High Precision for Hard Processes (HP2 2024)

Tuesday, 10 September 2024 - Friday, 13 September 2024

Book of Abstracts

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Methods for amplitudes and integrals / **2**

Master integrals for three-loop Higgs plus jet production

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I will present novel results for non-planar three-loop four-point Feynman integrals with one off-shell leg. The talk will cover various integration techniques, as well as observations on the function space. As a first application, I present an analytic result for a form factor of a local composite operator in maximally supersymmetric Yang-Mills theory.

Methods for amplitudes and integrals / **3**

Integrated Unitarity for Scattering Amplitudes

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We present a new method for computing multi-loop scattering amplitudes in Quantum Field Theory (arXiv:2403.18047). It extends the Generalized Unitarity method by constraining not only the integrand of the amplitude but also its full integrated form. Our approach exploits the relation between cuts and discontinuities of the amplitude. Explicitly, by the virtue of analyticity and unitarity of the S-matrix, the amplitude can be expressed in terms of lower-loop on-shell amplitudes dispersively integrated along cuts. As both cuts and discontinuities can be computed systematically in dimensional regularization, we validated our method by reproducing the four-gluon amplitude in two-loop massless Quantum Chromodynamics. Moreover, since our approach improves the performance of the calculation, we provide a new result for the four-loop four-point massless planar ladder Feynman integral. It is expressed in terms of Harmonic Polylogarithms with letters 0 and 1.

Plenary / **4**

Towards a fully general subtraction scheme: nested soft-collinear 2.0

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In this talk I will present recent progress in the generalisation of the nested soft-collinear subtraction scheme to multi-parton final state processes. The scheme has already been successfully applied to scatterings involving a limited number of coloured partons, and it has shown remarkable flexibility and good numerical performances. I will discuss how to overcome the difficulties that arise from going beyond the previous implementations, and the crucial ingredients to tackle hadron-hadron scattering into arbitrary final states at next-to-next-to-leading order in QCD.

Resummation, Parton Showers and Monte-Carlo / **5**

Heavy quarks' mass corrections to threshold resummation

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Perturbative calculations for processes that involve heavy flavours can be performed in two approaches: the massive scheme and the massless one. The former enables one to fully account for the heavy-quark kinematics, while the latter allows one to resum potentially-large mass logarithms. Furthermore, the two schemes can be combined to take advantage of the virtues of each of them. Both massive and massless calculations can be supplemented by soft-gluon resummation. However matching between massive and massless resummed calculations is difficult, essentially because of the non-commutativity of the soft and massless limits. In this talk, I will present a formalism to combine massive and massless resummed calculations. Our result consists of an all-order expression that consistently resums both mass and soft logarithms to next-to-leading logarithmic accuracy. Finally, I will comment on the phenomenological impact of these findings, presenting a comparison between our calculations and experimental data for heavy flavour fragmentation.

Electroweak and Higgs Physics, EFT and BSM / **6**

Two-loop mixed QCD-EW corrections to charged-current Drell-Yan

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The charged current Drell-Yan process plays a crucial role at hadron colliders since it provides the environment for a precise study of the gauge sector of the Standard Model and, in particular, for the determination of the W-boson mass. In this talk, we will present our recent computation of the mixed QCD-EW two-loop virtual amplitudes for this process, which constitute one of the main bottlenecks for the complete calculation of NNLO mixed QCD-EW corrections. We present the details of our calculation, performed via semi-analytical methods, with an emphasis on the evaluation of all the relevant two-loop Feynman integrals where the presence of one additional mass, compared to the neutral current case, makes the computation extremely challenging.

Plenary / **7**

Heavy Quark Fragmentation in e+e- Collisions to NNLO+NNLL Accuracy in Perturbative QCD

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Fragmentation of heavy quarks into heavy-flavoured hadrons receives both perturbative and non-perturbative contributions. We consider perturbative QCD corrections to heavy quark production

in e^+e^- collisions to next-to-next-to-leading order accuracy in QCD with next-to-next-to-leading-logarithmic resummation of quasi-collinear and soft emissions.

We study multiple matching schemes, and multiple regularisations of the soft resummation, and observe a significant dependence of the perturbative results on these ingredients, suggesting that NNLO+NNLL perturbative accuracy may not lead to real gains unless the interface with non-perturbative physics is properly analysed.

We confirm previous evidence that D^{*+} experimental data from CLEO/BELLE and from LEP are not reconcilable with perturbative predictions employing standard DGLAP evolution.

We extract non-perturbative contributions from e^+e^- experimental data for both D and B meson fragmentation. Such contributions can be used to predict heavy-quark fragmentation in other processes, e.g. DIS and proton-proton collisions.

Plenary / **8**

QCD splitting functions at four loops

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We present computations of the even-N moments of the flavour-singlet four-loop splitting functions to N=20. These results, obtained using off-shell operator matrix elements (OMEs). We construct approximations based on our moments for the OMEs and endpoint constraints. These approximations facilitate an approximate N3LO evolution of parton distributions which are sufficiently accurate for parton momentum fractions accessible at current colliders.

Electroweak and Higgs Physics, EFT and BSM / **9**

AsyInt for massive two-loop four-point integrals at high energies

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In this talk, I will present analytic techniques for massive two-loop four-point Feynman integrals at high energies and the toolbox AsyInt. In the high-energy region, the Feynman integrals involving massive particles, such as the top quark, Higgs and vector bosons, can be asymptotically expanded and directly calculated in the small-mass limit. With AsyInt, analytic results for higher-order terms in the expansion parameter and the dimensional regulator can be obtained.

Precision QCD corrections / **10**

Three-loop amplitudes for V+jet and H+jet production

Authors: Cesare Carlo Mella[1]; Johannes Henn[2]; Lorenzo Tancredi[1]; Nikolaos Syrrakos[1]; Petr Jakubčík[3]; Thomas Gehrmann[4]; William Torres Bobadilla[5]; Won Lim[2]

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I will present recent results for three-loop amplitudes with one off-shell and three on-shell legs, relevant for V+jet and H+jet production in hadron colliders at N3LO in QCD.

Plenary / **11**

The NNPDF4.0 aN^{3}LO Parton Distributions

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We extend the existing next-to-next-to-leading order (NNLO) NNPDF4.0 sets of parton distribution functions (PDFs) to approximate next-to-next-to-next-to-leading order (aN^{3}LO).
We construct an approximation to the N3LO splitting functions that includes all available partial information from both fixed-order computations and from small and large x resummation, and estimate the uncertainty on this approximation by varying the set of basis functions used to construct the approximation. We include known N3LO corrections to deep-inelastic scattering structure functions and extend the FONLL general-mass scheme to $\mathcal{O}(\alpha_s^3)$ accuracy.
We determine a set of aN^{3}LO PDFs by accounting both for the uncertainty on splitting functions due to the incomplete knowledge of N3LO terms, and to the uncertainty related to missing higher corrections (MHOU), estimated by scale variation, through a theory covariance matrix formalism. We assess the perturbative stability of the resulting PDFs, we study the impact of MHOUs on them, and we compare our results to the aN^{3}LO PDFs from the MSHT group. We examine the phenomenological impact of aN^{3}LO corrections on parton luminosities at the LHC, and give a first assessment of the impact of aN^{3}LO PDFs on the Higgs and Drell-Yan total production cross-sections.
We find that the aN^{3}LO NNPDF4.0 PDFs are consistent within uncertainties with their NNLO counterparts, that they improve the description of the global dataset and the perturbative convergence of Higgs and Drell-Yan cross-sections, and that MHOUs on PDFs decrease substantially with the increase of perturbative order.

Plenary / **12**

Semi-Inclusive DIS at NNLO in QCD

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We present the first results for the next-to-next-to leading order (NNLO) corrections to the semi-inclusive deep-inelastic scattering process in perturbative quantum chromodynamics. We consider scattering with polarized and unpolarized protons and obtain the complete contributions analytically for all parton channels. All relevant virtual and real emission Feynman diagrams have been computed using integration-by-parts reduction to master integrals and two approaches for their subsequent evaluation (parametric phase-space integration and method of differential equations). The numerical analysis demonstrates the significance of the NNLO corrections and their great impact on the reduction of the residual scale dependence.

Precision QCD corrections / **13**

Energy-Energy Correlation in the back-to-back region at N^3LL+NNLO in QCD

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We consider the Energy-Energy Correlation function in electron-positron annihilation to hadrons. We concentrate on the back-to-back region, performing all-order resummation of the logarithmically enhanced contributions in QCD perturbation theory, up to next-to-next-to-next-to-leading logarithmic (N^3LL) accuracy. Away from the back-to-back region, we consistently combine resummed predictions with the known fixed-order results up to next-to-next-to-leading order (NNLO). All perturbative terms up to order α_S^3 are included in our calculation, which exactly reproduces, after integration over the angular separation variable, the next-to-next-to-next-to-leading order (N^3LO) result for the total cross section. We regularize the Landau singularity of the QCD coupling within the so-called Minimal Prescription. We exhibit and discuss the reduction of the perturbative scale dependence of distributions at higher orders, as a means to estimate the corresponding residual perturbative uncertainty. We finally present an illustrative comparison with LEP data.

Electroweak and Higgs Physics, EFT and BSM / **14**

On the Electron Self-Energy to Three Loops in Quantum Electrodynamics

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We report on the analytic calculation of the Electron Self Energy in Quantum Electrodynamics at three loops. Feynman integrals appearing in the problem are evaluated via the method of differential equations. In particoular, we will discuss how to cast the system of differential equations – including elliptic secrors – in an eps-factorized form via suitable transformation(s), thus (almost) trivializing the solution.

This is work in progress in collaboration with Claude Duhr, Christoph Nega, Lorenzo Tancredi and Stefan Weinzierl.

Resummation, Parton Showers and Monte-Carlo / 16

Resonance-aware NLOPS matching for off-shell top-pair plus tW production with semileptonic decays

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The increasingly high accuracy of top-quark studies at the LHC calls for a theoretical description of $t\bar{t}$ production and decay in terms of exact matrix elements for the full $2 \to 6$ process that includes the off-shell production and the chain decays of $t\bar{t}$ and tW intermediate states, together with their quantum interference. Corresponding NLO QCD calculations matched to parton showers are available for the case of dileptonic channels and are implemented in the bb4l Monte Carlo generator, which is based on the resonance-aware POWHEG method. In this talk, I present the first NLOPS predictions of this kind for the case of semileptonic channels. In this context, the interplay of off-shell $t\bar{t}$ + tW production with various other QCD and electroweak subprocesses that yield the same semileptonic final state is discussed in detail. On the technical side, we improve the resonance-aware POWHEG procedure by means of new resonance histories based on matrix elements, which enable a realistic separation of $t\bar{t}$ and tW contributions. Moreover, I introduce a general approach which makes it possible to avoid certain spurious terms that arise from the perturbative expansion of decay widths in any off-shell higher-order calculation, and which are large enough to jeopardise physical finite-width effects. Presented results and simulation tools will be of paramount importance for future precision top-quark studies and for the modelling of irreducible backgrounds in BSM searches.

Resummation, Parton Showers and Monte-Carlo / 17

Open bottom production at hadron colliders at NNLO+NNLL

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In this talk, I will present the first calculation of open bottom production at hadron colliders at NNLO+NNLL, i.e. a next-to-next-to-leading-order calculation that resums collinear mass logarithms at next-to-next-to-leading-logarithmic accuracy. This new computation achieves significantly reduced scale uncertainties compared to previous calculations, with errors of just a few percent at high transverse momenta. I will explain how two separate calculations, one with $n_f = 4$ and one with $n_f = 5$, are combined and matched to obtain the final NNLO+NNLL result. To perform comparisons to data, the hadronisation and decay of the b-quark is included in the theory calculation where needed, yielding predictions for a wide range of final states.

Plenary / 18

Parton Showers with higher logarithmic accuracy

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Parton shower event generators are essential tools for establishing the quantitative connection between theory and experiment. However, their flexibility comes with a trade-off: they generally offer lower formal accuracy compared to state-of-the-art analytic calculations, which in turn have more limited applicability. The poor accuracy of the inevitably employed parton shower generators introduces systematic uncertainties that affect all measurements at colliders. In this talk, I will discuss the efforts made by the PanScales collaboration to improve the logarithmic accuracy of parton showers. Until recently, this accuracy was limited to the leading logarithms. Specifically, I will demonstrate how we can achieve Next-to-Leading Logarithm (NLL) accuracy. Furthermore, I will explore advancements beyond NLL. These developments are crucial for refining our understanding of fundamental particle interactions and reducing uncertainties in present and future collider measurements.

Precision QCD corrections / **19**

NNLO+PS predictions for Z boson production in association with b-jets at the LHC

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We present the first NNLO-accurate event generation for Z boson production in association with a bottom-quark pair. This is achieved by matching the NNLO calculation in the 4FS to a parton shower within the MiNNLO method, which we extend to accommodate the class of processes with a color singlet and a heavy-quark pair in the final state. We find that NNLO corrections to $Zb\bar{b}$ production are large and remarkably reduce the tension between 4FS predictions and Z+b-jet ATLAS and CMS measurements. The long-standing discrepancy between 4FS and 5FS predictions is therefore largely alleviated.

Methods for amplitudes and integrals / **20**

Minimal set of variables and high-energy building blocks at high multiplicity

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Extending the BFKL program beyond next-to-leading logarithms requires high-multiplicity central-emission vertices (CEV) and peripheral emission vertices (PEV). In this talk, I discuss how to conveniently extract these building blocks at tree level from amplitudes in general kinematics using a suitable (minimal) set of kinematic variables. Specifically, we determine all quark and gluon emission vertices with up to four partons in the final state and show how analytic expressions free of spurious poles can be obtained. We then analyse the properties of these emission vertices, demonstrate their factorization into lower-point vertices in soft and collinear limits and in further high-energy limits. Finally, we study additional identities satisfied by the set of PEVs and CEVs, including the photon decoupling identity, Kleiss-Kuijf relations, and SUSY Ward identities.

Electroweak and Higgs Physics, EFT and BSM / 21

High precision in Drell-Yan and electroweak input schemes

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At hadronic colliders, the Drell-Yan processes are crucial for testing the Standard Model via the template-fit determination of electroweak parameters, such as the W-boson mass and the weak mixing angle. Monte Carlo event generators play an important role to provide reliable templates for such measurements.
The Z_ew-BMNNPV code is dedicated to the simulation of neutral-current Drell-Yan in the POWHEG-BOX framework, delivering NLO QCD plus NLO EW accuracy with exact matching to QCD and QED parton showers. The most recent updates to the code are here presented: in particular, we discuss the implementation of several options for the electroweak input-parameter and renormalization schemes, e.g. the ones with the weak mixing angle in its effective or MSbar definition as input, which allow the high-precision determination of this parameter at hadron colliders. We provide a critical comparison among the predictions obtained within different schemes and quantify the related theoretical uncertainties.

Resummation, Parton Showers and Monte-Carlo / 22

RG-improved resummation of super-leading logarithms

Authors: Matthias Neubert[1]; Michel Stillger[2]; Patrick Hager[2]; Philipp Böer[2]; Xiaofeng Xu[2]

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The higher-order behavior of logarithmically enhanced contributions in non-global LHC observables is very intricate, in particular as double-logarithmic corrections – so-called super-leading logarithms (SLLs) – arise first at high orders in perturbation theory.
Their all-order resummation has been understood recently by means of a factorization formula in soft-collinear EFT.
In this talk, I will discuss improvements in the resummation of SLLs, including a renormalization-group treatment with a running coupling constant, as well as corrections from higher-order Glauber exchanges.

Electroweak and Higgs Physics, EFT and BSM / 23

Analytic results for double Higgs production at the LHC

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In this talk I will present recent efforts to calculate analytic results for double Higgs production at the LHC, concentrating on the virtual corrections to the gluon fusion channel.
On the one hand, I will report on recent results on electro-weak corrections to this process.
On the other hand, the extension of the calculation to NNLO QCD corrections is discussed.
Our methods are based on analytic expansions in forward kinematics and the high-energy limit, which can be effectively matched to cover the whole kinematic region of the process.
The results are important for the precise determination of the Higgs self coupling in the future, but are also applicable to a wide range of other collider signatures.

Methods for amplitudes and integrals / **24**

Analytic Waveforms in General Relativity from Scattering Amplitudes

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The remarkable detection of gravitational waves (GWs) by Ligo-Virgo-Kagra interferometers has opened the new era of multimessenger astrophysics. An analytic understanding of GWs waveform allows us to construct precise GWs templates, which are needed to detect signals via matched filtering analyses.
In this talk, I will combine the observable-based formalism (KMOC), the analytic properties of scattering amplitudes, generalised unitarity and the heavy mass expansion with a newly introduced IBP reduction for Fourier integrals, to provide an efficient framework for computing scattering waveforms. Such properties are based on a recent understanding of frequency space waveforms as twisted period integrals, which can be studied using Twisted Cohomology. Using these techniques, we were able to derive for the first time the analytic expression for the next-to-leading-order (NLO) waveform in General Relativity.

Electroweak and Higgs Physics, EFT and BSM / **25**

Electroweak logarithms in OpenLoops

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I will present a fully automated implementation of next-to-leading order electroweak (NLO EW) corrections in the logarithmic Sudakov approximation in OpenLoops. For energies above the electroweak scale, NLO EW corrections are logarithmically enhanced and for tails of kinematic distributions of crucial LHC processes yield correction factors of several tens of percent. The considered Sudakov approximation reproduces the full one-loop result at the percent level, while retaining tree-level computing complexity. The presented implementation relies on an efficient representation of the Denner-Pozzorini algorithm in terms of an effective vertex approach. The implementation is model independent, supports the computation of EW corrections to resonant processes, as well as to VBF/VBS-topologies, and is suitable for extensions to the two-loop NNLO EW level.

Electroweak and Higgs Physics, EFT and BSM / 26

Anomalous Couplings in Higgs plus Jet Production

Authors: Benjamin Campillo[1]; Gudrun Heinrich[2]; Lucas Kunz[1]; Matthias Kerner[1]

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We present NLO QCD results for Higgs boson production in association with one jet, including anomalous Higgs-top and Higgs-gluon couplings, and with full top quark mass dependence. We will compare the full theory with varied anomalous couplings to the Standard Model. Of special interest will be the $p_{T,H}$ distribution, since the high $p_{T,H}$ tail is sensitive to heavy new physics.

Electroweak and Higgs Physics, EFT and BSM / 27

NLO corrections to tri-boson production in the WZjj channel

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Tri-boson production, together with vector-boson scattering and Higgs-strahlung, is a privileged channel to study the EW structure of the Standard Model. Upcoming LHC running stages will soon allow to measure them at unprecedented accuracy and for all possible final states, which requires to push theory predictions to still unexplored frontiers.
In this talk I will present the first calculation for the process pp → μ+μ−e+νe j j at the LHC in a tri-boson phase space. All LO contributions have been accounted for, namely the O(α^6), which contains the genuine tri-boson signature, and the O(αs α^5) and O(αs^2 α^4), together with the two O(α^7) and O(αs α^6) NLO corrections. After having discussed some technical aspects of the computation, I will show some phenomenologically relevant results for the integrated and differential cross-sections.

Methods for amplitudes and integrals / 29

Five-parton scattering in the high-energy limit

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The availability of high-multiplicity multi-loop scattering amplitudes in QCD provides invaluable data for studying the theory under special kinematic configurations. Recent calculations of two-loop full-colour QCD amplitudes for the scattering of five partons have enabled us to explore their high-energy limit, known as Multi-Regge Kinematics (MRK). In this limit, a universal factorisation pattern is expected for the amplitude. However, starting at the next-to-next-to-leading logarithmic order (NNLL), the exchange of multiple reggeons (MR) disrupts this factorisation.

In this talk, I will first review the effective theory that accurately describes the high-energy limit and how it predicts the MR contributions. Once the latter are properly accounted for, the universal

factorisation pattern is restored. This restoration allowed us to extract a fundamental ingredient for the factorisation at NNLL: the Lipatov vertex at two-loop order. I will also delve into various technical details of how this calculation was carried out.

Plenary / 30

Exploring High-Purity Multiparton Scattering at Hadron Colliders

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In this talk I present a strategy to optimally disentangle multi-parton interactions from the primary scattering in a collision. The strategy enables probes of multi-parton interactions significantly beyond the state of the art, including their characteristic momentum scale, the interconnection between primary and secondary scatters, and the pattern of three and potentially even more simultaneous hard scatterings. This opens a path to powerful new constraints on multi-parton interactions for LHC phenomenology and to the investigation of their rich field-theoretical structure.

Plenary / 31

Expansions for multi-scale two-loop processes

Author: Ramona Groeber[1]

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I will show how expansion methods can be used to analytically evaluate multi-scale gluon fusion processes at two-loop order. In particular, an expansion for small transverse momentum covers most of the phase space for the gg-> ZZ, gg-> HZ and gg-> HH processes. When combined with a high-energy expansion the whole phase space is covered. Since this approach allows to express the amplitudes analytically, the results can be easily implemented into flexible Monte Carlo codes.

Electroweak and Higgs Physics, EFT and BSM / 32

Precision predictions in the gauge and scalar sectors of the super weak extension of the standard model

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The superweak (SW) force is a minimal, anomaly-free U(1) extension of the standard model (SM) with a complex scalar and three sterile right-handed neutrions. The SWSM is designed to explain

the origin of (i) neutrino masses and mixing matrix elements, (ii) dark matter, (iii) cosmic inflation, (iv) stabilization of the electroweak vacuum and (v) leptogenesis. In this talk we present precision predictions including quantum corrections in the gauge and scalar sectors of such U(1) extensions in general. We apply such predictions in the SWSM to constrain the parameter space in the gauge and scalar sectors of the model. Talk based primarily on papers 2204.07100, 2305.11931 and 2402.14786, all published in Physical Review D.

Plenary Stefano Catani / 33

Catani's collinear factorisation to all perturbative orders in QCD

Author: Prasanna Kumar Dhani[1]

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We consider the most general factorisation properties of scattering amplitudes in perturbative QCD in both collinear and collinear-soft limits. While scattering amplitudes obey strict collinear factorisation (SCF) in the time-like collinear region to all perturbative orders, SCF is known to break in the so-called space-like region. We generalise previously known results of SCF breaking to more than one collinear direction. We also extend our analysis to the simultaneous collinear-soft factorisation.

Plenary Stefano Catani / 34

The solution is in the vacuum

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The artificial separation between loop and tree-level contributions is at the origin of many technical difficulties in quantum field theory at high perturbative orders. The original motivation for the loop-tree duality (LTD), as explained in the seminal paper by Stefano Catani, was to circumvent this separation by opening the loops to tree-level objects in such a way that both contributions would be treated on the same footing. One of the unexpected properties of LTD is that the integrand of scattering amplitudes becomes manifestly causal. By exploiting this physically motivated property, we propose vacuum amplitudes in LTD as the optimal building blocks to assemble theoretical predictions at colliders.

Methods for amplitudes and integrals / 35

The next major release of Kira

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The reduction of Feynman integrals to a basis of master integrals plays a crucial role for many high-precision calculations and Kira is one of the leading tools for this task. Recently, we achieved significant performance improvements. In this talk we discuss those and some of the new features for the next major release.

Resummation, Parton Showers and Monte-Carlo / 36

Towards subleading power factorisation

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Calculations in perturbative QCD suffer from large logarithms that appear at all orders in the perturbation theory, endangering the perturbative description. In pursuit of precise predictions for (differential) cross sections, factorisation theorems have been established with the benefit to sum these large logarithms to all orders in perturbation theory, improving the predictive power of the theory. This procedure is well-understood at leading power in these large logarithms, but much work is still to be done at next-to-leading power (NLP). By extending known methods to resum the leading logarithm at NLP for single differential cross sections, I will show that one can compute leading logarithmic resummed cross sections differential in both a threshold variable (i.e. the limit where the radiation has little energy) and the rapidity of a final state particle. To improve these resummation formulas beyond the leading logarithm, further study needs to be done. For this purpose, I will introduce new jet functions that contribute to this subleading power behaviour. We check these definitions up to two loop against the region expansion of the QED form factor.

Resummation, Parton Showers and Monte-Carlo / 37

Crossing heavy-flavour thresholds in Fragmentation Functions

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Time-like matching threshold conditions are an ingredient of the DGLAP evolution for Fragmentation Functions in the Variable-Flavour-Number-Scheme. We introduce the theoretical framework by revising the next-to-leading order derivation. An extension of the formalism in electron-positron annihilation is derived at next-to-next-to leading order (NNLO) accuracy. We present an analytical form of the matching condition for light-flavour to hadron Fragmentation Function at NNLO. Outlooks regarding the missing NNLO threshold conditions are discussed.
Based on arXiv:2407.07623 in collaboration with Leonardo Bonino (UZH).

Electroweak and Higgs Physics, EFT and BSM / **38**

Light by Light Scattering at NLO in QCD+QED

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In this talk I plan to discuss the QCD+QED corrections to Light by Light scattering (LbL) process at next-to-leading order (NLO). The recent experimental observation of this fundamental process at the Large Hadron Collider has revived the interest to precisely predict its cross-section. We discuss two radically different computational approaches, both exact in the fermion mass dependence, thus offering a strong cross-check of our results. The first approach is a fully analytic method to calculate compact and well-organized two-loop helicity amplitudes. The second one is entirely numerical and leverages the Local Unitarity construction. Our two calculations agree with each other and conclude that including the exact fermion mass contribution typically increases the size of the NLO corrections. Moreover, we find that the exact result converges slowly to the massless limit of the high-energy regime, thus emphasizing the importance of including the full mass dependence at NLO. We also compare our results with the ATLAS measurement of LbL in ultra-peripheral lead-lead collisions, and find that the inclusion of exact NLO corrections reduces, but does not eliminate, the existing tension with theoretical predictions.

Resummation, Parton Showers and Monte-Carlo / **39**

Matching NLO calculations with NLL Panscales showers with initial-state partons

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The matching between fixed-order calculations and parton shower simulations represents one of the key building blocks for the construction of accurate and fully-differential predictions at colliders. While NLO matching with leading logarithmic accurate parton showers has been a solved problem for many years, there is currently no standard matching procedure with next-to-logarithmic (NLL) accurate showers. In this talk, I will present how to obtain NLO accurate predictions matched to NLL PanScales parton showers with efficient and positive-definite techniques for deep inelastic scattering and colour-singlet production in hadron collisions. Such a matching is a fundamental ingredient for the formulation of next-to-NLL showers.

Precision QCD corrections / **40**

NNLO Predictions for Tribosons Processes at the LHC

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Diboson processes being the key to study the electroweak triple gauge-boson couplings, triboson processes pave the way to investigate the quartic. Moreover, with leptonic decay products from multiple gauge bosons, they provide dominant backgrounds to many New Physics searches. With the increasing statistics collected by the LHC, and in particular in view of the HL-LHC running phase, precise predictions beyond the present NLO results are required to make the best out of the measurements. Exact two-loop amplitudes being yet unknown for triboson processes beyond triphoton production, a suitable estimation of these contributions is required. Studies on diboson production, where exact amplitudes are available, give us confidence on the applicability of this procedure and the robustness of our related error estimates. This approach allows us to present first differential predictions for triboson processes, together with their leptonic decay modes, that may be claimed to be NNLO-accurate.

Subtraction, slicing and loop/tree duality / **41**

Antenna subtraction for processes with identified particles at hadron colliders

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Precise theoretical predictions for observables with identified hadrons at hadron colliders are essential to understand how partons fragment into hadrons. The hadronization process is parametrized by process-independent fragmentation functions that encode the parton-to-hadron transition. To incorporate hadron fragmentation in higher-order QCD calculations requires a subtraction method to account for final-state collinear radiation associated with the fragmenting parton. To this aim we have extended the antenna subtraction method to hadron fragmentation processes with hadronic initial states at next-to-next-to-leading order (NNLO) in perturbative QCD. In this talk we describe the calculation of the full set of integrated antenna functions in initial-final fragmentation kinematics and their combination with mass-factorization counterterms. These results pave the way towards precise predictions for observables with identified hadrons at the LHC.

Methods for amplitudes and integrals / **42**

Decomposing Feynman integrals with intersection numbers

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Co-authors: Giacomo Brunello [1]; Giulio Crisanti [2]; Hjalte Axel Frellesvig [3]; Manoj Kumar Mandal [1]; Pierpaolo Mastrolia [1]

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We present a novel, simplified formulation of the recursive algorithm for evaluating intersection numbers of differential forms. This approach is

applied to derive the complete decomposition of two-loop planar and non-planar Feynman integrals in terms of a master integral basis.

The new algorithm extensively utilizes various emerging tensor structures derived from the polynomial division technique and local solutions to system of differential equations, facilitating efficient computer implementation. Additionally, we employ delta-forms as generators of relative twisted cohomology groups, which allows us to bypass the usage of analytic regulators.

More generally, this algorithm can be applied to derive relations among twisted period integrals relevant for physics and mathematical studies.

Plenary Stefano Catani / **43**

Precise predictions for ttH production at the LHC

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The top quark plays a pivotal role in particle physics, providing a powerful tool to test the SM and physics beyond it. Indeed, its large mass, near the electroweak scale, enables a detailed scrutiny of its interactions with the Higgs and electroweak bosons. Although its total rate is only few percent of the dominant Higgs production mode via gluon fusion, the hadroproduction of a top–antitop pair in association with a Higgs boson ($t\bar{t}H$) is crucial since it provides a direct access to the top Yukawa coupling. Given the precise experimental measurements expected at the HL-LHC, improving the accuracy of the corresponding theoretical predictions is of high priority.

In this talk we will present NNLO results in QCD, obtained by relying on the q_T-subtraction formalism for the treatment of infrared singularities arising at the intermediate stages of the calculation. A crucial ingredient are the relevant two-loop scattering amplitudes. The exact two-loop amplitudes being currently out of reach, we rely on physically motivated and reasonable approximations for this part of the calculation. Beyond our previously published results for the total cross section at NNLO, we will present a more sophisticated procedure, based on the combination of a soft-boson approximation and massification approach. We will also include the full tower of NLO EW corrections, thus providing the best theoretical prediction for $t\bar{t}H$ production up to date. Results for the total cross section as well as for several phenomenologically relevant distributions will be discussed.

Subtraction, slicing and loop/tree duality / **44**

Unresolved limits of polarised matrix elements

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NNLO calculations in QCD require an analytic understanding of the infrared singular structure involving up to two unresolved partons. Up to now this was achieved only for unpolarized matrix elements. We report on the progress on the calculation of splitting amplitudes arising in longitudinally

polarised QCD matrix elements at NNLO in the Larin γ_5 scheme. They are derived from DIS-like processes and verified in matrix elements of higher multiplicity. Our results will enable the calculation of NNLO corrections to longitudinal spin asymmetries in polarized collider processes.

Subtraction, slicing and loop/tree duality / **45**

Antenna Subtraction beyond NNLO

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In this talk I discuss the extension of the well-established antenna subtraction method beyond next-to-next-to-leading order in perturbative QCD. The definition of N3LO antenna functions for final-state radiation and their analytical integration are briefly reviewed. Subsequently, I analyse the structure of the subtraction terms needed to remove infrared singularities at N3LO in the context of low-multiplicity processes. Finally, I discuss future phenomenological applications.

Precision QCD corrections / **46**

Towards a numerical evaluation of $q\bar{q} \to t\bar{t}H$ at two loops

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We present progress on the calculation of the virtual NNLO corrections to $t\bar{t}H$ production in the qq-channel. We focus on the numerical evaluation of the master integrals with pySecDec, and the associated challenge of constructing a grid for a 5-point amplitude.

Methods for amplitudes and integrals / **47**

Polytope symmetries of Feynman integrals

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Feynman integrals can be evaluated in terms of generalized hypergeometric series known as A-hypergeometric functions, which were proposed by Gel'fand-Kapranov-Zelevinsky (GKZ) as a unified approach to hypergeometric functions. Among the properties of A-hypergeometric functions are symmetries associated with the Newton polytope. In ordinary hypergeometric functions these symmetries lead to linear transformations. In this talk, I will show how these lead to symmetries of Feynman integrals in the Lee-Pomeransky representation. Then, I will summarize the symmetries of n-gon integrals up to n=8, massive banana integrals up to 5-loop, and on-shell ladders up to 3-loop. Finally, I will discuss their relevance to finite integrals.

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AsyInt for massive two-loop four-point integrals at high energies

Author: Hantian Zhang[1]

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In this talk, I will present analytic techniques for massive two-loop four-point Feynman integrals at high energies and the toolbox AsyInt. In the high-energy region, the Feynman integrals involving massive particles, such as the top quark, Higgs and vector bosons, can be asymptotically expanded and directly calculated in the small-mass limit. With AsyInt, analytic results for higher-order terms in the expansion parameter and the dimensional regulator can be obtained.

Resummation, Parton Showers and Monte-Carlo / 49

Factorization and resummation for sequential recombination jet cross sections

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We extend the class of factorization theorems for non-global observables from fixed angular constraints to cross sections defined in terms of sequential jet clustering. The associated hard and soft functions depend not only on the directions of the hard partons, but also on their energy fractions. We derive the one-loop anomalous dimension of the hard functions that drives the leading-logarithmic resummation. The anomalous dimension imposes energy ordering, which simplifies the clustering sequence. We perform resummations for gap-between-jet observables defined with different jet algorithms and explain the effects of the clustering on the importance of secondary emissions and on the effective gap size.

Methods for amplitudes and integrals / 50

Three-loop ladder diagrams with two off-shell legs

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In this talk I will present a calculation of the three-loop four-point master integrals. They come from two three-loop ladder diagrams with two off-shell legs that have identical masses. The talk will mainly consist of two sections. First I will demonstrate the construction of a canonical basis and solve the differential equation it fulfills. Then it goes to the discussion of using the symbol technique to simplify the complicated analytic expressions of master integrals.

Subtraction, slicing and loop/tree duality / **51**

The NNLO soft function for N-jettiness in hadronic collisions

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In this talk I'll present our recent work calculating the N-jettiness soft function, based on an extension of the SoftSERVE framework to the general case of N+2 jets and beams for a priori general global observables. I will comment on our approach, present an explicit grid scanning the 2-jettiness soft function, and shed some light on the behaviour of the N-jettiness soft function at the edges of phase space, when two jets/beams become collinear.

Precision QCD corrections / **52**

Complete NLO QCD corrections to ZZ production in gluon fusion

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We present our results for complete next-to-leading order QCD corrections to ZZ production through gluon fusion. We combine the two-loop amplitudes with top quark mass dependence calculated numerically in a previous work with the analytic forms of massless, Higgs-mediated, and one-loop factorisable diagrams to obtain complete virtual corrections. We show that the choice of IR subtraction scheme used for virtuals has a significant impact on their size as well as required precision.

Methods for amplitudes and integrals / **54**

Recent development of NeatIBP

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The Feynman integral is a critical object in quantum field theory. It is very important in high energy physics. The integration-by-parts (IBP) reduction is one of the bottle-neck steps in the evaluation of

multi-loop Feynman integrals. NeatIBP is a program based on the syzygy method of IBP reduction. It generates much smaller sized IBP system compared to traditional Laporta's algorithm. This helps us to reduce the computation cost of IBP reduction. In this talk, we will present the recent development and progress of NeatIBP since its last publication. We will introduce new useful features in the new versions of NeatIBP. These new features include the automated interface with the popular Feynman integral reduction software Kira.

Electroweak and Higgs Physics, EFT and BSM / 55

Yukawa- and Higgs self-coupling corrections to di-Higgs production

Authors: Gudrun Heinrich[1]; Stephen Jones[2]; Matthias Kerner[1]; Tom Stone[2]; Augustin Vestner[1]

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The upcoming HL-LHC phase gives hope to tighten the experimental constraints on one of the core parameters of the SM: the Higgs self-coupling. The most prolific process to consider in this context is double Higgs boson production. Theoretical higher order calculations, both QCD and electro-weak, are required to match the experimental precision.

In this talk we present our calculation of electro-weak NLO contributions comprising Yukawa-type and Higgs self-coupling corrections at two-loop level.

Subtraction, slicing and loop/tree duality / 56

Generalised Antenna Functions for Higher-Order Calculations

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In the past few years, work has been done to construct antenna functions used in the antenna subtraction scheme directly from the limits we want them to have, rather than taking them directly from matrix elements. These "designer" antenna functions introduce fewer spurious singularities, and hence improve the simplicity of subtraction terms, especially at high multiplicity. Here, we report on further work to both construct and integrate generalised antenna functions at NNLO, which further simplifies the subtraction terms, as well as making manifest their algorithmic construction. We also present validation of this "generalised designer antenna" method by comparing to the known calculation of e+e- to 3 jet at NNLO.

Methods for amplitudes and integrals / 57

Tensor Reduction for high-rank multi-loop Integrals

Author: Sam Teale[1]

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A vital step in multi-loop Feynman integral calculations is tensor reduction. We present an efficient graphical approach to this problem and introduce OPITeR a code that implements this method for arbitrary tensor Feynman integrals. OPITeR can handle integrals of arbitrary loop up to tensor rank 20 with any number of spin indices. We present some applications in the context of R* renormalization calculations as well as asymptotic / subgraph expansions in momentum space, where high-rank tensors are frequently encountered.

Precision QCD corrections / **58**

Two-loop QCD amplitudes for $t\bar{t}H$ production from boosted limit

Author: Guoxing Wang[1]

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I will talk about a factorization formula for gauge-theory scattering amplitudes up to two loops in the high-energy boosted limit at leading power, which is then used to give the prediction for the production of a Higgs boson in association with a top-antitop quark pair ($t\bar{t}H$) at next-to-next-to-leading order (NNLO). This process holds significant importance in directly probing the top-quark Yukawa coupling and relates to various fundamental questions in high energy physics. I will focus on the factorization and calculation of two-loop amplitudes for $t\bar{t}H$ production at hadron colliders in the high-energy boosted limit. By combining the contributions from real emissions, our results can be utilized to compute the NNLO differential cross sections for $t\bar{t}H$ production in the high-energy boosted limit. This talk is mainly based on our two recent published papers JHEP 05 (2024) 082 and JHEP 07 (2024) 121.

Resummation, Parton Showers and Monte-Carlo / **59**

Renormalizing Soft-quark Functions and Anomalous Dimensions at Next-to-leading Power

Author: Xing Wang[None]

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Power corrections are crucial for the frontier precision study at colliders, and soft quarks play an important role starting from next-to-leading power. However, renormalizing soft-quark functions and, hence, deriving their anomalous dimensions are hard and have only received progress recently. In this talk, I will show how to renormalize soft-quark functions entering the light-quark-induced Higgs form factor and the Drell-Yan process in position space in a concise way. In particular, I will

also illustrate how to extract UV poles consistently in the context of introducing offshellness-related IR regulators inherited from factorization formulae.

Subtraction, slicing and loop/tree duality / **60**

New tools for N-jettiness computations

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The N-jettiness slicing has been a successful approach for the calculation of cross sections at next-to-next-to-leading order (NNLO) in perturbative QCD, and has a strong potential for computations at the following order. Recently we derived a compact representation of the renormalized N-jettiness soft function free of infrared and collinear divergences through NNLO. The convergence of the N-jettiness scheme can be systematically improved by the addition of power corrections, for which there has been significant interest in understanding the subleading power contributions and their importance.

Methods for amplitudes and integrals / **61**

Two-loop amplitude reduction in the HELAC framework

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I will present recent progress in constructing a generic two-loop amplitude reduction algorithm within the computational framework of HELAC. Following the well-known OPP reduction approach at one loop, a two loop amplitude approach is developed. I will also discuss the differences between the 4-2ε and pure 4 dimensional reduction fitting as well as the implications on the so-called rational terms which incorporate the mismatch between 4 and D = 4-2ε dimensions.

Resummation, Parton Showers and Monte-Carlo / **62**

Towards the Automation of Quarkonium Production Cross Sections with MadGraph

Authors: Ajjath Abdul Hameed[1]; Hua-Sheng SHAO[2]; Lukas Simon[3]

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We introduce a forthcoming extension to MadGraph5_aMC@NLO, enabling the automated computation of cross sections for processes involving quarkonium particles within the non-relativistic QCD (NRQCD) factorization framework. To achieve next-to-leading order (NLO) accuracy in the strong coupling constant α_s, we have refined the FKS subtraction formalism. Our approach is applicable to the production of S- or P-wave quarkonium bound states in association with any number of elementary particles, thereby offering a comprehensive solution for a wide range of scenarios. Key contributions of our work include the derivation of local and integrated soft counterterms specifically designed for colour-singlet and colour-octet P-wave bound states. These advancements are crucial for accurately modeling heavy quarkonium inclusive and associated production processes, thereby enhancing our understanding of quarkonium dynamics in high-energy phenomena.

Methods for amplitudes and integrals / **63**

Calculation of the soft anomalous dimensions with time-like and light-like Wilson lines

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Soft singularities of scattering amplitudes are important for both theoretical and practical reasons. It is well known that these singularities are captured by correlators of Wilson lines which follow the classical trajectory of energetic partons participating in the process and intersect at the hard interaction vertex. Such correlators feature ultraviolet singularities, which allow us to compute the soft anomalous dimension, provided the infrared is regularized. However, while correlators of time-like Wilson lines which intersect each other are multiplicatively renormalizable, strictly light-like Wilson lines feature also collinear singularities and lose multiplicative renormalizability. This feature complicates their regularization and the separation between infrared and ultraviolet singularities. Indeed, the soft anomalous dimensions of massless scattering amplitudes is rather different from that of massive ones, and the relation between them is subtle.
In this talk, I will start from a regularization scheme for time-like Wilson lines, and analyse the limit where some of the Wilson lines become light-like. The method we use is the combination of differential equations and expansion by regions. This provides insight on the non-analytic contributions which distinguish between the complete result and the strict light-like limit (referred to as the 'hard region'). Using a two-loop example I will show that all multiple poles in epsilon present in the strict limit cancel in the sum of regions, leaving behind a single pole, representing the contribution to the soft anomalous dimension. I will then turn to three loops, where I present a calculation of the hard region with one time-like and three light-like Wilson lines.

Precision QCD corrections / **64**

NNNLO zero-jettiness soft function

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We report on computing the NNNLO zero-jettiness QCD soft function, the last missing ingredient required for the first application of the subtraction scheme with jettiness as a slicing variable at the NNNLO level.

Precision QCD corrections / **65**

The Variable Flavor Number Scheme at NNLO and N^{3}LO:

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In this talk, we combine the four-flavor scheme (4FS) and five-flavor scheme (5FS) into a single prediction such that it retains finite mass effects through a certain order in perturbation theory while at the same time resums the collinear logarithms to all orders in the strong coupling constant (α_s). We match the N^{3}LO 5FS result for the neutral-current Drell-Yan process including contributions from both photon and Z-boson exchange, with the NLO 4FS computation where the bottom quark is treated as a massive final-state particle. We also match the NNLO five-flavor scheme result for the charged-current Drell-Yan process in exchange of virtual W^+/W^- boson. In this we account for both massive bottom and charm quarks and hence we match five-flavor scheme results against three-flavour schemes.

Precision QCD corrections / **66**

Quark Mass Effects in Higgs Production

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We examine the effect of finite top- and bottom-quark masses on the Higgs production cross section in the gluon-gluon fusion channel. We employ both $\overline{\text{MS}}$ and on-shell renormalisation for the quark masses and provide a thorough comparison. Furthermore, we explore alternative treatments of quark masses, in particular in the four-flavour scheme, and investigate their impact on the cross section. Our work also presents novel predictions for differential cross sections in the Higgs rapidity. The results lead to a significant reduction of scale uncertainties, and our analysis enables us to offer well-grounded recommendations for future research in this area.

Precision QCD corrections / **67**

Nf-part of the NNLO virtual correction to the production of three massive vector bosons

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I will present our recent calculation of previously unavailable NNLO contributions to electroweak vector boson production. For the first time at two loops, we enable their direct numerical integration by tackling infrared, ultraviolet and threshold singularities simultaneously using local subtractions.

I will discuss our numerical method and describe the next steps towards calculating the full NNLO contribution.

Methods for amplitudes and integrals / 68

On the numerical evaluation of Feynman integrals for higher-order calculations

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We discuss modern techniques for the numerical computation of master integrals as series solutions of differential equations.

Subtraction, slicing and loop/tree duality / 69

A Numerical Implementation of the LASS Subtraction Scheme

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NNLO QCD corrections are indispensable for Today's and tomorrow's colliders. Several subtraction schemes are available in the literature. The LASS (Local Analytic Subtraction Scheme) as it is developed in Turin offers a possible way to obtain NNLO QCD predictions with this version of subtraction. Its simple analytical integrals make it tempting to generalize even to hadron collisions. Before this crucial step a proof-of-concept numerical implementation is needed for electron-positron collisions. In my talk I would like to give highlights of our effort to create the first numerical implementation of the scheme focusing on the contribution with double-parton emission.

Precision QCD corrections / 70

Triple real contributions to zero-jettiness soft function at N3LO

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In this talk, we present some technical details in the calculation of triple real contributions to the zero-jettiness soft function at N3LO. We use extended reverse unitarity to handle Heaviside functions in the integral reduction and compute master integrals by solving differential equations with respect to an auxiliary parameter. Additional complications introduced by the analytic regulator are discussed.

Methods for amplitudes and integrals / **71**

Finite Feynman Integrals in Momentum and Parameter Space

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The infrared structure of scattering amplitudes offers a natural path to organize bases of Feynman integrals according to their divergence properties. In this talk, I will describe two complementary approaches to this organization: an analytic approach that builds upon the theory of Landau singularities in momentum space, and a geometric approach based on the parametric representation of the integral. Focusing on the class of locally finite integrals, I will explore the relationship between these two methods and discuss potential applications of the results.

Resummation, Parton Showers and Monte-Carlo / **72**

Towards an accurate and efficient event generation for multi-jet processes

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We propose an event generation for LHC multi-jet processes (up to 10 external particles) in a two-step procedure based on the colour expansion of the tree-level matrix-element. In this way, in the first step the phase-space integration is performed on the leading-colour accurate expansion of the amplitudes. At this step, we compare several choices of the integration variables. In a second step, the leading-colour accurate events are reweighted to achieve next-to-leading colour accurate and full-colour accurate events. We investigate the efficiency of the various integration variable choices and assess the efficiency of the full picture of generating tree-level events of high multiplicities.

Plenary / **73**

Recent experimental precision measurements at CMS

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Thanks to the increasing amount of data provided by the LHC and the new techniques adopted, experiments are entering the era of precision measurements. The increasing precision of the results allows the standard model of particle physics to be tested more and more thoroughly.
This talk will present recent precision measurements of standard model parameters performed by the CMS collaboration.

Precision QCD corrections / **74**

Higher-order computations for top-quark production at hadron colliders: implications for top-quark mass and PDF fits

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One of the motivations underlying the efforts towards higher-order computations of heavy-flavour production is the possibility to better constrain parton distribution functions as well as heavy-quark mass values. In this contribution we focus on the top-quark case and we discuss the impact of including higher-order corrections to top-antitop and single-top production at hadron colliders on the extraction of tne aforementioned quantities. We discuss in particular our recent extractions of top-quark mass values at fixed (PDFs + alpha_s(M_Z)), considering a number of modern PDF fits, as well as our simultaneous fit of top-quark mass, PDFs and alpha_s(M_Z), using as a basis state-of-the-art collider data on top-quark production compared to NNLO theory predictions. The computation of the latter has been automated through the MATRIX+PineAPPL framework in the case of multi-differential predictions, leading to tables of predictions that can be shared with the collider community and used for any new fit. We also sketch further possible improvements in the theory computations, which would lead to even more precise and accurate PDF and top-quark mass fits.

Plenary / **75**

Feynman Integrals in Parameter Space: Hidden Regions and Contour Deformation

Authors: Anton Olsson[1]; Einan Gardi[2]; Franz Herzog[2]; Stephen Jones[3]; Tom Stone[4]; Yao Ma[5]

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Understanding the singularity structure of Feynman integrals in parameter space is useful both for formulating numerical procedures for their evaluation (e.g. sector decomposition) and for understanding their asymptotic behaviour, as captured by the method of regions. A promising direction of exploration in this regard is the geometric description of Feynman integrals in parameter space.

In this talk, using Landau singularity analysis, we study the appearance of "hidden" regions not associated with endpoint singularities in parameter space, and so not straightforwardly captured by the geometric approach. We demonstrate that in the strict on-shell limit such Landau singularities can prevent the direct numerical evaluation of integrals in parameter space and describe how they can be re-parameterised and dissected to circumvent this problem. Using similar techniques, we demonstrate how knowledge of the variety of the second Symanzik polynomial can be used to obtain strictly positive integrands even in the Minkowski Regime, circumventing the need for contour deformation and significantly improving the numerical performance.

Electroweak and Higgs Physics, EFT and BSM / 76

SIMUnet: an open-source tool for simultaneous global fits of EFT Wilson coefficients and PDFs

Authors: Elie Hammou[1]; James Moore[2]; Luca Mantani[3]; Maeve Madigan[2]; Manuel Morales Alvarado[2]; Maria Ubiali[None]; Mark Costantini[2]; Zahari Kassabov[2]

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We present the open-source SIMUnet code, designed to fit Standard Model Effective Field Theory (SMEFT) Wilson coefficient alongside Parton Distribution Functions (PDFs) of the proton. SIMUnet can perform SMEFT global fits, as well as simultaneous fits of the PDFs and of an arbitrarily large number of SMEFT degrees of freedom, by including both PDF-dependent and PDF-independent observables. SIMUnet can also be used to determine whether the effects of any New Physics models can be fitted away in a global fit of PDFs. SIMUnet is built upon the open-source NNPDF code and is released together with documentation, and tutorials. To illustrate the functionalities of the new tool, we present a new global analysis of the SMEFT Wilson coefficients accounting for their interplay with the PDFs. We increment our previous analysis of the LHC Run II top quark data with both (i) the Higgs production and decay rates data from the LHC, and (ii) the precision electroweak and diboson measurements from LEP and the LHC.

Electroweak and Higgs Physics, EFT and BSM / 77

Two-loop amplitudes for W-boson production in association with two photons at the LHC

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I will present a computation of two-loop amplitudes contributing to W+2 photon production at the Large Hadron Collider. We adopt a hybrid approach where analytic results are derived for the leading colour contribution while the subleading colour amplitudes are evaluated numerically, both within the finite-field framework. The size of subleading colour contribution is studied, by evaluating the amplitudes on a small set of physical phase-space points.

Plenary / **78**

Precise predictions for the EFT

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I will review progress in computation of EFT contributions to LHC processes, including higher order QCD and EW contributions (and their potential automation), as well as the inclusion of renormalisation group effects in the predictions. I will discuss the impact of these corrections for LHC phenomenology with some examples in the top, EW and Higgs sectors

Methods for amplitudes and integrals / **79**

Taming IBPs with Transverse Integration

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Reduction of Feynman integrals to a basis of linearly independent master integrals is a crucial step in any perturbative calculation, but also one of its main bottlenecks. In this talk I will present an improvement over the traditional approach to IBP reduction, that exploits transverse integration identities. Given an integral family to be reduced, the key idea is to find sectors whose corner integrals correspond to either diagrams with fewer external legs or diagrams that can be factorized as products of lower-loop integrals. Then, using transverse integration identities, i.e. a tensor decomposition in the subspace that is transverse to the external momenta of the diagrams, we map integrals belonging to these sectors and their subsectors to (products of) integrals belonging to new and simpler integral families, characterized by either fewer generalized denominators, fewer external invariants, lower loops or combinations thereof. Integral reduction is thus drastically simpler for the newer families. I will include some applications to cutting-edge two-loop families which show significant improvements with respect to traditional methods.

Plenary / **80**

Euler-Mellin-Feynman Integrals and Intersection Theory

Author: Pierpaolo Mastrolia[1]

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I elaborate on the vector space structures of Euler-Mellin-Feynman Integrals, emerging from the application of Intersection Theory of (twisted) De Rahm Co-homology, and discuss the crucial role of the intersection numbers as fundamental mathematical quantities, ruling linear relations (integration-by-parts identities or contiguity relations, differential and difference equations), as well as quadratic relations (Riemann bilinear relations), and higher order relations obeyed by those integrals.
I comment on the correspondence between the vector space of integrals and the D-module structure of the differential operators acting on them.
I report on the methods we introduced for evaluating intersection numbers of differential n-forms, and their application to the direct decomposition of integrals in terms of master integrals, to be considered as the generators of the vector space.
I conclude on the applicability of these novel techniques and ideas in various areas of modern Physics and Mathematics.

Plenary / **81**

NNLO corrections with local subtractions

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We discuss a methodology for calculating second-order cross sections based on the use of local subtractions for soft and collinear singularities and built implementing suitable momentum mappings and well known universal limiting formulae. With appropriate adjustments, it is possible to carry out the analytical calculation of the integrated version of the subtractions, which brings reliable numerical control of predictions.

Subtraction, slicing and loop/tree duality / **82**

Local cancellation of IR singularities: an automated algorithm based on OpenLoops+LTD

Author: Gloria Bertolotti[1]

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We elaborate on the construction of a new automated NLO generator developed within the OpenLoops framework. This new algorithm employs the Loop Tree Duality (LTD) method to achieve the local cancellation of IR singularities by directly combining virtual and real corrections at the integrand level. In this talk we focus on a novel technique that enables local IR cancellations in a general and automated way, and present first numerical results.

Plenary / **83**

Towards an automated generator based on OpenLoops+LTD

Author: Stefano Pozzorini[1]

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We present ongoing work towards the development of an automated NLO generator in the OpenLoops framework. This new algorithm combines key features of the Loop Tree Duality (LTD) and OpenLoops methods. In particular, virtual and real corrections are combined in a way that enables the local cancellation of IR singularities. To this end we introduce a new technique that supports the calculation of IR safe observables in a similarly flexible and automated manner as within state-of-the-art parton-level generators. This new framework will serve as a basis for the development of an automated NNLO generator.

Resummation, Parton Showers and Monte-Carlo / **84**

Sherpa 3.0: status and updates

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Accurate and fully differential predictions are crucial inputs for the precise experimental analyses at collider experiments and are typically provided by parton shower Monte Carlo programs. The event generator Sherpa with its focus on the inclusion of higher-order EW and QCD effects is available in a new version 3.0 this year and we will summarise its new features and current developments for upcoming releases in the near future.

Resummation, Parton Showers and Monte-Carlo / **85**

The QED-MC@NLO method

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As experimental precision continues to improve, it becomes increasingly important for the theory community to incorporate electroweak corrections alongside higher-order QCD effects in our predictions. In this talk, I will introduce the QED-MC@NLO method, which matches a QED parton shower with an NLO electroweak calculation. I will discuss some implementation details and present results from important use cases. Additionally, I will demonstrate how this method extends to combined QCD+EW NLO calculations, matched to an interleaved parton shower.

Plenary / **86**

Overview of ATLAS precision measurements and Monte Carlo generators usage

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Overview of ATLAS precision measurements and Monte Carlo generators usage

Methods for amplitudes and integrals / **87**

Locally finite two-loop amplitudes for multi Higgs production in gluon fusion

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A universal numerical method for computing loop amplitudes would enable precise theoretical predictions for a broad range of phenomenological relevant processes. A major obstacle in developing such methods is the treatment of infrared and ultraviolet singularities, which must be eliminated at the integrand level before numerical integration becomes feasible.
In this talk, I will introduce a framework under development aimed at constructing locally finite two-loop amplitudes for arbitrary process. The framework is based on the universality of infrared singularities, realizing infrared factorization manifestly at the local level. As a specific example, I will explain the construction of locally finite two-loop amplitudes for gluon-fusion processes with an arbitrary number of Higgs final states. We find that infrared singularities reside in simple amplitudes of well-known 2 -> 1 processes. Anticipating the generalization of our method, I will also discuss our progress on more complex QCD processes, which require novel techniques to achieve local Ward identity cancellations of collinear singularities.

Plenary / **88**

Towards Z+jet NNLO event generation matched to parton showers in the GENEVA Monte Carlo

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I will briefly review the GENEVA framework, which combines the resummation of a jet resolution variable
up to N3LL with the NNLO fixed-order corrections into a single event generator, eventually matched to the parton shower.
This provides the highest accuracy in the strong coupling constant at both small and large jet resolution scales.
I will focus on the recent progress and challenges in the implementation of the Z+ jet production and the LHC
and discuss possible developments.

Plenary / **89**

Novel geometric approach to scalar Effective Field Theories

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Geometric formalisms have been long employed to describe QFTs of scalar fields and, in the past few years, they have been successfully applied to the study of SM EFT and Higgs EFTs.
The talk will first give an overview of these methods, highlighting their power and their shortcomings. It will then introduce a novel geometric formalism that aims at resolving some of the latter, which is based on the mathematical notion of jet bundles. The talk is based on 2308.00017 and an upcoming publication

Plenary / **91**

Status and challenges in precision cross section computations

Author: Alexander Yohei Huss[None]

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To be announced

Plenary / **92**

Factorization restoration through Glauber gluons

Author: Thomas Becher[None]

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We analyze the low-energy dynamics of gap-between-jet cross sections at hadron colliders, for which phase factors in the hard amplitudes spoil collinear cancellations and lead to double logarithmic behavior. Based on a method-of-regions analysis, we identify contributions from perturbative active-active Glauber-gluon exchanges which have precisely the right structure to make the cross sec-
tion consistent with PDF factorization below the veto scale associated with the gap. The Glauber contributions we identify are unambiguously defined without any regulators beyond dimensional regularization.

Methods for amplitudes and integrals / **93**

Baikov Package - A package for loop-by-loop Baikov Parametrization

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The Baikov representation of Feynman integrals, and in particular its loop-by-loop variant, has proven itself useful for a number of purposes. Specifically for generalized cuts, twisted cohomology, and the unveiling of geometric structures.
For that reason I have made a package implementing that parametrization. In my talk I will present the package, and discuss some strategies for how best to use it. I will also show a number of examples including a recent result from perturbative gravity.

Plenary Stefano Catani / 94

About Stefano Catani

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HP2 2026 annoucement

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