Quantum Field Theory and Collider Phenomenology

Johannes Blümlein,
on behalf of the Phenomenology Groups @ Hamburg and Zeuthen

Recent Phenomenology and QFT Highlights

DESY, PRC Hamburg October 22, 2015

Contents

1. Overview
2. Highlights on Physics Results
3. Perspectives and Plans

Our Research:

Higgs properties,
e.w. symmetry breaking

tools,
parameter fitting
event generators

constructing, constraining,
testing BSM models

close cooperation with
experimental groups

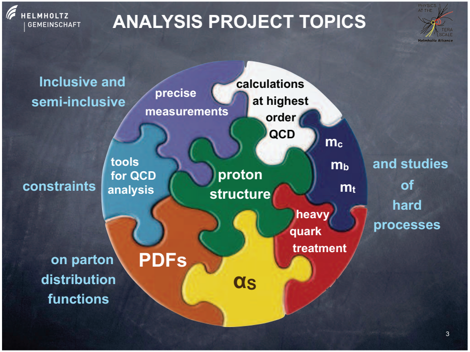
high precision predictions
of Standard Model parameters

multidisciplinary cooperation
with mathematics & computer
algebra

Examples of Physics Results

(since the last meeting)

Terascale Alliance Working Group

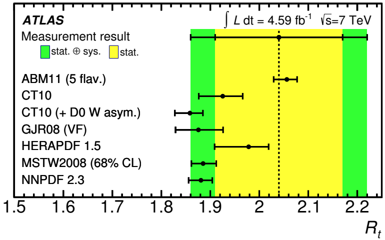


Some of the cooperations continue and are extended: jets @ LHC

ABM13-15 Analysis: $\alpha_s(M_Z)$; ATLAS single top and ABM.

$$m_c(m_c) = 1.24 \pm 0.03(exp) \; {}^{+0.03}_{-0.02} \; (scale) \; {}^{+0.00}_{-0.07} \; (th)$$

$$m_b(m_b) = 3.97 \pm 0.14(exp) \; {}^{+0.00}_{-0.11} \; (th)$$



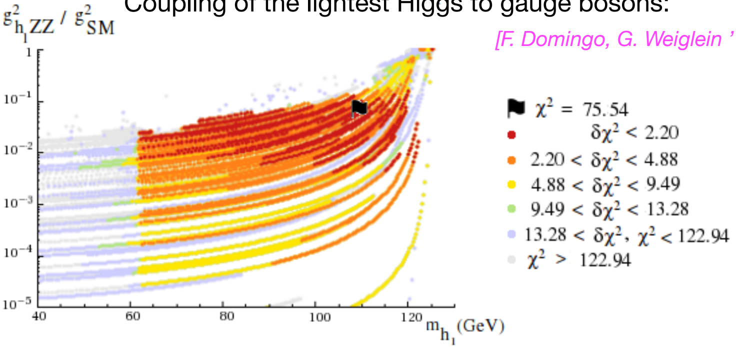
Phys.Rev. D90 (2014) 112006

	$\alpha_s(M_Z)$	
Alekhin[2001]	0.1143 ± 0.0013	DIS [1]
BBG[2004]	$0.1134 \, {}^{+0.0019}_{-0.0021}$	valence analysis, NNLO [2,3]
GRS	0.112	valence analysis, NNLO [4]
ABKM	0.1135 ± 0.0014	HQ: FFNS $n_f = 3$ [5]
ABKM	0.1129 ± 0.0014	HQ: BSMN-approach[5]
JR	0.1124 ± 0.0020	dynamical approach [6]
JR	0.1158 ± 0.0035	standard fit [6]
BB	0.1132 ± 0.0022	valence analysis, NNLO [7]
MSTW	0.1171 ± 0.0014	[8]
Thorne	0.1136	DIS+DY+HT* [9]
ABM11$_J$	$0.1134 - 0.1149 \pm 0.0012$	Tevatron jets (NLO) incl. [10]
ABM12	0.1133 ± 0.0011	[11]
ABM12	0.1132 ± 0.0011	without jets, [11]
NN21	0.1173 ± 0.0007	[12]
CTEQ 2013	0.1140	(without jets) [13]
CTEQ 2015	$0.1150^{+0.0060}_{-0.0040}$	$\Delta\chi^2 > 1$ [14]
Gehrmann et al.	$0.1153 \pm 0.0017 \pm 0.0023$	e^+e^- thrust [15]
Abbate et al.	$0.1140 \pm 0.0015 \pm 0.0006$	e^+e^- thrust [16]
CMS	0.1151 ± 0.0033	$t\bar{t}$ [17]
NLO Jets ATLAS	$0.1151^{+0.0093}_{-0.0087}$	[18]
NLO Jets CMS	0.1148 ± 0.0052	3/2 jet ratio [19]
BBG	$0.1141 \, {}^{+0.0020}_{-0.0022}$	valence analysis, N^{3}LO(*) [3]
world average	0.1170 ± 0.0007	PDG upcoming (w.o. lattice) [20]

In extended Higgs sectors, example: NMSSM, the signal at 125 GeV may not be the lightest Higgs

Coupling of the lightest Higgs to gauge bosons:

[F. Domingo, G. Weiglein '15]



$\Rightarrow$ SM-like Higgs at 125 GeV + singlet-like Higgs at lower mass
The case where the signal at 125 GeV is not the lightest Higgs arises generically if the Higgs singlet is light

$\Rightarrow$ Strong suppression of the coupling to gauge bosons

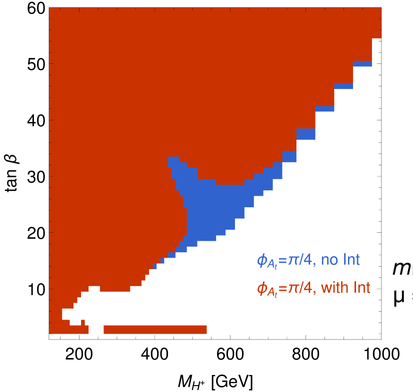
Search for heavy Higgs bosons at the LHC: impact of interference effects

Exclusion limits from neutral Higgs searches in the MSSM with and without interference effects: *[E. Fuchs, G. Weiglein '15]*

CP-violating case, $\phi_{A_t} = \pi / 4$

H, A are nearly mass degenerate: large mixing possible in CP-violating case!

Incoherent sum is not sufficient!



m_h^{mod+} scenario, μ = 1000 GeV

⇒ Large CP-violating interference effects between H, A possible

Cosmological relaxation of the Higgs mass

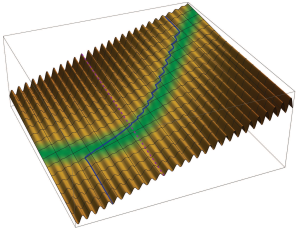
A new approach to the Hierarchy problem has been recently proposed

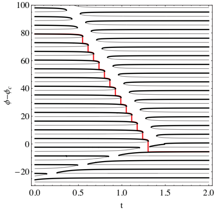
Graham, Kaplan, Rajendran '15

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

The idea is not to cancel the divergent radiative correction to the Higgs mass
but to have a rolling field scanning a large range of Higgs mass.
When EW symmetry occurs, the Higgs vev back-reacts
and stops the rolling of the scanning field.

Self-organized criticality of the EW scale





We built a model where the Higgs mass is naturally stable
and where there is no new physics threshold at the weak scale

Phenomenological signatures

Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

only BSM physics below 10^9GeV

two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim (10^{-20} - 10^2)\,\text{GeV}$$

$$m_\sigma \sim (10^{-45} - 10^{-2})\,\text{GeV}$$

technically natural set-up
i.e. no large interaction radiatively generated

~interesting cosmology signatures~

◎ BBN constraints

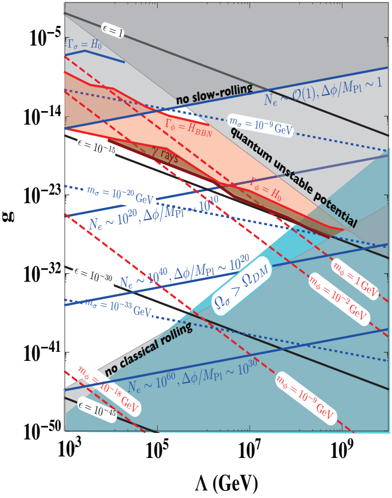
◎ decaying DM signs in γ-rays background

◎ ALPs

◎ superradiance

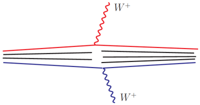
~interesting signatures @ SHiP~

◎ production of light scalars by B and K decays

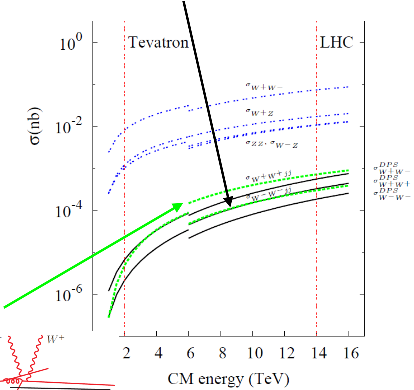


Multiparton interactions

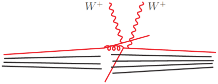
M. Diehl



- several partons interact in single pp collision
- important in specific kinematics / for specific processes
- closely related with physics of underlying event
- relevant measurements by all 4 LHC collaborations
- reliable description in QCD remains outstanding task



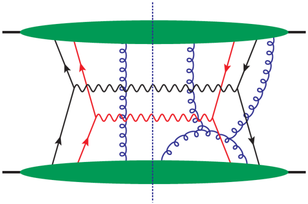
example: WW production
both a standard candle (W^+W^-)
and a search channel
($W^+W^+ \to$ same sign leptons)



plot: J. Gaunt et al, 2003

Multiparton interactions

- does double parton scattering factorise at all?
  is basis of all phenomenology
  - ★ difficult already for single scattering: decoupling of soft-gluon exchange (spectator partons rescatter)
  - ★ effects cancel by unitarity
- can generalise proof of soft-gluon cancellation from single to double Drell-Yan process
  (after careful review of single Drell-Yan case)

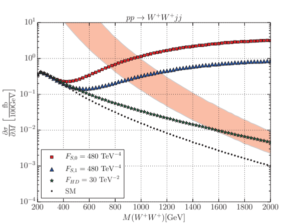


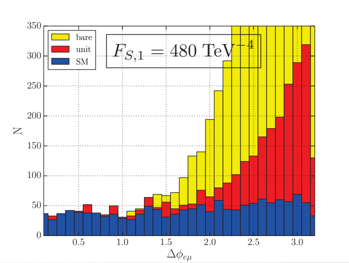
M. Diehl , J. Gaunt, D. Ostermeier, P. Plössl, A. Schäfer

JRR pars II: Vector Boson Scattering @ LHC

- Vector Boson Scattering (VBS) major measurement of LHC runs II/III   Gianotti, CERN 01/2014
- Light Higgs suppression makes VBS prime candidate for BSM searches
- Model-independent EFT descriptions (almost) useless: either weakly-coupled resonances in reach or strongly-coupled sectors   Kilian/Ohl/Reuter/Sekulla, 1408.6207
- Parameterize new physics by dim 6/dim 8 operators, calculate unitarity limits
- K-matrix unitarization implemented in `WHIZARD` (both for operators and resonances)

$$\mathcal{L}_{HD} = F_{HD} \ \mathrm{tr}\left[\mathbf{H}^\dagger\mathbf{H} - \frac{v^2}{4}\right] \cdot \mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger (\mathbf{D}^\mu\mathbf{H})\right]$$
$$\mathcal{L}_{S,0} = F_{S,0} \ \mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger \mathbf{D}_\nu\mathbf{H}\right] \cdot \mathrm{tr}\left[(\mathbf{D}^\mu\mathbf{H})^\dagger \mathbf{D}^\nu\mathbf{H}\right]$$
$$\mathcal{L}_{S,1} = F_{S,1} \ \mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger \mathbf{D}^\mu\mathbf{H}\right] \cdot \mathrm{tr}\left[(\mathbf{D}_\nu\mathbf{H})^\dagger \mathbf{D}^\nu\mathbf{H}\right]$$



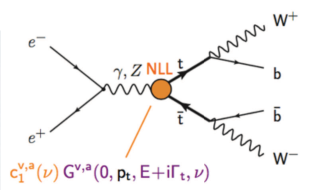


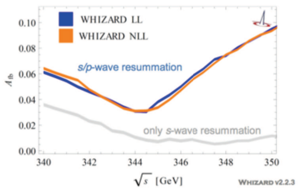
ATLAS derived limits on anomalous couplings using this formalism: 1405.6241

J.R.Reuter   DESY Wissenschaftsrat, 22.10.2015

JRR pars IV: WHIZARD @ NLO/NNLL (top threshold)

- Resummed top threshold as eff. vertex/form factor in WHIZARD Bach/Chokoufe/Hoang/JRR/Stahlhofen/Weiss
- $G^{v,a}(0, p_t, E + i\Gamma_t, \nu)$ from TOPPIK code [Jezabek/Teubner], included in WHIZARD





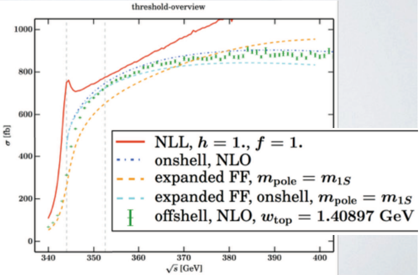
$$R^{\gamma,Z}(s) = \underbrace{F^v(s)R^v(s)}_{\text{s-wave: LL+NLL}} + \underbrace{F^a(s)R^a(s)}_{\text{p-wave}\sim v^2\text{:NNLL}}$$

BUT: differentially p-wave at NLL !

- Default parameters:

$$\mathbf{M_{1S} = 172\ GeV}, \quad \Gamma_t^{\text{NLO}} = 1.409\ \text{GeV}$$
$$\alpha_s(MZ) = 0.118$$

Threshold/Continuum Matching: WIP



NNLO Developments.

N-jettiness subtractions for NNLO calculations

[Gaunt, Stahlhofen, FT, Walsh; JHEP 1509 (2015) 058]

- Subtractions are central part of NNLO calculations to handle IR divs

⇒ First general NNLO subtraction scheme for arbitrary QCD final states

- ▶ Based on N-jettiness factorization in SCET
- ▶ NNLO quark and gluon beam functions are key ingredient [Gaunt, Stahlhofen, FT, JHEP 1404 (2014) 113 JHEP 1408 (2014) 020]

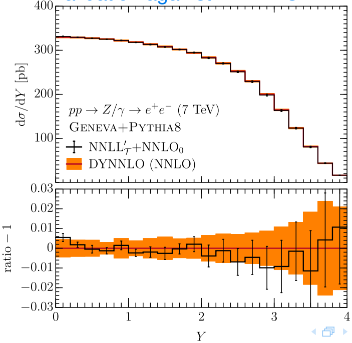
GENEVA: Monte Carlo at NNLO

- NNLO+parton shower matching is the current MC frontier

⇒ First general NNLO+PS

- ▶ Use N-jettiness subtractions and higher-order resummation to combine fully-differential NNLL′+NNLO calculation with PYTHIA8 parton shower and hadronization

Validation against DYNNLO



Drell-Yan at NNLL′+NNLO matched to Pythia8.

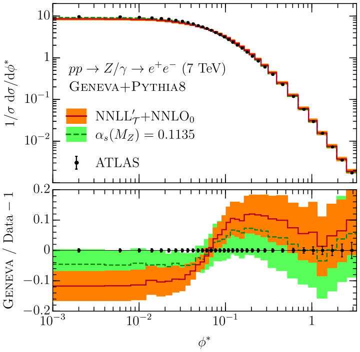
[Alioli, Bauer, Berggren, FT, Walsh, 1508.01475 (to appear in PRD)]

GENEVA

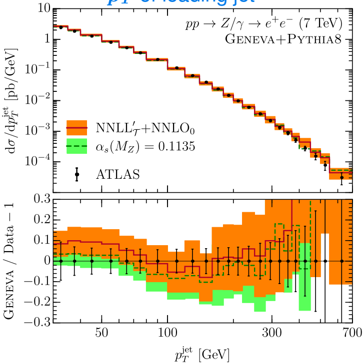
Completed implementation for $pp \to Z/\gamma \to \ell^+\ell^-$

- Comparison to LHC data

ϕ^* of diplepton system



p_T of leading jet

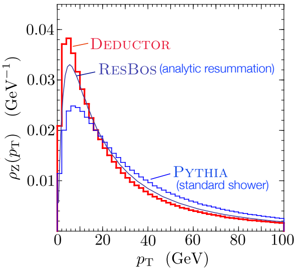


- In preparation: public release, implementation of more processes

Parton Shower Development

Zoltán Nagy
Davison E. Soper

- The focus is to do theoretical studies and use parton shower as theory prediction
- Providing a pQCD, all order theory definition,
  - Genuine higher order effects in the shower evolution
  - Higher order effects in the hard part (*"matching"*) become part of the shower definition.
- Taking care of quantum effects
  - Color interferences, spin correlations
- Understand the large logarithms and their summation in parton shower for simple and "less-simple" observables
  - Visible logarithms (like Drell-Yan transverse momentum)
  - Invisible logarithms (like threshold effects)
  - Exotic logarithms (Coulomb gluons, ...)
  - Using parton shower predictions for PDF fits
- Understanding the relation to BFKL physics
- DEDUCTOR is a program that implements these ideas at first order level.



http://www.desy.de/~znagy/deductor

Massive Feynman integrals - AMBRE version 3

The Mathematica project AMBRE is an interface to the package MB (M. Czakon) and aims at the semi-automatic derivation of Mellin-Barnes representations for a general class of Feynman integrals.

AMBRE is the only open-source alternative to several open-source packages based on sector decomposition: FIESTA (Smirnov et al.), SECDEC (Heinrich et al.), sector_decomposition (Weinzierl et al.)

New AMBRE version in test

- Non-planar integrals
- One- to three-loop functions
- In Euclidean and Minkowskian metrics
- With higher tensor ranks (tested: rank four)

Ongoing semi-automated numerical improvements of MB

- Up to 6...12 digits of accuracy, also in the much more complicated Minkowskian
- Up to n-dimensional MB-representations (now: 6 dimensions)
- Use of several numerical strategies, partly relying on the CUBA library (T. Hahn)

Project MBsums

Derive multiple sums for MB-integrals as a preparation for a subsequent automated analytical summation

Scalar one-loop integrals with general masses and scales

JB, K.H. Phan, T. Riemann with partners at RISC/Linz: fully analytic results are derived for

- 1-point to 4-point functions.
  Higher point functions may be reduced to them by well-known reduction schemes.
- One-loop scalar Feynman integrals in arbitrary dimensions D, with $D = n - 2\epsilon$, and it is $n = 2, 4, 6, 8, \cdots$.
- The ϵ-expansion of the analytic result in D dimensions to high powers.

This is needed for:

- Higher-loop calculations, where the complete corrections and renormalization need one-loop pieces (up to various legs).
- One-loop calculations with many external legs, where in the course of reductions inverse Gram determinants are introduced.
  The knowledge of Feynman integrals in $D > d$ dimensions, where $d = 4 - 2\epsilon$, stabilizes the numerics.

$\Longrightarrow$ (general.) hypergeometric functions, Appell functions, Lauricella functions.

Massive Feynman integrals - A lattice QCD application

Analytic solutions for massive high-rank tensor one-loop Feynman integrals for a lattice QCD application

QCDSF collab. performs one-loop lattice perturbation computations, needing a large number of analytic solutions for 'ordinary' massive high-rank indexed one-loop tensor Feynman integrals in the Euclidean.
The principal structure of their integrals is

$$\int_{-\pi/a}^{\pi/a} \frac{d^4k}{(2\pi)^4} F(\cos(a\,k_i), \sin(a\,k_i), \cos(a\,p), \sin(a\,p), m)\,, \qquad (1)$$

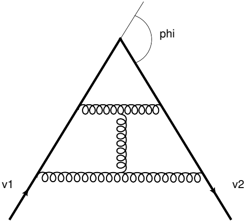
where a is the lattice spacing, m the mass and p generically denotes one ore more external momenta. F is a rational function of the trigonometric functions. One commonly used approach (Kawai,Seo) is to compute those integrals by Taylor expansion in the external momenta over the Brillouin zone and the integral in the limit $a \to 0$.
Technically, one needs analytical results for ordinary continuum integrals in the Euclidean space.
Example:

$$I_{2,4} = \int_{-\infty}^{\infty} \frac{d^Dk}{(2\pi)^D} \frac{k_\mu\, k_\nu\, k_\sigma \ldots}{(k^2)^2\,[(k-p)^2+m^2]^2} \quad \text{etc.}$$

Cusp (soft) anomalous dimension at 3 loop order

Fundamental quantity in QCD, applications e.g. in soft resummation

[Grozin, Henn, Korchemsky, Marquard PRL '15]



$$\Gamma^{(3)}_{\rm cusp} = c_1\, C_F C_A^2 + c_2\, C_F (T_f n_f)^2 + c_3\, C_F^2 T_f n_f + c_4\, C_F C_A T_f n_f\,,$$

with

$$c_1 = \frac{1}{4}\left[\tilde{A}_5 + \tilde{A}_4 + \tilde{B}_5 + \tilde{B}_3\right] + \frac{67}{36}\tilde{A}_3 + \frac{29}{18}\tilde{A}_2 + \left(\frac{245}{96} + \frac{11}{24}\zeta_3\right)\tilde{A}_1\,,$$

$$c_2 = -\frac{1}{27}\tilde{A}_1\,, \quad c_3 = \left(\zeta_3 - \frac{55}{48}\right)\tilde{A}_1\,,$$

$$c_4 = -\frac{5}{9}\left[\tilde{A}_3 + \tilde{A}_2\right] - \frac{1}{6}\left(7\zeta_3 + \frac{209}{36}\right)\tilde{A}_1\,.$$

$\tilde{A}_i, \tilde{B}_i$ are functions containing harmonic polylogarithms of weight i

$\overline{\text{MS}}$–on-shell relation at four-loop order

Fundamental relation between heavy quark masses in different renormalization schemes [Marquard, Smirnov, Smirnov, Steinhauser PRL '15]

- $\overline{\text{MS}} \to$ on-shell

$$
\begin{aligned}
M_t &= m_t \left(1 + 0.4244\,\alpha_s + 0.8345\,\alpha_s^2 + 2.375\,\alpha_s^3 + (8.49 \pm 0.25)\,\alpha_s^4\right) \\
&= 163.643 + 7.557 + 1.617 + 0.501 + 0.195 \pm 0.005 \text{ GeV}\,,
\end{aligned}
$$

$$
\begin{aligned}
M_b &= m_b \left(1 + 0.4244\,\alpha_s + 0.9401\,\alpha_s^2 + 3.045\,\alpha_s^3 + (12.57 \pm 0.38)\,\alpha_s^4\right) \\
&= 4.163 + 0.401 + 0.201 + 0.148 + 0.138 \pm 0.004 \text{ GeV}\,.
\end{aligned}
$$

- threshold masses $\to m_{\overline{\text{MS}}}$

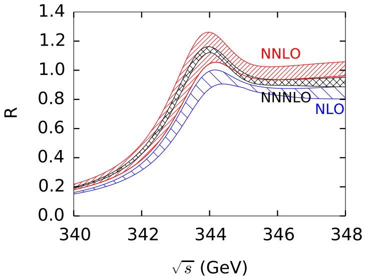
$$
\begin{aligned}
\frac{m_t(m_t)}{\text{GeV}} &= 163.643 \pm 0.023 + 0.074\Delta_{\alpha_s} - 0.095\Delta_{m_t}^{\text{PS}}\,, \\
\frac{m_t(m_t)}{\text{GeV}} &= 163.643 \pm 0.007 + 0.069\Delta_{\alpha_s} - 0.096\Delta_{m_t}^{\text{1S}}\,, \\
\frac{m_b(m_b)}{\text{GeV}} &= 4.163 \pm 0.004 + 0.007\Delta_{\alpha_s} - 0.018\Delta_{m_b}^{\text{PS}}\,, \\
\frac{m_b(m_b)}{\text{GeV}} &= 4.163 \pm 0.006 + 0.008\Delta_{\alpha_s} - 0.019\Delta_{m_b}^{\text{1S}}
\end{aligned}
$$

$t\bar{t}$ production @ ILC @ NNNLO

- complete NNNLO prediction for

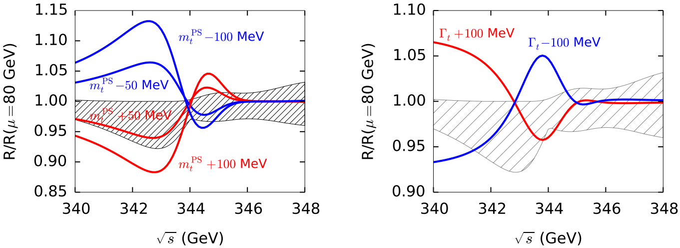
$$e^+e^- \to t\bar{t}$$

  at threshold in the framework of PNRPCD
- only moderate corrections compared to NNLO
- error bands overlap partially
- finally, stabilization of peak height and position
- overlap of error bands with NNLO result



[Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser]

Sensitivity to top mass and width



- reasonable sensitivity to mass and width of the top quark
- 50 MeV theory uncertainty for mass measurement feasible, but more detailed experimental study needed

3-loop heavy flavor corrections to F_2

J. Ablinger, A. Behring, J. Blümlein, A. De Freitas, A. Hasselhuhn, A. von Manteuffel, C. Raab, M. Round, C. Schneider, F. Wißbrock, (DESY,Z RISC Linz, IHES, Mainz [TH Phys & Math]:

- 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: Complete 3-Loop NNLO renormalization, WC & VFNS moments Bierenbaum, JB, S. Klein
- 2010: All logarithmic terms calculated for general Mellin variable, as well as all known contr. to the Wilson coefficients were calculated for general N.

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

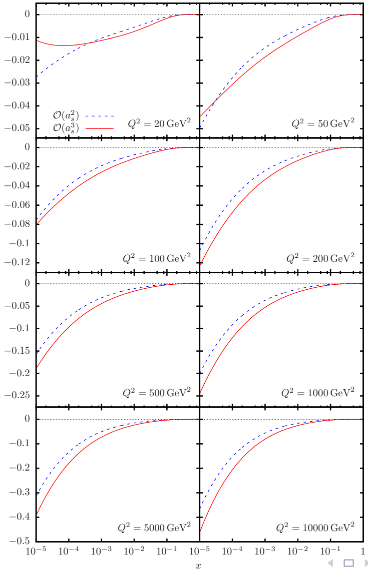
- Four of five contributing Wilson coefficients are calculated completely $L_{q,2}^{\rm NS}, L_{q,2}^{\rm PS}, L_{g,2}^{\rm S}, H_{q,2}^{\rm PS}$. with first numerical results; Likewise: 7 of 8 massive OMEs!
- Use and development of new analytic summation and integration techniques; new higher transcendental functions

The 3-Loop Wilson Coefficients at large Q^2: 2014

$$
\begin{aligned}
L^{\rm NS}_{q,(2,L)}(N_F+1) &= a_s^2\Big[A^{(2),\rm NS}_{qq,Q}(N_F+1)\ \delta_2 + \hat{C}^{(2),\rm NS}_{q,(2,L)}(N_F)\Big] \\
&+ a_s^3\Big[A^{(3),\rm NS}_{qq,Q}(N_F+1)\ \delta_2 + A^{(2),\rm NS}_{qq,Q}(N_F+1) C^{(1),\rm NS}_{q,(2,L)}(N_F+1) + \hat{C}^{(3),\rm NS}_{q,(2,L)}(N_F)\Big] \\
L^{\rm PS}_{q,(2,L)}(N_F+1) &= a_s^3\Big[\ A^{(3),\rm PS}_{qq,Q}(N_F+1)\ \delta_2 + A^{(2)}_{gq,Q}(N_F)\ \ N_F\tilde{C}^{(1)}_{g,(2,L)}(N_F+1) + N_F\hat{\tilde{C}}^{(3),\rm PS}_{q,(2,L)}(N_F)\Big] \\
L^{\rm S}_{g,(2,L)}(N_F+1) &= a_s^2 A^{(1)}_{gg,Q}(N_F+1) N_F\tilde{C}^{(1)}_{g,(2,L)}(N_F+1) + a_s^3\Big[\ A^{(3)}_{qg,Q}(N_F+1)\ \delta_2 \\
&\quad + A^{(1)}_{gg,Q}(N_F+1)\ \ N_F\tilde{C}^{(2)}_{g,(2,L)}(N_F+1) + A^{(2)}_{gg,Q}(N_F+1)\ \ N_F\tilde{C}^{(1)}_{g,(2,L)}(N_F+1) \\
&\quad + A^{(1)}_{Qg}(N_F+1)\ \ N_F\tilde{C}^{(2),\rm PS}_{q,(2,L)}(N_F+1) + N_F\hat{\tilde{C}}^{(3)}_{g,(2,L)}(N_F)\Big]\ , \\
H^{\rm PS}_{q,(2,L)}(N_F+1) &= a_s^2\Big[\ A^{(2),\rm PS}_{Qq}(N_F+1)\ \delta_2 +\ \tilde{C}^{(2),\rm PS}_{q,(2,L)}(N_F+1)\Big] + a_s^3\Big[\ A^{(3),\rm PS}_{Qq}(N_F+1)\ \delta_2 \\
&\quad + \tilde{C}^{(3),\rm PS}_{q,(2,L)}(N_F+1) + A^{(2)}_{gq,Q}(N_F+1)\ \tilde{C}^{(1)}_{g,(2,L)}(N_F+1) \\
&\quad + A^{(2),\rm PS}_{Qq}(N_F+1)\ C^{(1),\rm NS}_{q,(2,L)}(N_F+1)\Big]\ , \\
H^{\rm S}_{g,(2,L)}(N_F+1) &= a_s\Big[\ A^{(1)}_{Qg}(N_F+1)\ \delta_2 +\ \tilde{C}^{(1)}_{g,(2,L)}(N_F+1)\Big] + a_s^2\Big[\ A^{(2)}_{Qg}(N_F+1)\ \delta_2 \\
&\quad + A^{(1)}_{Qg}(N_F+1)\ C^{(1),\rm NS}_{q,(2,L)}(N_F+1) +\ A^{(1)}_{gg,Q}(N_F+1)\ \tilde{C}^{(1)}_{g,(2,L)}(N_F+1) \\
&\quad + \tilde{C}^{(2)}_{g,(2,L)}(N_F+1)\Big] +\ a_s^3\Big[\ A^{(3)}_{Qg}(N_F+1)\ \delta_2 +\ A^{(2)}_{Qg}(N_F+1)\ C^{(1),\rm NS}_{q,(2,L)}(N_F+1) \\
&\quad + A^{(2)}_{gg,Q}(N_F+1)\ \tilde{C}^{(1)}_{g,(2,L)}(N_F+1) +\ A^{(1)}_{Qg}(N_F+1)\Big\{C^{(2),\rm NS}_{q,(2,L)}(N_F+1) \\
&\quad + \tilde{C}^{(2),\rm PS}_{q,(2,L)}(N_F+1)\Big\} +\ A^{(1)}_{gg,Q}(N_F+1)\ \tilde{C}^{(2)}_{g,(2,L)}(N_F+1) +\ \tilde{C}^{(3)}_{g,(2,L)}(N_F+1)\Big]
\end{aligned}
$$

J. Ablinger et al. 2014

The 3-Loop PS-contribution to $F_2(x, Q^2)$



3-Loop Variable Flavor Number Scheme: 2015

$$f_k(n_f+1,\mu^2) + f_{\bar{k}}(n_f+1,\mu^2) = A_{qq,Q}^{\rm NS}\left(n_f,\frac{\mu^2}{m^2}\right) \otimes \left[f_k(n_f,\mu^2) + f_{\bar{k}}(n_f,\mu^2)\right] + \tilde{A}_{qq,Q}^{\rm PS}\left(n_f,\frac{\mu^2}{m^2}\right) \otimes \Sigma(n_f,\mu^2) + \tilde{A}_{qg,Q}^{\rm S}\left(n_f,\frac{\mu^2}{m^2}\right) \otimes G(n_f,\mu^2)$$

$$f_{Q+\bar{Q}}(n_f+1,\mu^2) = \tilde{A}_{Qq}^{\rm PS}\left(n_f,\frac{\mu^2}{m^2}\right) \otimes \Sigma(n_f,\mu^2) + \tilde{A}_{Qg}^{\rm S}\left(n_f,\frac{\mu^2}{m^2}\right) \otimes G(n_f,\mu^2)\,.$$

$$G(n_f+1,\mu^2) = A_{gq,Q}^{\rm S}\left(n_f,\frac{\mu^2}{m^2}\right) \otimes \Sigma(n_f,\mu^2) + A_{gg,Q}^{S}\left(n_f,\frac{\mu^2}{m^2}\right) \otimes G(n_f,\mu^2)\,.$$

$$\Sigma(n_f+1,\mu^2) = \sum_{k=1}^{n_f+1}\left[f_k(n_f+1,\mu^2) + f_{\bar{k}}(n_f+1,\mu^2)\right] = \left[A_{qq,Q}^{\rm NS}\left(n_f,\frac{\mu^2}{m^2}\right) + n_f\tilde{A}_{qq,Q}^{\rm PS}\left(n_f,\frac{\mu^2}{m^2}\right) + \tilde{A}_{Qq}^{\rm PS}\left(n_f,\frac{\mu^2}{m^2}\right)\right] \otimes \Sigma(n_f,\mu^2) + \left[n_f\tilde{A}_{qg,Q}^{\rm S}\left(n_f,\frac{\mu^2}{m^2}\right) + \tilde{A}_{Qg}^{\rm S}\left(n_f,\frac{\mu^2}{m^2}\right)\right] \otimes G(n_f,\mu^2)$$

2015
The choice of matching scales is not free and varies with the process in case of precision observables. Blümlein, van Neerven [hep-ph/9811351]

3-Loop Variable Flavor Number Scheme: 2015

$$
\begin{aligned}
f_k(n_f+1,\mu^2)+f_{\bar{k}}(n_f+1,\mu^2) &= A_{qq,Q}^{\rm NS}\left(n_f,\frac{\mu^2}{m^2}\right)\otimes\left[f_k(n_f,\mu^2)+f_{\bar{k}}(n_f,\mu^2)\right] \\
&+\tilde{A}_{qq,Q}^{\rm PS}\left(n_f,\frac{\mu^2}{m^2}\right)\otimes\Sigma(n_f,\mu^2)+\tilde{A}_{qg,Q}^{\rm S}\left(n_f,\frac{\mu^2}{m^2}\right)\otimes G(n_f,\mu^2) \\
f_{Q+\bar{Q}}(n_f+1,\mu^2) &= \tilde{A}_{Qq}^{\rm PS}\left(n_f,\frac{\mu^2}{m^2}\right)\otimes\Sigma(n_f,\mu^2)+\tilde{A}_{Qg}^{\rm S}\left(n_f,\frac{\mu^2}{m^2}\right)\otimes G(n_f,\mu^2)\,. \\
G(n_f+1,\mu^2) &= A_{gq,Q}^{\rm S}\left(n_f,\frac{\mu^2}{m^2}\right)\otimes\Sigma(n_f,\mu^2)+A_{gg,Q}^{S}\left(n_f,\frac{\mu^2}{m^2}\right)\otimes G(n_f,\mu^2)\,. \\
\Sigma(n_f+1,\mu^2) &= \sum_{k=1}^{n_f+1}\left[f_k(n_f+1,\mu^2)+f_{\bar{k}}(n_f+1,\mu^2)\right] \\
&= \left[A_{qq,Q}^{\rm NS}\left(n_f,\frac{\mu^2}{m^2}\right)+n_f\tilde{A}_{qq,Q}^{\rm PS}\left(n_f,\frac{\mu^2}{m^2}\right)+\tilde{A}_{Qq}^{\rm PS}\left(n_f,\frac{\mu^2}{m^2}\right)\right]\otimes\Sigma(n_f,\mu^2) \\
&+\left[n_f\tilde{A}_{qg,Q}^{\rm S}\left(n_f,\frac{\mu^2}{m^2}\right)+\tilde{A}_{Qg}^{\rm S}\left(n_f,\frac{\mu^2}{m^2}\right)\right]\otimes G(n_f,\mu^2)
\end{aligned}
$$

Our last paper has been selected as Editor's Suggestion by Physical Review D yesterday.

Cooperation with World Leading Computer Algebra Sites

RISC Linz: Summation, Combinatorics ⇕

FORM (NIKHEF) ⇕

DESY, TH

⇕ MapleSoft (Waterloo,ON)

⇕ Wolfram Research (Urbana, IL)

EU-TMR cooperation with MapleSoft & WolframResearch has been extended by 3 years within Higgstools.

Excellent PhD Student training sites.Same PhD Students were hired already by the companies.

WolframResearch would like to get into continuous cooperation (Dir. Res & Developm. R. Germundson).

Invitation to plenary talks at next years mathematica-conference.

Spill-Off: New Mathematics

- 1998: Harmonic Sums [Vermaseren; JB]
- 2003: Shuffle Algebras to high weights [JB]
- 2009: Exact analytic continuation of harmonic sums [JB]
- 2011: (generalized) Cyclotomic Harmonic Sums, polylogarithms and numbers [Ablinger, JB, Schneider]
- 2013: Systematic Theory of Generalized Harmonic Sums, polylogarithms and numbers [Ablinger, JB, Schneider]
- 2014: Finite nested Generalized Cyclotomic Harmonic Sums with (inverse) Binomial Weights [Ablinger, JB, Raab, Schneider]
- 2015: New non-iterative functions in single-mass Feynman integrals [Ablinger, Behring, JB, De Freitas, von Manteuffel, Schneider]

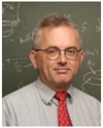
Particle Physics Generates NEW Mathematics.

Kolleg Mathematik-Physik Berlin




Prof. D. Kreimer Prof. M. Staudacher Prof. K. Mohnke Prof. J. Plefka
Theor. Physics & Mathematics HU Berlin






Prof. H. Ensault — FU Berlin (M)

Prof. J. Blümlein — DESY, Zeuthen (TP)

Prof. H. Nicolai — AEI,Potsdam (TP)

Prof. F. Brown — IHES, Paris (M)

Mission: Cooperation between Mathematicians and Theoretical Physicists combining efforts in Number Theory, Algebraic Geometry, Higher Order Quantum Field Theory, String Theory and Quantum Gravity in exchanging and developing technology and mutual structural insight and common education of young scientists.

Loops and Legs in Quantum Field Theory, Leipzig, April 2016

Regular bi-annual World Conference on new developments on multi-leg and multi-loop processes

Perspectives and Plans

- The period of the years until 2019 constitutes a core era of important measurements at the LHC with a high discovery potential and many precision measurements.
- The Theory Group will accompany these measurements with large scale precision calculations, the design of analysis codes for experimental analyses, including signal MC simulation and cooperate with the LHC and other experimental groups at DESY and at other sites in Germany.
- We will continue to search for effects of BSM predictions in the upcoming LHC data and refine BSM models.
- We will broaden technology developments in calculation of higher order and multi-leg Feynman diagrams together with national and international partners in theoretical physics, mathematics and computer algebra in the SM and its promising extension, to be prepared for new discoveries. This includes also resummations, MC, and the treatment of special processes.
- We are engaged in the education of students and PhD students providing special lectures at a variety of places throughout Germany.

Summary

Higgs properties,
e.w. symmetry breaking

tools,
parameter fitting
event generators

constructing, constraining,
testing BSM models

close cooperation with
experimental groups

high precision predictions
of Standard Model parameters

multidisciplinary cooperation
with mathematics & computer
algebra

We are looking forward to the LHC run II
and the realization of an ILC,
and to much deeper precision and discovery horizons in
particle physics to be unraveled also with
the help of theory.