Theory: Quantum Field Theory and Collider Phenomenology

Johannes Blümlein,
DESY

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The Research Topics

Quantum Field Theory and Collider Phenomenology:

- Standard Model:
  - Multileg-processes & Monte Carlo for HE colliders
  - Massless and massive 3-loop calculations
  - High precision pdf extraction from world data and $\alpha_s(M_Z)$
  - non-forward scattering and multi parton scattering
  - LHC phenomenology: standard candles, top & Higgs
  - Mathematical methods for loop calculations and computer algebra
- Beyond the Standard Model:
  - Calculation of HE processes in extensions of the Standard Model
  - Systematic search for BSM signatures at LHC
  - Automated testing of the various new extensions of the Standard Model using all available world data
  - MC simulation of BSM processes at the LHC
- Mutual collaboration with experimental groups
  at DESY, CERN and with Universities on various topics.

Staff, Fellows, Students

- Hamburg:
  Collider Phenomenology: M. Diehl, J. Reuter, G. Weiglein, A. Weiler
  Cosmology: W. Buchmüller, T. Konstandin, O. Lebedev, A. Ringwald, A. Westphal
  String Theory: I. Kirsch, V. Schomerus, J. Teschner
- Zeuthen:
  QFT & Collider Phenomenology: J. Blümlein, S. Moch, T. Riemann
  NIC: K. Jansen, H. Simma, R. Sommer
- Phenomenology Annex:
  DESY-H: Fellows: 7, PhD Students: 6
  DESY-Z: Fellows: 5, PhD Students: 4
- Funds: DESY + DFG (SFB's, GK, including guest programmes), European Union (EC-TMR), LEXI, Alexander-von-Humboldt Foundation, Studienstiftung des Deutschen Volkes, Helmholtz-Alliance

Mission

- Coordinative tasks:
  - Participation in the Analysis Center of the Helmholtz Alliance physics at the Terascale
  - Organization of international conferences and workshops: QFT, LHC physics, BSM phenomenology
  - Guest scientist programme $\longrightarrow$ promotion of new national and international collaborations
  - National and international collaboration with experimental and theoretical groups in collider physics
  - Networking with a large number of universities and other research centers
- Special aspects:
  - Center for large scale computations: Computer algebra calculations on special computers (up to 192 Gb RAM) $\sim$ 1 Tb RAM, 20 Tb fast disk in total; FORM, mathematica, maple
  - On-site theoretical expertise for detailed support the HERA & LHC and ν-physics groups

The Standard Model @ High Precision: $\alpha_s(M_Z^2)$

$\alpha_s(M_Z^2)$ from NNLO DIS(+) analyses

	$\alpha_s(M_Z^2)$	
BBG	$0.1134\ ^{+0.0019}_{-0.0021}$	valence analysis, NNLO
GRS	0.112	valence analysis, NNLO
ABKM	0.1135 ± 0.0014	HQ: FFNS $N_f = 3$
JR	0.1124 ± 0.0020	dynamical approach
JR	0.1158 ± 0.0035	standard fit
MSTW	0.1171 ± 0.0014	
ABM	0.1147 ± 0.0012	FFNS, incl. combined H1/ZEUS data
ABM11$_J$	$0.1134 - 0.1149 \pm 0.0012$	Tevatron jets (NLO) incl.
CTEQ	0.118 ± 0.005	
NNPDF	$0.1174 \pm 0.0006 \pm 0.0001$	
Gehrmann et al.	$0.1153 \pm 0.0017 \pm 0.0023$	e^+e^- thrust
Abbate et al.	$0.1135 \pm 0.0011 \pm 0.0006$	e^+e^- thrust
BBG	$0.1141\ ^{+0.0020}_{-0.0022}$	valence analysis, $\mathrm{N^3LO}$

$$\Delta_{\mathrm{TH}}\alpha_s = \alpha_s(\mathrm{N^3LO}) - \alpha_s(\mathrm{NNLO}) + \Delta_{\mathrm{HQ}} = +0.0009 \pm 0.0006_{\mathrm{HQ}}$$

$\alpha_s(M_Z^2)$

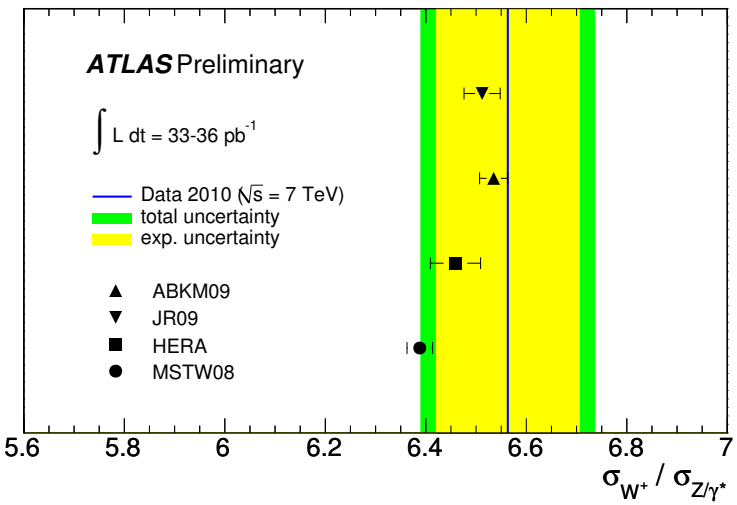
$\alpha_s(M_Z^2)$ from further processes

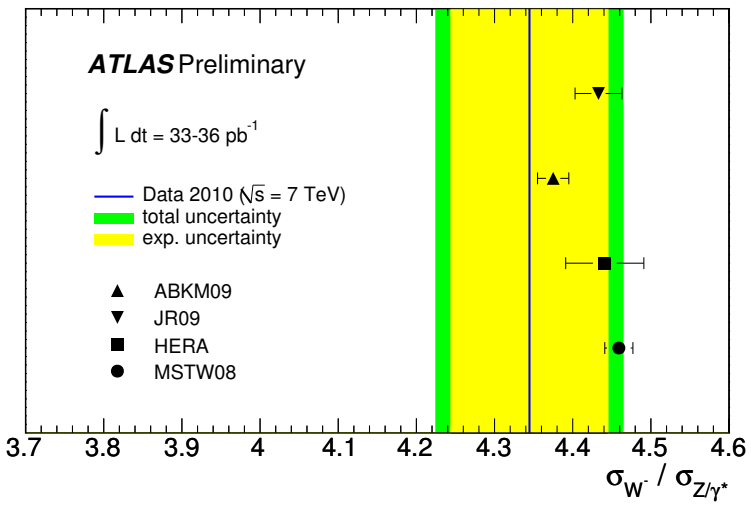
	$\alpha_s(M_Z^2)$	
3 jet rate	0.1175 ± 0.0025	Dissertori et al. 2009
Z-decay	0.1190 ± 0.0026	BCK 2008
τ decays	0.1212 ± 0.0014	Pich 2010
τ decays	0.1202 ± 0.0019	BCK 2008
τ decays	0.1180 ± 0.0008	Beneke, Jamin 2008
τ decays	0.1169 ± 0.0025	Boito et al. 2011 (FOPT)
lattice	0.1183 ± 0.0008	HPQCD 2008
Average 2011	0.1185 ± 0.0008	S. Bethke

Despite the statistical and systematic errors are getting smaller, there is no final consensus on the value of $\alpha_s(M_Z^2)$ yet.

$W^{\pm}$ and Z^0 production cross sections at the LHC (NNLO)

Recent measurements of $W^{\pm}$ and Z-production cross sections at ATLAS spring conferences

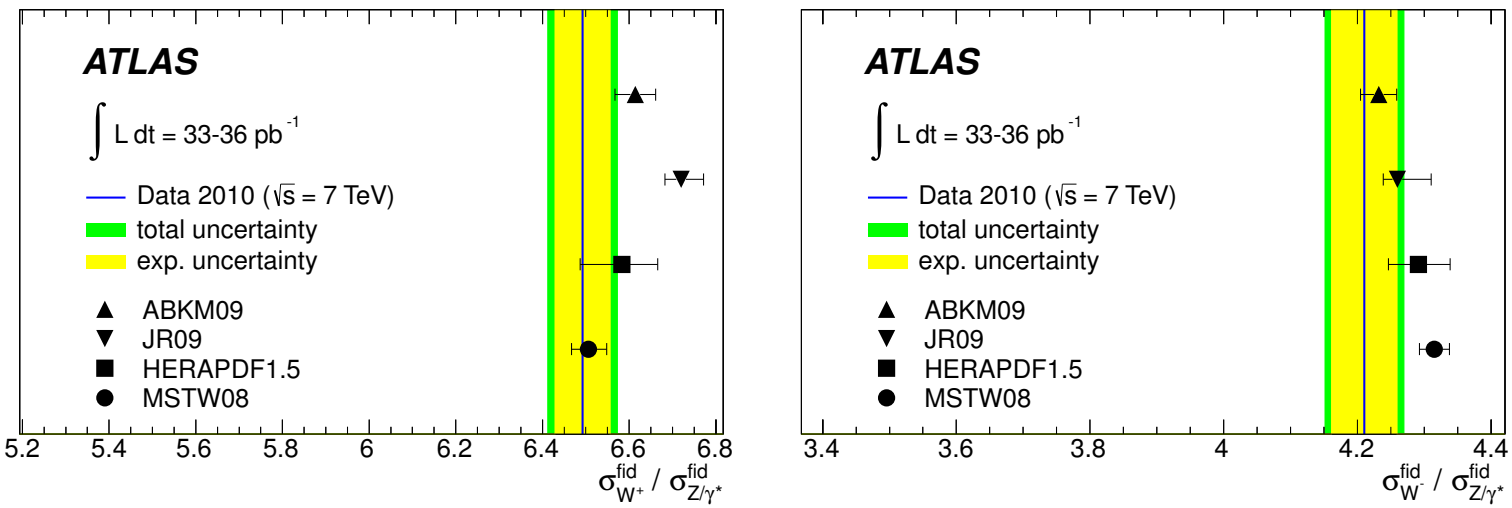




$W^{\pm}/Z$ cross section ratios will constrain parton distributions:
ATLAS, CMS, LHCb
Similarly, this is expected from off-resonance Drell-Yan data.
$\Longrightarrow$ quark, anti-quark sensitivity

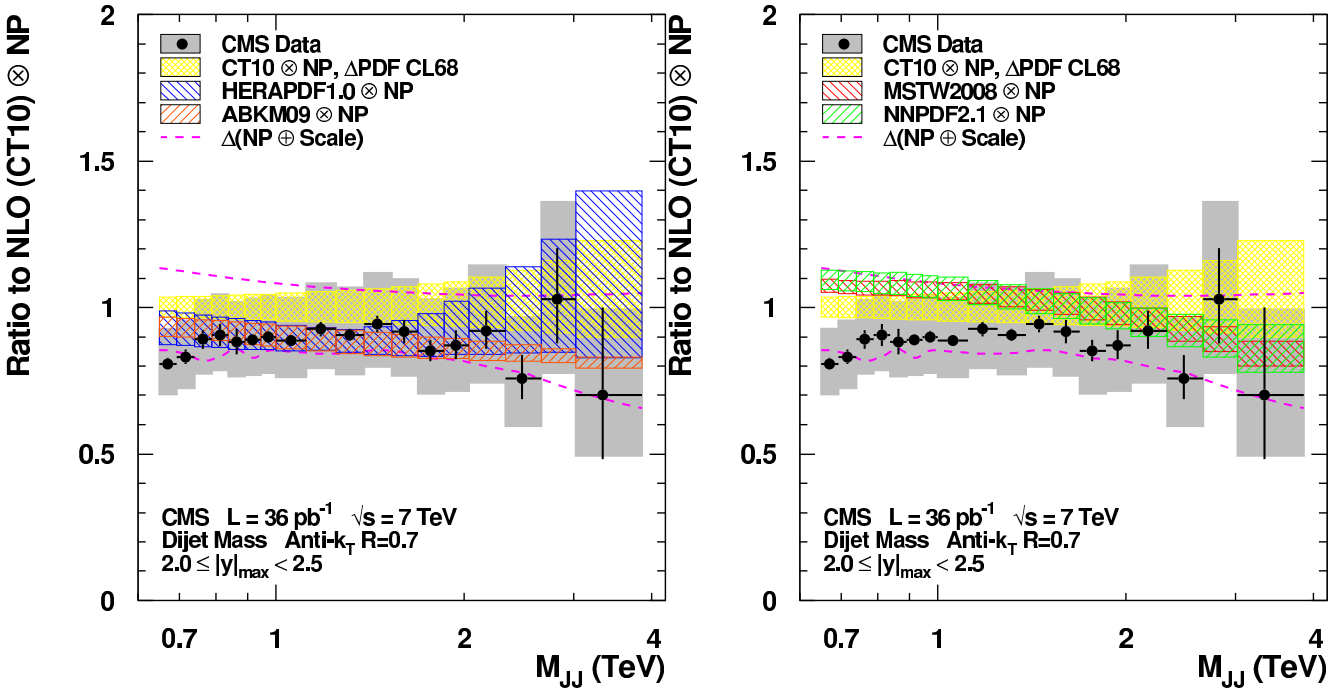
$W^{\pm}$ and Z^0 production cross sections at the LHC (NNLO)

Recent measurements of $W^{\pm}$ and Z-production cross sections at ATLAS arXiv:1109.5141: much improved systematics; use fiducial region only.



$W^{\pm}/Z$ cross section ratios will constrain parton distributions:
ATLAS, CMS, LHCb
Similarly, this is expected from off-resonance Drell-Yan data.
$\Longrightarrow$ quark, anti-quark sensitivity
$\Longrightarrow$ 5 fb^{-1} on tape will lead to brilliant differential distributions.

Jet measurement at LHC (NLO +resum.)



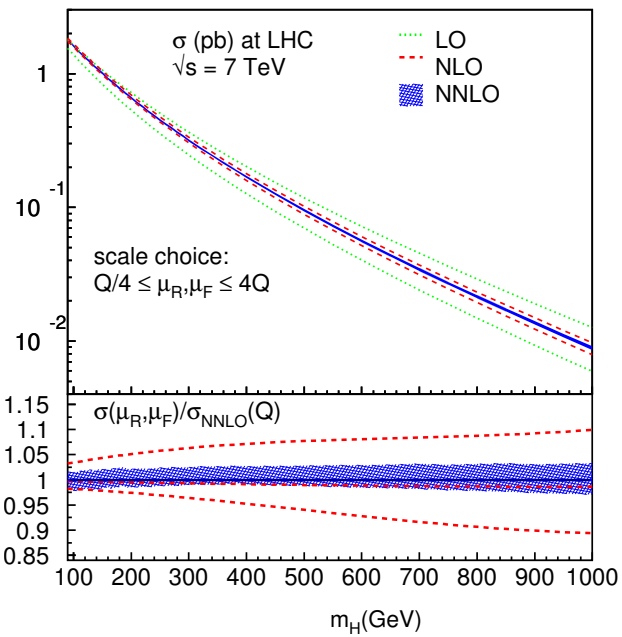
ABKM, HERAPDF → predictions ! further pdfs

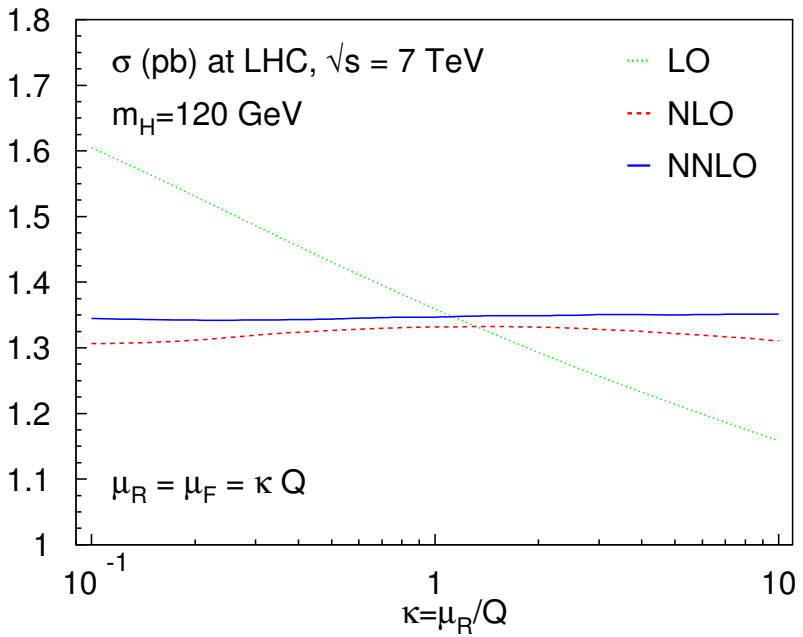
CMS di-jet data (Analysis by K. Rabbertz, CERN-CMS-NOTE-2011-004, June 11, 2011)

$\Longrightarrow$ gluon sensitivity

VBF: Higgs Cross Section

P. Bolzoni, F. Maltoni, S. Moch, M. Zaro, 1109.3717



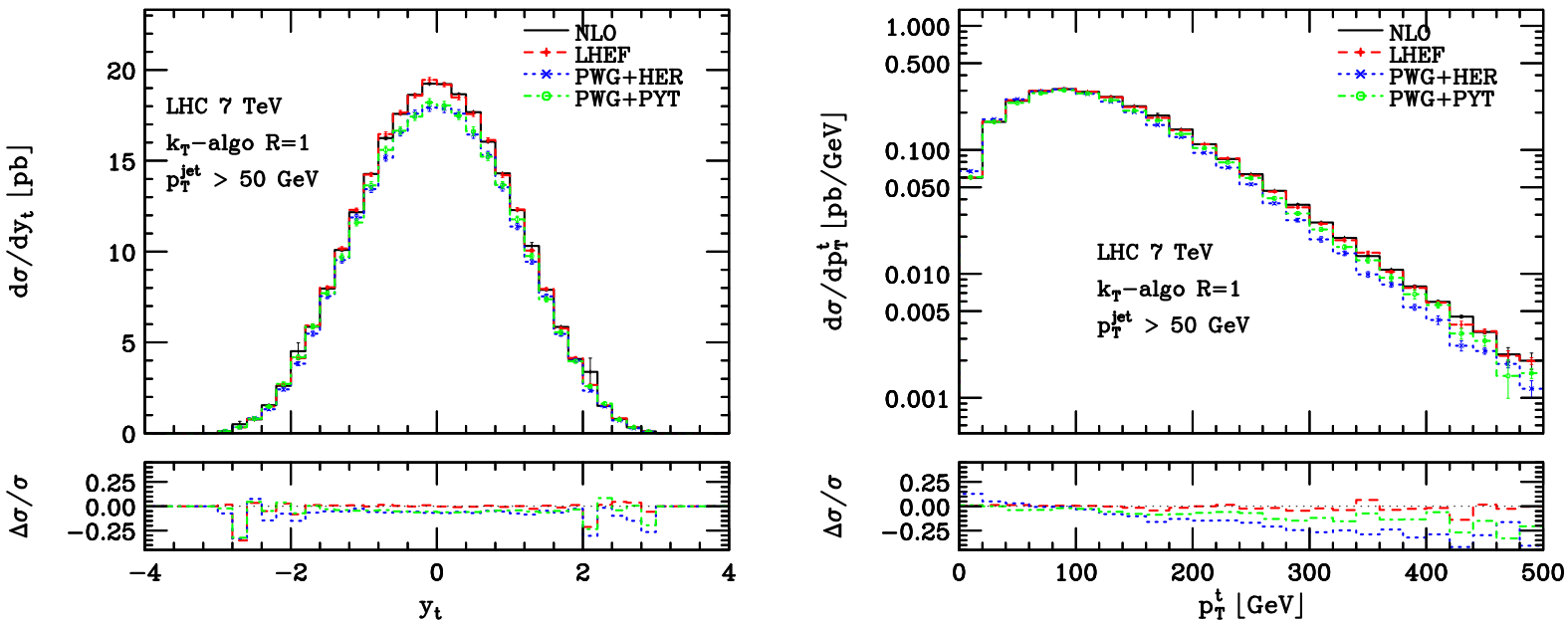


NNLO vector boson fusion contribution. $\sim$ 10 % of the cross section

Much improved scale dependence.

NLO $t\bar{t}$ + jet production including showers

S. Alioli, S. Moch, P.Uwer:

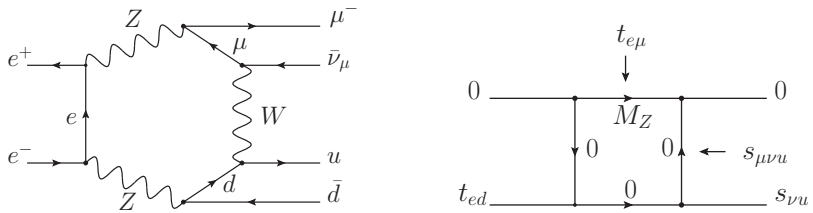


Realistic MC simulations, including FS showering. Implemented in POWHEG.

T. Riemann, J. Fleischer, V. Yundin:

NLO contributions to massive $2 \to 3, 4, \ldots$ production at LHC, ILC, and meson factories

Project:
Tensor reduction with an algebraic method using dimensional shifts



A six-point topology (a) leading to four-point functions (b) with realistically vanishing Gram determinants.

A reduction of $I^{[d+]^2}_{4,ij}$ into simpler integrals

$$\nu_{ij} I^{[d+]^2}_{4,ij} = \frac{\binom{0}{i}_4}{\binom{0}{0}_4}\frac{\binom{0}{j}_4}{\binom{0}{0}_4}(d-2)(d-1) I^{[d+]^2}_4 + \frac{\binom{0i}{0j}_4}{\binom{0}{0}_4} I^{[d+]}_4 - \frac{\binom{0}{j}_4}{\binom{0}{0}_4}\frac{d-2}{\binom{0}{0}_4}\sum_{t=1}^{4}\binom{0t}{0i}_4 I^{[d+],t}_3 + \frac{1}{\binom{0}{0}_4}\sum_{t=1}^{4}\binom{0t}{0j}_4 I^{[d+],t}_{3,i} \qquad (1)$$

Relative accuracy of tensor coefficient E_{3333} in a small Gram-4 region

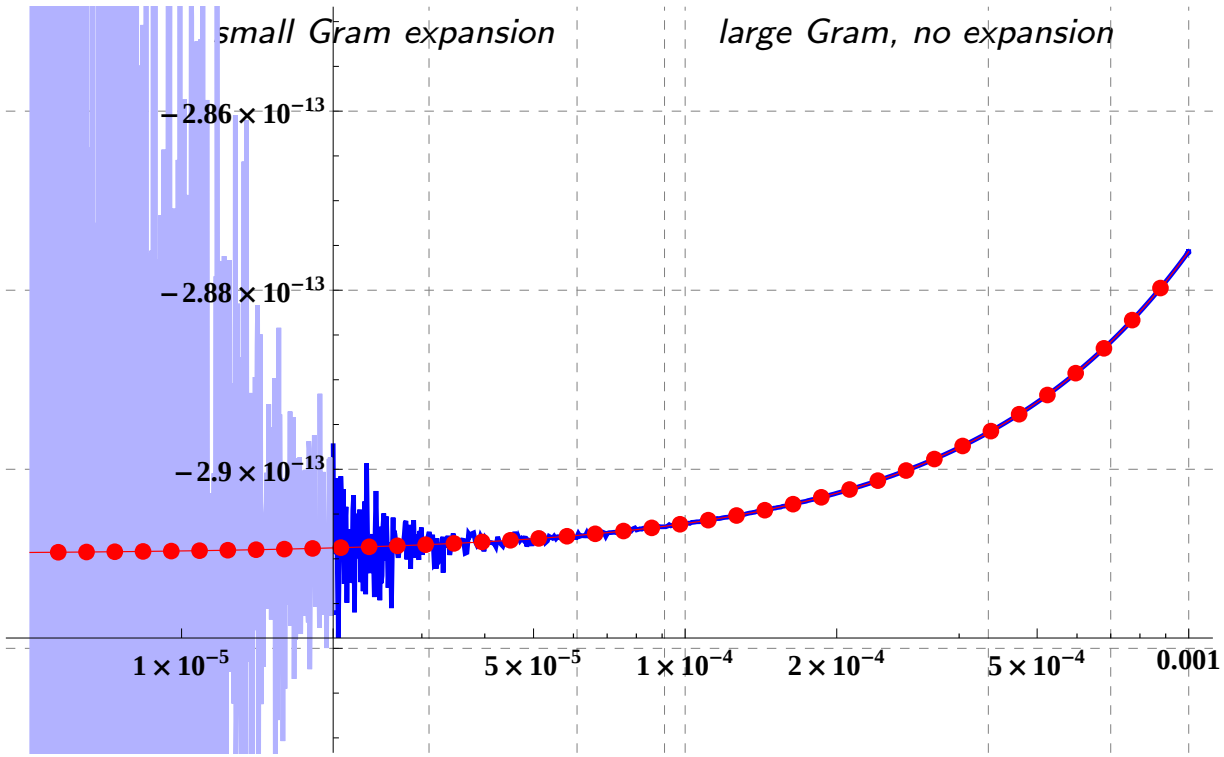
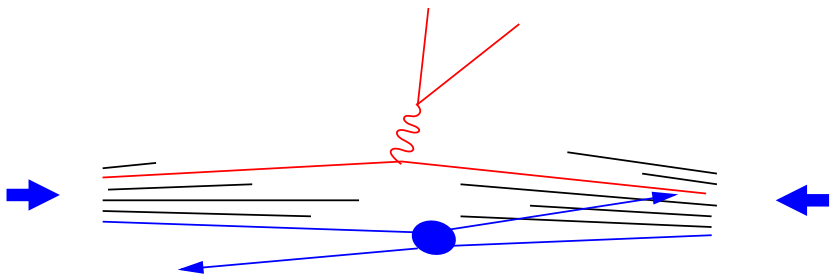


Figure: courtesy V. Yundin, 2011, made with the PJFry package

Markus Diehl: multi-parton interactions in QCD

- always take place in hadron-hadron collisions
  at high energy several interactions can be hard
- affect final-state distributions
  estimated to be relevant for many processes at LHC
- active field of research, several workshops since LHC startup

  Workshop MPI@LHC 2011 in Hamburg from 21–25 November

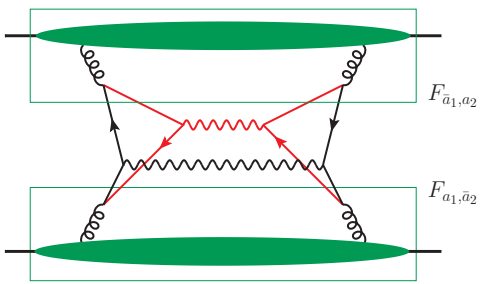


- phenomenology and implementation in MC generators
  relies on several simplifications
- aim: systematic theoretical treatment in QCD
  as basis to improve phenomenology

Multi-parton interactions: results

Diehl, Ostermeier, Schäfer 2011

- operator definition for multi-parton distributions suitable for studies in lattice QCD
- correlations in color and spin of partons $\rightarrow$ observable consequences
- evolution equations and Sudakov logarithms



- revealed double counting problem between single and double hard scattering

  e.g. $gg \rightarrow ZZ$
  vs. $(q\bar{q} \rightarrow Z) \otimes (q\bar{q} \rightarrow Z)$

work in progress

- double Drell-Yan process to study multi-parton interactions at LHC
- more realistic models for multi-parton distributions
- elements of a factorization theorem for multiple hard interactions

3-loop heavy flavor corrections to F_2

J. Ablinger, J. Blümlein, A. Hasselhuhn, C. Schneider, F. Wißbrock :

- NNLO corrections to $F_2(x, Q^2)$ are mandatory: light partons + heavy quarks
- Focus on the corrections for $Q^2/m^2 \geq 10$.
- 2009: NNLO corrections of the moments of $F_2(x, Q^2)$, including VFNS
- 2011: All logarithmic terms calculated for general Mellin variable

$$A_{ij}^{(3)}\left(\frac{m^2}{Q^2}\right) = a_{ij}^{(3),3}\ln^3\left(\frac{m^2}{Q^2}\right) + a_{ij}^{(3),2}\ln^2\left(\frac{m^2}{Q^2}\right) + a_{ij}^{(3),1}\ln\left(\frac{m^2}{Q^2}\right) + a_{ij}^{(3),0}$$

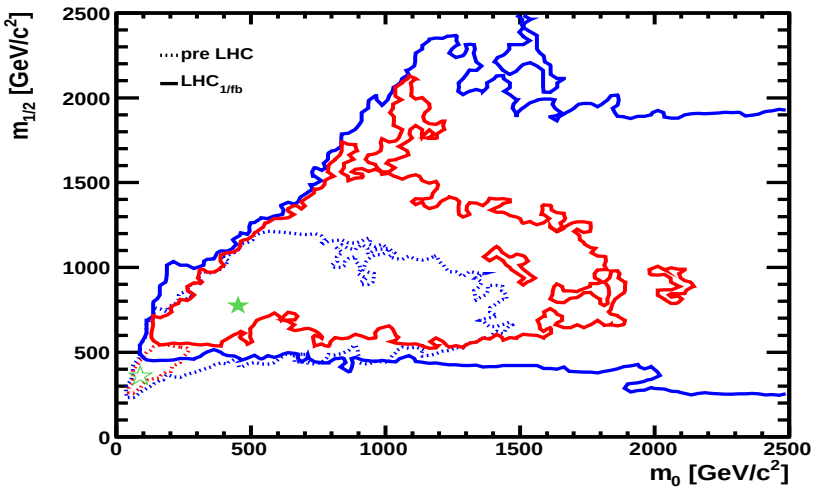
- Two of five contributing Wilson coefficients are calculated completely: $L_{q,2}^{\rm PS}, L_{g,2}^{\rm S}$.
- Two-mass contributions (m_c & m_b) are nearly finished
- Use and development of new analytic summation and integration techniques; new higher transcendental functions
- Applications to CC interactions $\Longrightarrow$ HERA, ICECUBE

Beyond the Standard Model

Global fit in the CMSSM including 2011 LHC data ($1\ \mathrm{fb}^{-1}$) and XENON100 results

68% and 95% CL contours, pre- and post-LHC

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, M. Dolan, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, D. Martínez Santos, K. Olive, S. Rogerson, F. Ronga, G. Weiglein '11*]

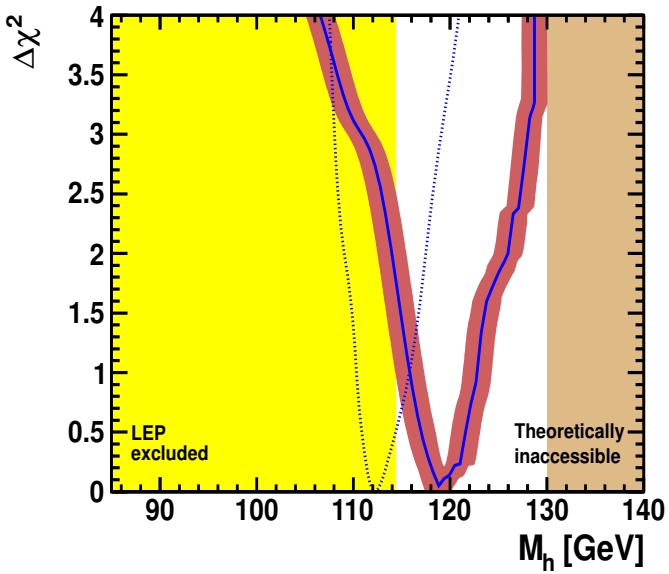


$\Rightarrow$ Preferred region "opens up", overall χ^2 worsened
Shift towards higher mass scales, higher values of $\tan\beta$

Comparison: GMSB yields much larger splitting between coloured and colour-neutral part of the spectrum

Indirect prediction for the Higgs mass in the CMSSM: pre-LHC vs. LHC2011

χ^2 fit for $M_{\rm h}$, without imposing direct search limit

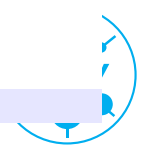


⇒ Inclusion of limits from LHC SUSY searches leads to upward shift in indirect prediction for $M_{\rm h}$

⇒ Best fit value for $M_{\rm h}$ above the LEP limit, tension released

Jürgen Reuter: reserach activities and plans

- Exceptional SUSY GUTs:
  SUSY GUTs based on E_6 Collider phenomenology, Dark Matter, Model building, RGEs, Parameter scans, Flavour Symmetries
- Impact of early LHC results on non-SUSY BSM models:
  exclusion limits from inclusive analysis, toy models, focus on strongly interacting UV completions: Randall-Sundrum and Little Higgs models
  joint SFB project with Andreas Weiler
- General New Physics Searches at LHC:
  Characteristics of SUSY/parity-driven decay chains, NLO corrections
- Phenomenologically driven model building:
  T parity in Little Higgs model, invisible Higgs models etc.
- Monte Carlo multi-purpose event generators (a.k.a. WHIZARD):
  BSM implementations, LHC physics, ILC/CLIC physics, NLO implementations, Parton showers



Andreas Weiler (DESY, Hamburg site)

Longtime project: *ATOM (an Automated Tester Of Models)*

Recast experimental searches to test any new physics model.
- Checks all LHC analyses at the same time: "see *what sticks*".
- Implemented all 36 missing energy searches of ATLAS&CMS.
- Susy paper upcoming *(w/ people at Berkeley & Tel Aviv)*

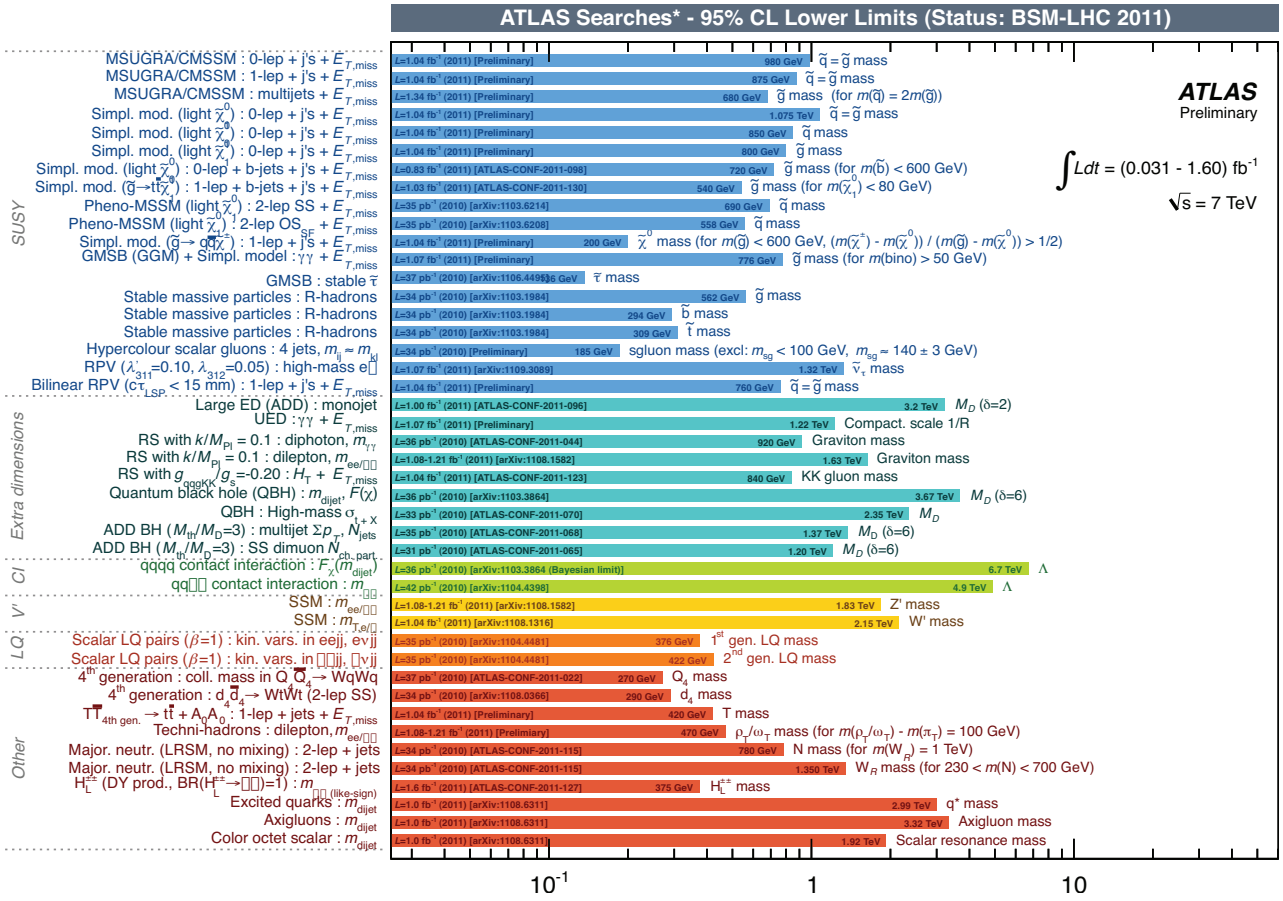
Some recent papers

'If no Higgs then what?' : *(SM without Higgs) = strongly coupled @ TeV.*
- Consistent description? Unitarization by resonances
- First time calculation of inelastic channels: where perturbative?
- LHC reach ? Defined simplified model.

'What the neutron knows about the top' : *discovered that CP violation in top sector severely constrained by neutron EDM.*
- finite matching correction of top chromo-electric → Weinberg op.:
- no hope at LHC to compete with EDMs on top CPV.

'Flavor and CP symmetric composite Higgs': *Solved the flavor problem of composite Higgs models with a GIM mechanism.*
- Previously unfeasible b/c of electro-weak precision constraints.
- Consequence: composite proton. Shown that *ultra-visible at LHC.*

BSM: Present Exclusions



SUSY exclusion reaches masses $\sim$ 1 TeV

ATLAS, BEM-LHC, Trieste, 2011

Teaching

- Regular lecture courses on Quantum Field Theory, Elementary Particle Phenomenology, Extensions of the SM, Cosmology, Astroparticle Physics, including special courses @ SFB 676, at the Universities of HU Berlin, Dortmund, Hamburg, and Potsdam
- EU Research and Training Network: "LHCPhenonet" - lectures at network schools for PhD students
- Graduate School 1504 "Mass, Spectrum, Symmetry in the Era of LHC", Berlin, DESY, Dresden
- PDF Schools and Workshops - Tera-scale Helmholtz Alliance
- CAPP 2011, Z
- Autumn School on Particle Physics & Cosmology, HH

Increasing number of request by students to carry out Diploma/Master- and PhD Theses at DESY $\rightarrow$ grants.

Networking

- SFB/Transregio 9 "Computational Particle Physics" (DESY, HU Berlin, KIT, RWTH) $\longrightarrow$ 2014
- SFB 676 "Particles, Strings, and the Early Universe" (DESY, U. Hamburg)
- LEXI Hamburg
- Mutual cooperations in the Tera-scale Helmholtz Alliance
- Research cooperation with Universities in Aachen, Berlin, Berkeley, Bonn, Dortmund, Durham, Freiburg, Karlsruhe, Katowice, Linz, Liverpool, Ljubljana, Louvain, Paris, Potsdam, Prague, Regensburg, Santander, St. Petersburg, Tel Aviv, Urbana, Warsaw, and CERN, IHEP Serpukhov, KEK, MPI Munich, NIKHEF
- EU Research and Training Network: "HadronPhysics2" $\rightarrow$ 2011
- EU Research and Training Network: "HadronPhysics3" 2012 $\rightarrow$
- EU Research and Training Network: "LHCPhenonet" 2011 $\rightarrow$
- DESY-RISC collaboration on new mathematical methods in loop calculations $\longrightarrow$ 5th anniversary: Feb. 2012
- planned EU TMR network "HiggsFATE", (10 nodes; 1: both DESY sites)

Conferences

- DESY Theory Workshop, annually
- 11th Loops and Legs in Quantum Field Theory, Wernigerode, Apr. '12, bi-annually
- 4th LHC Higgs Cross Section WS, BNL, May '11
- Gluons and the quark sea at high energies: distributions, polarization, tomography, Seattle, Sep/Nov '10; excell. Proceedings finished.
- 2nd Standard Candle Workshop, Z, June '11
- 7th Patras WS on Axions, WIMPs and WISPs, Patras, June '11
- QCD @ the LHC - 2, St. Andrews, Aug. '11
- ACAT 2012, Uxbridge, Sep. '11
- Implications of LHC results for TeV-scale physics, CERN, Aug/Sep '11
- Advanced conformal field theory and application, Paris, Sep.-Dec. '11
- Multiple Partonic Interactions, HH, Nov. '11

Conferences

- Strengthen the collaboration with Japan: Bi-national Workshop Modern Trends in Quantum Chromodynamics, Oct. 2011, DFG+DESY

Perspectives in the Era of the LHC

- Long-term involvement of DESY in the LHC programmes as well as ILC/CLIC. This includes both Standard Model and BSM Physics, in various demanding issues in quite a series of key areas.
- Further service for the whole HEP community is a substantial part of our mission through: close collaboration, supply of special codes, topical conferences, schools, teaching
- Training of young researchers in mutual ways - in cooperation with universities - is of central importance.

Very good complementarity between both DESY Theory groups and NIC, supplementing each other, with various nice overlaps, forms together a rather strong unit to perform large-scale long-term research.

Back-up slides

BSM $\oplus$ Higgs phenomenology: A light Higgs in SUSY cascades

Example: NMSSM scenario, light $\mathcal{CP}$-even Higgs, $20\ \mathrm{GeV} < M_{\mathrm{h}_1} < 110\ \mathrm{GeV}$, in agreement with all search limits (large singlet component) [*O. Stål, G. Weiglein '11*]

$\Rightarrow$ Higgs production in chargino and neutralino decays in SUSY cascades

$$\tilde{q} \to q\tilde{\chi}_i^0 \to q\tilde{\chi}_1^0 h_k \to q\tilde{\chi}_1^0 b\bar{b}$$

$$\tilde{g} \to g\tilde{q} \to gq\tilde{\chi}_i^0 \to gq\tilde{\chi}_1^0 h_k \to gq\tilde{\chi}_1^0 b\bar{b}$$

Monte Carlo $\oplus$ fast detector simulation

SM $t\bar{t}$ backgrounds and SUSY backgrounds considered

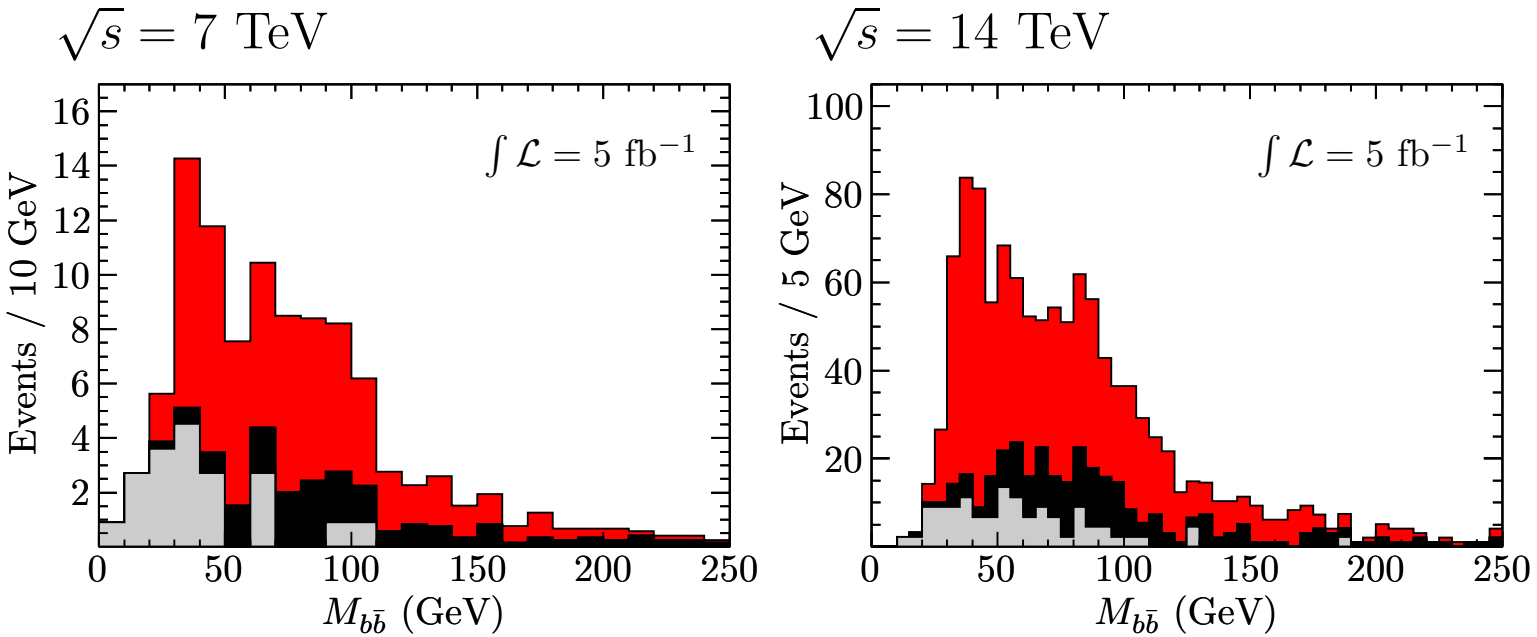
Selection: # of jets, b-tags, p_{T} of jets $1 + 2$, miss. E_{T}, $\Delta R(bb)$

Scenario in which squark and gluino masses are close to the present LHC limits

Results for $b\bar{b}$ jet invariant mass distribution:

SUSY signal, SUSY background, SM $t\bar{t}$ background (grey)

$\int \mathcal{L} = 5\ \mathrm{fb}^{-1}$, $M_{\mathrm{h}_1} \approx 40\ \mathrm{GeV}$ [*O. Stål, G. Weiglein '11*]



⇒ Signal over background ratio looks encouraging
h_1 peak and Z peak visible

⇒ We could get a signal for SUSY + Higgs at once

Andreas Weiler

(DESY, Hamburg site)

General Direction: *BEYOND THE SM AT THE LHC*

phenomenology & model building

What are the expectations at LHC beyond the simplest susy scenarios? How to look for them?

What can be learned from early searches? Can we reuse experimental results to constrain other models?

Can we come up with a better theory of the weak scale?

Ensure that LHC results are

1) as generally useful as possible and

2) *'no stone is left unturned'*