

# Proposal for Cumulative Thesis

Vasily Sotnikov

June 19, 2019

## Relevant Publications

### 1. NLO QCD predictions for $Wb\bar{b}$ production in association with up to three light jets at the LHC

F. R. Anger, F. Febres Cordero, H. Ita and V. Sotnikov

Phys. Rev. D **97**, no. 3, 036018 (2018), doi:10.1103/PhysRevD.97.036018

In this article the next-to-leading QCD corrections to the associated production of  $W$ -bosons, a  $b\bar{b}$  pair, and up to three light jets are presented. The computation is done in the four-flavor-number scheme, thus including effects due to the non-vanishing bottom-quark mass. The results obtained in this work provide a prediction for an important irreducible background to  $H(\rightarrow b\bar{b})W$  studies.

The computation of one-loop matrix elements required for this project became possible due to my work on the major upgrade of the BLACKHAT library to handle massive fermions in automated numerical unitarity. The key developments are:

- unitarity cuts for a complete set of diagrams with internal massive particles in the loop
- an algorithm for the extraction of the rational part through a modified spectrum of particles in the loop
- in-house multi-precision implementation of master integrals with internal masses.

I also have carried out the study of numerical stability of the new version of the BLACKHAT library. My main contribution to the writeup of this publication is in the description of formal aspects of virtual matrix element computation.

### 2. Planar Two-Loop Five-Parton Amplitudes from Numerical Unitarity

S. Abreu, F. Febres Cordero, H. Ita, B. Page and V. Sotnikov

JHEP **1811**, 116 (2018), doi:10.1007/JHEP11(2018)116

In this work we computed for the first time all two-loop five-parton helicity amplitudes relevant for the computation of NNLO QCD corrections to the production of tree jets at hadron colliders in the leading color approximation. The computation is carried out with the recently developed two-loop numerical unitarity methods, which we extend for use with finite field arithmetics. We exploit decomposition of the integrand into master and surface terms that is independent of the parton type. We present reference values for helicity amplitudes, which are obtained by combining the master-integral coefficients with the known master integrals.

For this project I have developed and implemented the formalism for consistent definition of helicity amplitudes with quarks in dimensional regularization, suitable for application in the framework of numerical computations with multi-loop  $D$ -dimensional unitarity.

Other technical contributions which has been crucial for this project include:

- extension of the  $D$ -dimensional tree-level amplitude generator to handle fermions
- a general solution to the compatibility of fermions with evaluations over finite fields
- extensive validation of the new results (divergent structure, comparison to literature, etc.)

As a result of my work I became a main developer of the C++ framework CARAVEL for exploring multi-loop amplitudes with numerical unitarity.

I have contributed substantially to the preparation of all parts of the manuscript, with the focus on the definition of helicity amplitudes and presenting the main results of the paper.

### 3. Analytic Form of the Planar Two-Loop Five-Parton Scattering Amplitudes in QCD

S. Abreu, J. Dormans, F. Febres Cordero, H. Ita, B. Page and V. Sotnikov  
JHEP **1905**, 084 (2019), doi:10.1007/JHEP05(2019)084

In this work we present the analytic form of all two-loop five-parton helicity amplitudes required for the computation of NNLO QCD corrections to the production of three jets at hadron colliders in the leading-color approximation. We demonstrate how a combination of numerical evaluation of amplitudes through numerical unitarity with a dedicated algorithm of multivariate rational function reconstruction allows to obtain the analytic form of the amplitudes from exact numerical evaluations over finite fields. Their systematic simplification using multivariate partial-fraction decomposition leads to a particularly compact form. We show that with these methods, a sample with a size comparable to that required for numerical Monte-Carlo integration is sufficient to produce analytic expressions.

Here I have designed and implemented an algorithm which significantly optimizes the treatment of  $D$ -dimensional particles in the loops and allows to carry out all numerical evaluations with particle states taken to be in six dimensions. This replaces reconstruction of the dependence on the dimensional regulator from sample values. This development made the analytical reconstruction of amplitudes with quarks from numerical evaluations possible, which was not feasible before.

I have also contributed to many other parts of the project, such as building a framework for automated evaluation and reconstruction of large number of amplitudes. My main contribution to the writeup of the publication is in the description of the new algorithms employed for the evaluation of amplitudes, as well as presentation of the results.

### Ongoing Work

I am currently actively involved in the ongoing research projects which will results in further significant results and publications in the near future.

Some of the details of my work on the dimensional regularization of helicity amplitudes in the framework of numerical unitarity can be found in the (yet) unpublished article “*On the Dimensional Regularization of QCD Helicity Amplitudes With Quarks*,” F. R. Anger and V. Sotnikov, arXiv:1803.11127 [hep-ph].



## Promotionsausschuss

### Begleitschreiben zu Antrag einer Kumulativen Doktorarbeit von Vasily Sotnikov.

In meiner Rolle als Erstbetreuer von Vasily Sotnikov unterstütze ich seinen Antrag zur Einreichung seiner wissenschaftlicher Arbeiten als kumulative Dissertation. Vasily hat zu herausragenden wissenschaftlichen Publikationen in sehr signifikanter und oft federführender Weise beigetragen.

Im Rahmen seiner Promotion konnten wir die folgenden Artikel gemeinsam veröffentlichen:

1. NLO QCD predictions for  $Wbb$  production in association with up to three light jets at the LHC [Phys. Rev. D **97**, no. 3, 036018 (2018)]
2. Planar Two-Loop Five-Parton Amplitudes from Numerical Unitarity [JHEP **1811**, 116 (2018)]
3. Analytic Form of the Planar Two-Loop Five-Parton Scattering Amplitudes in QCD [JHEP **1905**, 084 (2019)]

Weitere Publikationen basierend auf seiner wissenschaftlichen Arbeit sind in den kommenden Monaten geplant.

Ich bestätige, dass Vasily klar ein Hauptautor der Publikationen ist, wie in seinem beigelegten Schreiben "Proposal for Cumulative Thesis" korrekt und detailliert ausgeführt.

Weiters übermittle als Beilage Schreiben unserer Co-Autoren Samuel Abreu, Ben Page, Jerry Dormans sowie seines Zweitbetreuers Prof. Fernando Febres Cordero. Die Schreiben bestätigen jeweils Vasily's zentralen Beitrag zu den genannten Publikationen.

Mit freundlichen Grüßen,

Prof. Dr. Harald Ita

Albert-Ludwigs-Universität  
Freiburg

Physikalisches Institut

Prof. Dr. Harald Ita

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Freiburg, Tuesday, 18 June 2019

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**cumulative thesis / Sotnikov**

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**Fernando Febres Cordero** <ffebres@physik.uni-freiburg.de>  
To: Harald Ita <harald.ita@physik.uni-freiburg.de>

Thu, Jun 20, 2019 at 12:55 PM

Dear Harald,

could you please forward the below statement to the Doctoral examination committee.

In my role as the 2nd supervisor of Vasily Sotnikov I support him submitting the PhD thesis in the cumulative format. I confirm that he did excellent work during his PhD and contributed in very significant way to our joint publications. We could publish the following papers,

- 1) NLO QCD predictions for  $Wbb$  production in association with up to three light jets at the LHC [Phys. Rev. D **97**, no. 3, 036018 (2018)]
- 2) Planar Two-Loop Five-Parton Amplitudes from Numerical Unitarity [JHEP **1811**, 116 (2018)]
- 3) Analytic Form of the Planar Two-Loop Five-Parton Scattering Amplitudes in QCD [JHEP **1905**, 084 (2019)]

Additional publications may appear in the coming months.

I acknowledge that Vasily's contributions to the papers were very significant and he clearly qualifies as a main author.

Furthermore, I confirm the presentation of Vasily's contributions in the attached statement "Proposal for Cumulative Thesis" submitted by Vasily.

Best wishes,

Fernando Febres Cordero

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**Vasiliy's papers**

2 messages

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**Samuel Abreu** <abreusamuel@gmail.com>  
To: Harald Ita <harald.ita@physik.uni-freiburg.de>

Wed, Jun 19, 2019 at 8:38 PM

Dear Harald,

Vasiliy Sotnikov was a coauthor in the papers:

- 1) Planar Two-Loop Five-Parton Amplitudes from Numerical Unitarity [JHEP **1811**, 116 (2018)]
- 2) Analytic Form of the Planar Two-Loop Five-Parton Scattering Amplitudes in QCD [JHEP **1905**, 084 (2019)]

In both cases he made a significant contribution to the work presented and was one of the main authors of the papers.

Best regards,  
Samuel

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**H Ita** <harald.ita@physik.uni-freiburg.de>  
To: Samuel Abreu <abreusamuel@gmail.com>

Thu, Jun 20, 2019 at 1:59 PM

Thanks!  
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**Authorship of the paper: [JHEP 1905, 084 (2019)]**

2 messages

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**Jerry** <jerry.dormans@physik.uni-freiburg.de>

Thu, Jun 20, 2019 at 11:21 AM

To: H Ita &lt;harald.ita@physik.uni-freiburg.de&gt;

Cc: Vasily Sotnikov &lt;vasily.sotnikov@physik.uni-freiburg.de&gt;

Dear Harald,

I am sending this email to confirm that Vasily Sotnikov has been a co-author on the paper

Analytic Form of the Planar Two-Loop Five-Parton Scattering Amplitudes in QCD [JHEP **1905**, 084 (2019)].

Furthermore, I acknowledge that he has contributed a significant amount of the work necessary to compute the results presented in the above mentioned paper and as such is a main author of the publication.

Best regards,  
Jerry Dormans

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**H Ita** <harald.ita@physik.uni-freiburg.de>

Thu, Jun 20, 2019 at 1:58 PM

To: Jerry &lt;jerry.dormans@physik.uni-freiburg.de&gt;

thanks. --H.

[Quoted text hidden]

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**Co-Author Attestation.**

2 messages

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**Ben Page** <ben.page@physik.uni-freiburg.de>  
To: H Ita <harald.ita@physik.uni-freiburg.de>

Thu, Jun 20, 2019 at 2:07 PM

Dear Professor Ita,

I write to confirm the co-authorship of Vasily Sotnikov in the papers, "Planar Two-Loop Five-Parton Amplitudes from Numerical Unitarity" published in [JHEP **1811**, 116 (2018)] and "Analytic Form of the Planar Two-Loop Five-Parton Scattering Amplitudes in QCD" published in [JHEP **1905**, 084 (2019)]. Furthermore, I affirm that the contribution made by Vasily was significant and that he is a main author of these two papers.

Best regards,

Ben Page

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**H Ita** <harald.ita@physik.uni-freiburg.de>  
To: Ben Page <ben.page@physik.uni-freiburg.de>

Thu, Jun 20, 2019 at 2:17 PM

Thanks!

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