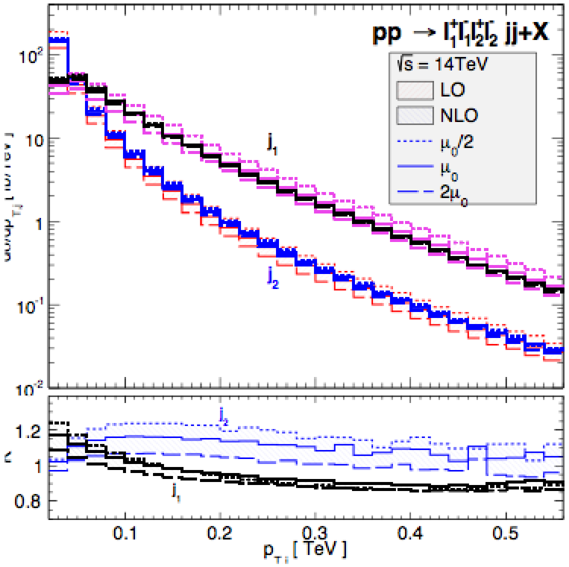
Three-loop computation of the ttH and H^4 beta-functions by M. Zoller and K. Chetyrkin is the state-of-the-art contribution to this discussion.

Can stability of EW vacuum provide constraints on extensions of the Standard Model? The MSSM example was studied by Nierste, Bobrowski, Hollik etc.

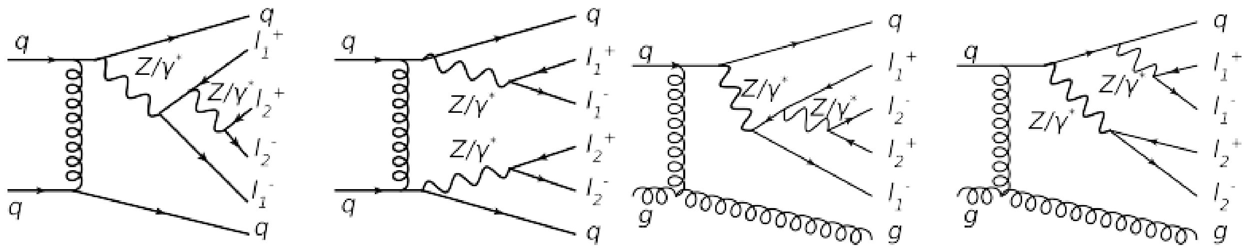
Vector boson production

Production of pairs of vector bosons at colliders is a very important process as a signal (SM benchmark, triple gauge-boson coupling) and as a background for Higgs studies and SUSY searches. There are many studies of various aspects of this process world-wide, including some influential studies by researchers of the Training Group.

1) Development of VBFNLO program (Zeppenfeld et al.) provides an important tool for both experimental and theoretical communities to study many of the processes with pairs of vector bosons at next-to-leading order in QCD.

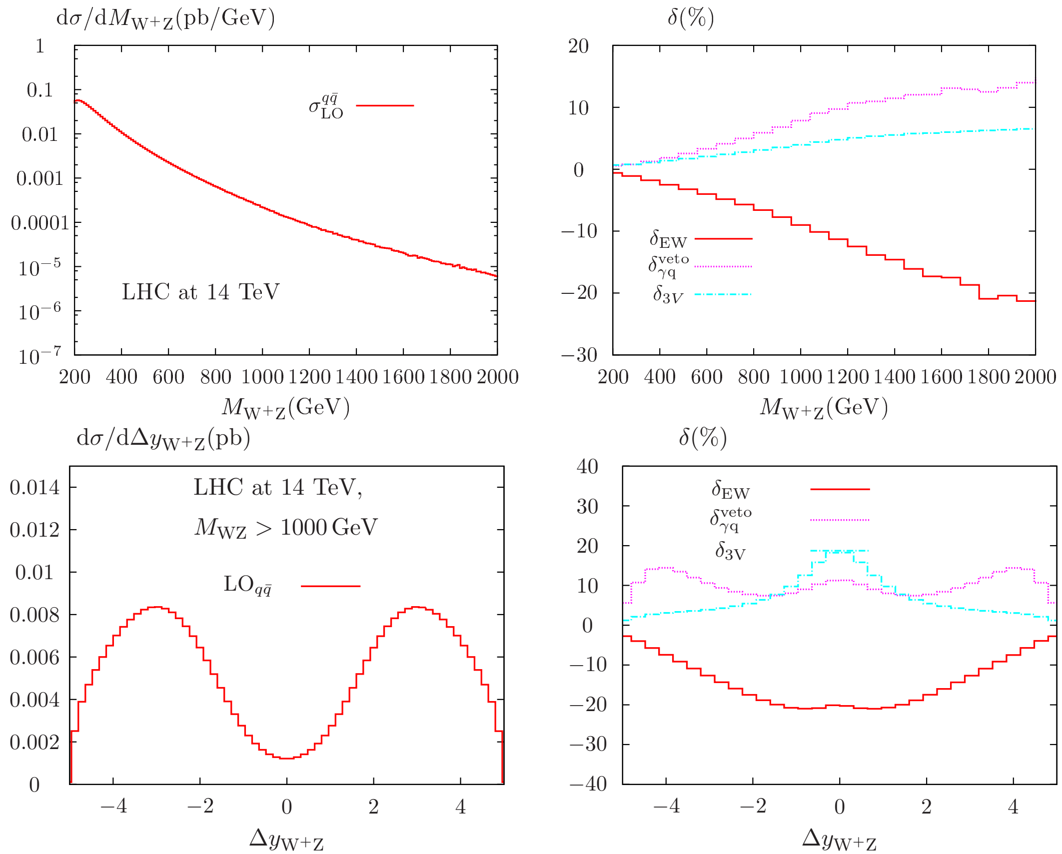


VBFNLO includes leptonic decays of the vector bosons, anomalous couplings for some processes, explicit BSM contributions (two Higgs doublet, warped extra-dimensions) for some of the key processes.



ZZ-production in association with 2 jets

2) Further studies of this process at the Research Training Group included complete calculation of electroweak radiative corrections (Kühn, Bierweiler; Baglio, Ninh, Weber et. al) and inclusion of these corrections to the parton shower event generator HERWIG (Kühn, Gieseke).

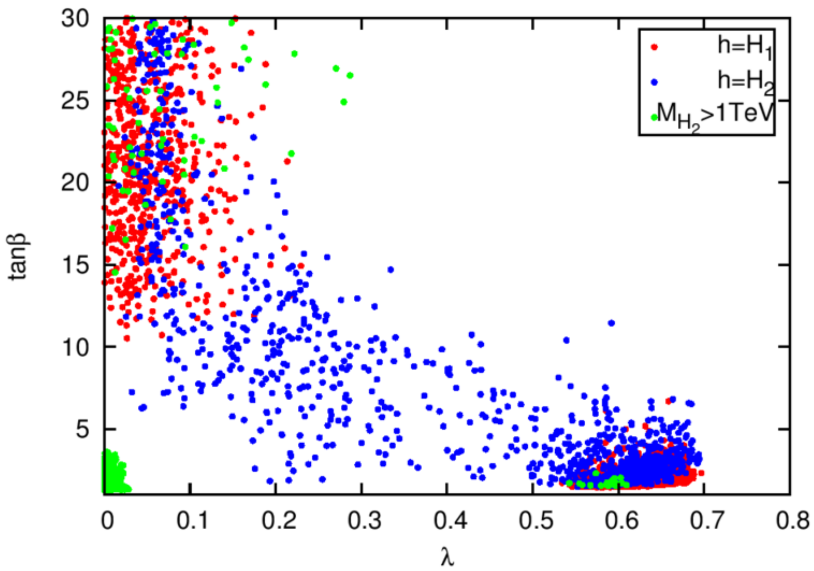


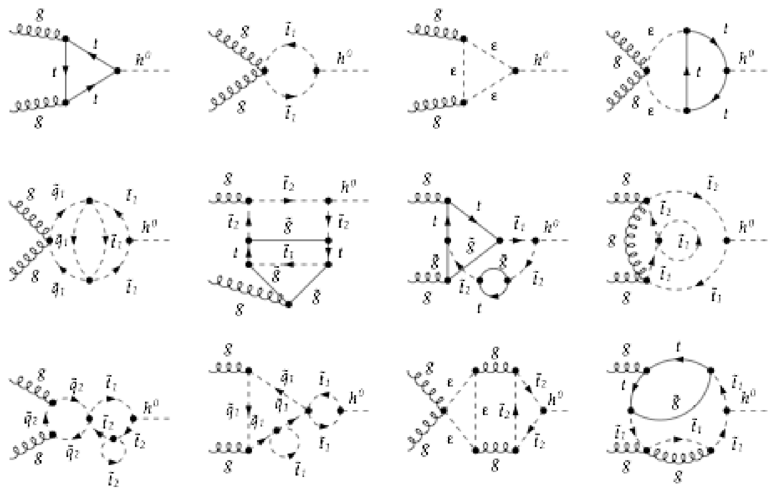
Left: Differential LO cross sections for W^+Z production at LHC14. Right: various EW corrections relative to the quark-induced LO process. Top: invariant-mass distribution; Bottom: WZ rapidity-gap distribution for $M_{WZ} > 1$ TeV.

Supersymmetric effects at the LHC

Supersymmetry remains to be one of the most popular extensions of the Standard model . There is significant amount of research done at the Research Training Group that aims at finding smoking gun signals for SUSY discovery at the LHC, at improving theoretical description of supersymmetric signals and at studying supersymmetric contributions to observables that can be precisely studied.

1. Discovery prospects for NMSSM Higgs bosons at 13TeV LHC (Mühlleitner, Walz)
2. SUSY effects in Higgs couplings to gluons at higher orders in QCD (Steinhauser, Zerf)
3. Squark production at NLO QCD with quark decays and parton showers (Mühlleitner, Popenda)

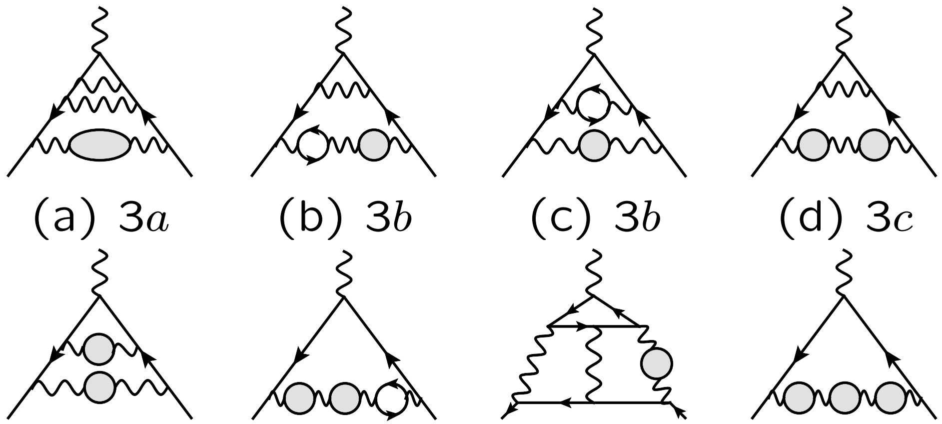




QFT methodology and computational particle physics

For many physics goals progress in methodology is important. Such research (especially in multi-loop methodology) is traditionally strong in Karlsruhe but in recent years new interesting directions appeared.

1) Technological developments in multi-loop computations (reduction algorithms, master integrals, differential equations, numerical methods) (Steinhauser, Melnikov)
2) Effective field theories for non-relativistic bound states in QED and QCD (Steinhauser)



(a) $3a$ (b) $3b$ (c) $3b$ (d) $3c$
(e) $3c$ (f) $3c$ (g) $3b$,lbl (h) $3d$

Sample NNLO Feynman diagrams contributing to a_μ^{had}.

QFT methodology and computational particle physics

3) NLO QCD computations and their optimization (Zeppenfeld)

4) NNLO QCD subtraction terms for computations of multi-particle processes at colliders (Melnikov)

5) Theoretical and practical improvements of parton shower event generators (Gieseke)

QFT methodology and computational particle physics

6) Calculations of $\Gamma(H \to \text{hadrons})$ and $\Gamma(Z \to \text{hadrons})$ in order α_s^4

(Baikov, Chetyrkin, Kühn,...)

$$\Gamma(H \to f\bar{f}) = \frac{G_F M_H}{4\sqrt{2}\pi} m_f^2(\mu) R^s(s = M_H^2, \mu)$$

$$R^s(s) = \mathbf{Im}\Pi^{ss}(-s - i\varepsilon)/(2\pi s)$$

$$R^s(s, \mu^2 = s) = 1 + \ldots a_s + \ldots a_s^2 + \ldots a_s^3 + [39.34 - 220.9 n_f + 9.685 n_f^2 - 0.0205 n_f^3] a_s^4$$

$$\Gamma(Z \to f\bar{f}) = \ldots\ a_s^4$$

Flavour physics

studies transitions between fermions of different generations.

$$\begin{pmatrix} u_L, u_L, u_L \\ d_L, d_L, d_L \end{pmatrix} \quad \begin{pmatrix} c_L, c_L, c_L \\ s_L, s_L, s_L \end{pmatrix} \quad \begin{pmatrix} t_L, t_L, t_L \\ b_L, b_L, b_L \end{pmatrix}$$

$$\begin{matrix} u_R, u_R, u_R & \quad & c_R, c_R, c_R & \quad & t_R, t_R, t_R \\ d_R, d_R, d_R & & s_R, s_R, s_R & & b_R, b_R, b_R \end{matrix}$$

$$\begin{pmatrix} \nu_{e,L} \\ e_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\mu,L} \\ \mu_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\tau,L} \\ \tau_L \end{pmatrix}$$

$$e_R \qquad \mu_R \qquad \tau_R$$

Flavour transitions in the Standard Model

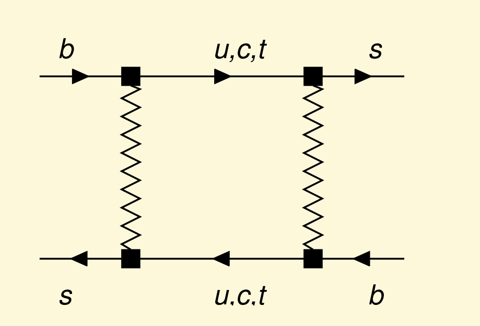
Flavour-changing transitions only occur in W couplings. Example: W coupling to b and u:

$$L_W = \frac{g_2}{\sqrt{2}} \left[V_{ub} \overline{u}_L \gamma^\mu \, b_L \, W_\mu^+ \; + \; V_{ub}^* \overline{b}_L \gamma^\mu \, u_L \, W_\mu^- \right]$$

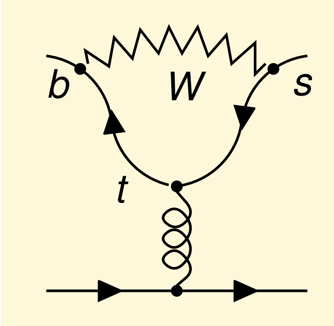
The flavour-changing couplings involve the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix V. A physical complex phase in V permits CP violation, meaning that the weak interaction treats particles differently from antiparticles.

Flavour-changing neutral current (FCNC) processes

Examples:



$B_s - \overline{B}_s$ mixing



penguin diagram

FCNC processes are highly sensitive to physics beyond the SM.Exploiting the unitarity of V one can determine all CKM elements from tree-level processes.

$\Rightarrow$ View FCNC processes as new physics analysers rather than ways to measure V_{jk}.

Theoretical research at KIT (Nierste, Blanke,...)

The precision reached at LHCb and expected from the future experiment Belle II calls for:

i) calculation of QCD radiative corrections,

ii) better control over hadronic uncertainties,
$\longrightarrow$ define new observables, eliminate hadronic uncertainties through judicious combinations of measurements

iii) calculation of FCNC processes in dedicated models of new physics such as the Minimal Supersymmetric Standard Model.

Conclusions

The KIT offers an exciting opportunity to get engaged in cutting-edge research in theoretical particle physics.

The particle physics research program is diverse (physics at hadron colliders, Higgs physics, flavor physics and CP violation, perturbative QCD, parton shower event generators, supersymmetric extensions of the SM, perturbative and non-perturbative QFT) and offers many excellent opportunities for existing and prospective graduate students.

The research program is of high relevance: its focus points are

1) phenomenological and theoretical aspects of physics at the LHC (which restarts into an exciting phase II with higher energy and with higher luminosity in a few months); and Belle II (which will explore flavor physics at an unprecedented level of precision);

2) innovative methodological research in both perturbative and non-perturbative quantum field theory.

Focus on these topics guarantees many opportunities to perform exciting and relevant research in the future.