Andrea Wulzer

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PERSONAL INFORMATION

Born March 17, 1979, Rome (Italy). OrcID: 0000-0002-4523-1940

EDUCATION

Master in Physics, Rome Univ. "La Sapienza"	**1998-2002**
Ph.D. in Physics, ISAS-SISSA, Trieste	**2002-2005**

POSTDOCTORAL FELLOWSHIPS

Postdoc at IFAE, with A. Pomarol and M. Quiros	**2005-2007**
Postdoc at EPFL, in the group of R. Rattazzi	**2007-2010**
Research Associate at ETH, in the group of C. Anastasiou	**2010-2011**

EMPLOYMENT HISTORY

Permanent Researcher Univ. of Padova	**2011-2017**
Associate Professor Univ. of Padova	**2017-2022**
Joint CERN/EPFL Staff Member	**2016-2022**
ICREA Research Professor	**2022-**

SELECTED TALKS

Recent:

Keynote talk at the CEPC International Workshop, Barcelona	**2025**
GGI workshop "Exploring the energy frontier with muon beams", Florence	**2025**
Planck 2025, Padova	**2025**
KCMS workshop, Sabuk-eup, Gangwon-do, South Korea	**2025**
Workshop on AI in high energy physics, KIAS, Seoul, South Korea	**2025**
The "AI goes MAD^2 Workshop", IFT, Madrid	**2024**
The LFC24 Workshop, SISSA, Trieste	**2024**
Workshop "The Flavor Path to New Physics", Zurich	**2024**
Hokkaido Workshop "Particle Physics at Crossroads", Japan	**2024**
The "Zurich Phenomenology Workshop"	**2024**
The "Higgs 2023" conference, Beijing	**2023**
The "Higgs Hunting 2023" conference, Orsay	**2023**
Colloquium at LPSC, Grenoble	**2023**

Before 2023:

ACAT 2022 conference, Bari	**2022**
The "Hammers & Nails 2022" conference, Weizmann Institute of Science, Israel	**2022**
The "28th IFT Xmas Workshop" Madrid	**2022**
Workshop "PHYSTAT-Anomalies", CERN	**2022**
Colloquium at IFAE, Barcelona	**2021**
Colloquium at IFIC, Valencia	**2021**

The 14th International Workshop on Top Quark Physics (TOP2021)	**2021**
PITT PACC Workshop: "Muon Collider Physics"	**2020**
Open Symposium — Update of the Europ. Strat. for Part. Phys., Granada	**2019**
The "Hammers & Nails 2019" workshop, Weizmann Institute of Science, Israel	**2019**
The LHC Physics Conference, Puebla, Mexico	**2019**
SUSY 2018, Barcelona	**2018**
The "BSM: Where do we go from here?" conference, GGI, Florence	**2018**
The "Zurich Phenomenology Workshop"	**2017**
The 2017 CERN-CKC Workshop, Jeju, South Korea	**2017**
The "Beyond the Standard Model – Exploring the Frontier", Johns Hopkins Workshop	**2017**
EPS Conference on High Energy Physics	**2015**
The 21st International Symposium on Particle, Strings and Cosmology (PASCOS 2015)	**2015**
The"Higgs Effective Field Theory 2015" conference, Chicago	**2015**
Aspen workshop "Exploring the Physics Frontier with Circular Colliders"	**2015**
KEK workshop on Beyond the Standard Model	**2014**
The"MC4BSM" workshop, Daejeon, Korea	**2014**
The "BSM Higgs Workshop @ LPC", Fermilab	**2014**
The "Naturalness 2014" conference, Tel Aviv	**2014**

SUPERVISION

F. Montagno, IFAE	**2023-present**
G. Crosso, CERN & Univ. of Padova	**2018-2023**
S. Chen., EPFL	**2018-2022**
L. Ricci, EPFL	**2018-2022**
O. Matsedonskyi, Univ. of Padova	**2011-2013**
J. Mrazek, EPFL (co-supervision with R. Rattazzi)	**2009-2011**

I have assigned a total of 7 Master thesis, in Padova, at EPFL and at ETH-Zurich. Many of my highest-impact papers are in collaboration with students or junior postdocs.

GRANTS

I am the co-PI of the Spanish National Grant of the BSM theory group at IFAE (550 K€, from 2024 to 2027).

In 2018 I obtained a grant from the Swiss National Science Foundation (with the project "New Opportunities at the Energy Frontier"). This is an excellence competitive funding scheme, which awarded me with a considerable (around 550 KCHF) grant that supported my research group for four years.

In 2015 I obtained a grant from the University of Padova for hiring one postdoc.

I gave a decisive scientific and organizational contribution to the obtention of a grant (the "FIRB" Italian Government grant "A new strong force, the origin of masses, and the LHC"), through which 3 postdocs were hired in the Padova group from 2013 to 2015.

ROLES IN COMMITTEES AND WORKING GROUPS

I chair the Physics Working Group of the International Muon Collider Collaboration (IMCC).

I was part of the "Muon Collider Working Group", a small group that provided a firts high-level assessment of the (physics and feasibility) potential of a very high energy muon collider, to be submitted for the European Strategy Update 2020 process. Our assessment, and our suggestion to create an international collaboration on muon colliders, have been endorsed in the Strategy Deliberation Document. The collaboration (IMCC) was created in 2021.

I was part of the International Advisory Committee of the "ECFA Study Group on Physics, Experiment and Detector for a future Higgs Factory" (chair: Karl Jakobs).

I was the convener for the CLICdp "Physics Potential" Working Group. This entailed organizing several workshops and the writeup of scientific reports on the physics potential of CLIC also in the context of the European Strategy for Particle Physics Update 2020.

I was part of the group that provided the scientific input for the European Strategy for Particle Physics Update 2020. This was reported in the "Physics Briefing Book" and in a talk I gave at the Granada Symposium.

I was a convener of the Inter-experimental Machine Learning CERN Working Group.

CONFERENCES, WORKSHOPS AND LECTURES ORGANIZATION

I organized the "Muon Collider Workshop" at the Kavli Institute for Theoretical Physics (KITP) at the University of California, Santa Barbara, held in 2023.

I organized the workshop "The LHC Precision Program" at the Benasque center "Pedro Pascual", in 2023.

I was convener of the "PhysTeV 2023" Les Houches workshop.

I organized a workshop on "Machine Learning for Theoretical Physics" held in 2022 at the Galileo Galilei Institute (GGI) in Florence. This has been the first event in Italy bringing together researchers in the areas of astronomy, cosmology, condensed matter and particle physics working on applying and developing Machine Learning methodologies in their disciplines and seeking for cross-fields cooperation.

I chaired for 3 years the CERN committee that organizes the Summer Student Lecture Program. It is a stimulating challenge to run a five-weeks program on all aspects of CERN research, targeting students of varied level of expertise and of background, ranging from theoretical to experimental physics, computer science and engineering. It is also instructive to see how the interest of the students can be stimulated towards disciplines that are far from their expertise by good lectures.

I am co-founder of the Ph.D. school "GGI Lectures on the Theory of Fundamental Interactions", which I organized in 2013 (limited edition held in Padova), 2014, 2015 and 2017. The school is very successful and regularly running.

I was part of the program committee of the LHCP-2021 conference.

I was convener of the "EFT" parallel session of the "SM@LHC 2021" workshop.

In 2016 I organized the conference "A First Glance Beyond the Energy Frontier" at ICTP.

INVITED LECTURES

Lectures at the GGI School on fundamental interactions	**2024**
Lectures at the "BUSSTEPP@50" Summer School	**2021**
Lectures at the "CERN Winter School on Supergravity, Strings and Gauge Theory"	**2018&2019**
Lectures at the "TAE International Summer School on High Energy Physics"	**2017**
Lectures at the CERN "European School on High Energy Physics"	**2015**
Lectures at the ICTP "Summer School on Particle Physics"	**2015**
Lectures at the "Cargese International School for Theoretical Particle Physics"	**2014**

TEACHING

Since 2024 I teach the High Energy Physics part of the course "Introduction to the physics of the cosmos" for the master co-organized by IFAE at the UAB (Universitat Autónoma de Barcelona). The course is directed to students with a varied background and it provides a solid introduction to the fundamental QFT principles and concepts, followed by an overview of the Standard Model.

From 2019 to 2021 I taught "Gauge Theories and the Standard Model" for the Master and PhD Program at EPFL. The course provides an extensive introduction to the Standard Model theory, from its theoretical foundations to its phenomenological manifestations.

In 2017 and 2018 I taught a course on "Before the Standard Model" for the PhD Program at EPFL. The course covers basic methodological and conceptual aspects of "Beyond the Standard Model" (BSM) physics, such as low-energy Effective Field Theories, Goldstone Bosons, power-counting and Spurion analysis, and the Naturalness arguments, without dealing with any BSM scenario. On the contrary, the concepts are explained and applied in the context of low-energy descriptions of the Standard Model itself like the Fermi Theory and Chiral Perturbation Theory.

From 2012 to 2015 I taught "Theory of Fundamental Interactions" at the Master's Program in Padova, and other courses for PhD students on Composite Higgs and other BSM topics.

RESEARCH ACCOMPLISHMENTS

My research on theoretical high energy physics established me as a leader of the field, with particularly high-impact results on Composite Higgs model-building and on several aspects of LHC collider phenomenology including both direct and indirect manifestations of new physics through precision physics. My ambition of a theoretical research that extents its breadth towards experiments allowed me to have a real impact on LHC experimental practice. My scientific and managerial work on muon colliders triggered a new interest on this idea, with potential very far-reaching impact if a muon collider will be eventually built.

I authored 52 few-authors publications on international peer-reviewed journals, 27 working group reports (7 of which published). I also authored a book, "The Composite Nambu–Goldstone Higgs", published by Springer in the series "Lecture Notes in Physics". The complete list of papers is available at this link. My papers count a total of 14 330 citations on INSPIRE (5 455 of which since 2023) with 155 average citations per paper and an h-index of 52. Of my 38(16) papers with more than 100(250) citations, 18(5) are few-authors articles (and the book, with 584 citations), the others from working group reports. The reports on muon collider physics—whose realization I have lead as IMCC Physics convener—collected about thousand citations.

A selection of my papers, with a brief description, is listed below grouped by subject and in rough chronological order.

Extra Dimensions, Holography and Phenomenology

I explored phenomenological applications of extra-dimensional field theories to Electroweak physics and to hadron physics. The most representative results are:

Baryon Physics in Holographic QCD

A. Pomarol and A. Wulzer.

Nucl. Phys. B **809** (2009) 347. 96 INSPIRE citations.

We showed that the simplest holographic model of QCD mesons automatically delivers baryons as topological solitons. The size of the solitonic solution is stabilized by the Chern–Simons term and its radius is large enough to ensure calculability. The construction addresses the fundamental limitation (i.e., the lack of calculability) of the ordinary Skyrme model of baryons. In two follow-up papers we used the model to compute the static properties of baryons and further extended it to incorporate explicit chiral symmetry breaking.

A Confining Strong First-Order Electroweak Phase Transition

G. Nardini, M. Quiros and A. Wulzer.

JHEP **0709** (2007) 077. 131 INSPIRE citations.

We proposed exploiting for baryogenesis the "confining" phase transition that occurs in five-dimensional models with the Higgs localized on the IR brane. Since this transition was shown to occur in a supercooled regime, our simple observation was that it creates the out-of-equilibrium condition for baryogenesis with the sphalerons inactive inside the bubbles.

Composite Higgs

I have been working extensively on the possibility of the Higgs boson emerging as the bound state of a new strongly-interacting dynamics. In particular on the (particularly convincing) scenario in which the Higgs is a Nambu–Goldstone boson associated with a spontaneously broken global symmetry of the new strong sector. It is interesting to study this option as a solution to the Naturalness Problem, in which case it is expected to manifest itself at the LHC experiments. However since "Naturalness" is not a fully sharply defined notion and since the question on the composite or fundamental nature of the Higgs boson is relevant per se, the Composite Higgs scenario is also a benchmark for future colliders projects even if no hint had to be observed at the LHC. My results in this area include:

Light Top Partners for a Light Composite Higgs

O. Matsedonskyi, G. Panico and A. Wulzer.

JHEP **1301**, 164 (2013). 315 INSPIRE citations.

We clarified the robust structural reasons why certain coloured fermionic particles, the top partners, are necessarily light if the Higgs is as light as we observe it and the model is Natural.

On the Tuning and the Mass of the Composite Higgs

G. Panico, M. Redi, A. Tesi and A. Wulzer.

JHEP **1303**, 051 (2013). 217 INSPIRE citations.

We showed how the light-Higgs/light-partners connection survives in less "canonical" composite Higgs models, which we discovered to be favored from Naturalness considerations, where the right-handed top quark is taken to be part of the composite sectors.

The Other Natural Two Higgs Doublet Model

J. Mrazek, A. Pomarol, R. Rattazzi, M. Redi, J. Serra and A. Wulzer.

Nucl. Phys. B **853** (2011) 1. 292 INSPIRE citations.

The first comprehensive investigation of "non-minimal" Composite Higgs models with an extended Goldstone-bosons Higgs sector and of the structural conditions for their phenomenological viability. An extended Composite Higgs sector is not merely a logical possibility because the notion of "minimality" should be intended as a request of simplicity of the underlying strong sector and there are several simple options for the underlying sector that produce more than one Higgs doublet.

The Composite Twin Higgs scenario

R. Barbieri, D. Greco, R. Rattazzi and A. Wulzer.

JHEP **1508**, 161 (2015). 156 INSPIRE citations.

We clarified under what conditions the so-called "Twin Higgs" mechanism can be implemented in the composite Higgs scenario, resulting in models where the mass of the top partners is not directly linked with the one of the Higgs. Our main achievement has been to explain this effect in terms of peculiar symmetries and selection rules that Naturally enforce a cancellation in the Higgs potential and in particular in the mass-term.

The Composite Nambu–Goldstone Higgs

G. Panico and A. Wulzer.

Lect. Notes Phys. **913**, pp. (2016). 584 INSPIRE citations.

An extensive and quantitative review of composite Higgs published as a "Lecture Notes in Physics". An original and pedagogical reformulation of the material is given, together with fully original results. It is by now the standard reference for the Composite Higgs scenario. It is cited and appreciated also by founders of the field such as Raman Sundrum.

LHC Direct Searches for New Particles

There is a long way to go from the theoretical formulation of a new physics model to an LHC experimental search program that truly probes it effectively and explores all its possible manifestations in the theoretically most motivated region of its parameter space. The papers below successfully bridged this gap

Heavy Vector Triplets: Bridging Theory and Data

D. Pappadopulo, A. Thamm, R. Torre and A. Wulzer.

JHEP **1409**, 060 (2014). 389 INSPIRE citations.

A variety of BSM scenarios (e.g., composite Higgs or extensions of the SM gauge group) predict massive vector resonances in the triplet of the SM group (i.e., Heavy Vector Triplets or HVT) and, depending on the scenario, these particles behave differently at the LHC. We identified the minimal set of phenomenological parameters needed to describe the HVT collider phenomenology in general terms, in a way that can reproduce any specific HVT model. Through these parameters one can efficiently explore the space of theoretical possibilities. The HVT model has been used as benchmark for several experimental analyses and the strategy proposed in the paper has been extensively employed for the presentation of the experimental results.

A First Top Partner Hunter's Guide
A. De Simone, O. Matsedonskyi, R. Rattazzi and A. Wulzer.
JHEP **1304**, 004 (2013). 386 INSPIRE citations.
Having established on robust grounds that top partners have to be light, searching for them at the LHC becomes a robust test of the composite Higgs scenario. With this motivation I wrote the paper above where we characterized the top partners collider phenomenology. Also this paper is a standard reference for experimental analyses and phenomenological work in this area.

On the Interpretation of Top Partners Searches
O. Matsedonskyi, G. Panico and A. Wulzer.
JHEP **12** (2014), 097. 164 INSPIRE citations.
In this paper we outlined concrete analysis strategies for a comprehensive and informative interpretation of the LHC searches incorporating the (potentially dominant) contribution of the single Top Partners production mechanism.

The LHC Precision Program

Comparing theory predictions to precise experimental measurements is a valid strategy for fundamental physics exploration, which is complementary to the search for the direct production of the new particles predicted by new physics models. This strategy potentially extends the sensitivity to new particles that are too heavy to be produced and its deployment relies less on the (possibly unreliable) guidance offered by hypothetical new physics models. It is thus essential to establish if and how such a precision program can be pursued with LHC data. An earlier paper on this subject is

Anomalous Couplings in Double Higgs Production
R. Contino, M. Ghezzi, M. Moretti, G. Panico, F. Piccinini and A. Wulzer.
JHEP **1208**, 154 (2012). 176 INSPIRE citations.
We assessed the potential of the LHC to probe an anomalous coupling $t\bar{t}hh$ through the production of two Higgs bosons. The latter coupling is present and relatively sizable in composite Higgs models and the double Higgs production cross-section displays a good sensitivity to it.

More recent papers, that define the key contributions I gave to the LHC (and future colliders) precision program with the development of high-PT probes of new physics, are

Energy helps accuracy: electroweak precision tests at hadron colliders
M. Farina, G. Panico, D. Pappadopulo, J. T. Ruderman, R. Torre and A. Wulzer,
Phys. Lett. B **772** (2017) 210. 221 INSPIRE citations.
Generically, new physics effects due to heavy (above direct reach) new particles become larger in the high-energy tail of the kinematical distributions. Based on this simple observation, the paper shows how to build powerful probes of new physics by sufficiently accurate measurements of distributions at the high energy available at the LHC. Neutral and charged di-lepton production at high transverse momentum (high-PT) is considered for a quantitative illustration, showing that these relatively simple measurements have the potential to extend by more than one order of magnitude the present-day sensitivity to two specific deformations of the SM encapsulated in the so-called W and Y "oblique" electroweak precision tests parameters. On top of proposing high-PT probes as a new methodological avenue for the exploitation of LHC data, the result proves that radical progress is possible at the LHC also on SM deformations that, like W and

Y, have been probed already by the very accurate measurements performed at the LEP collider. Before our paper this was considered to be impossible, and new physics effects in the Higgs and top sector (and other SM deformations that LEP could not probe effectively) were considered as the only target of the LHC precision program. The paper thus extended the breadth of the program also in terms of new physics targets.

Electroweak Precision Tests in High-Energy Diboson Processes
R. Franceschini, G. Panico, A. Pomarol, F. Riva and A. Wulzer,
JHEP **1802** (2018) 111. 123 INSPIRE citations.
The paper studies high-PT probes in the next-to-simplest LHC process consisting in the production of two (longitudinally-polarized) vector bosons or one vector boson and one Higgs. The relevant SM deformations (namely those whose effects grow with energy in diboson production) are classified, and the classification is employed to outline a program of measurements of different diboson processes and their combined interpretation. A quite detailed sensitivity projection is performed for one of these processes, and used to estimate the potential reach in new physics scenarios of different classes.

Diboson Interference Resurrection
G. Panico, F. Riva and A. Wulzer,
Phys. Lett. B **776** (2018), 473-480. 116 INSPIRE citations.
We designed and characterized kinematical variables associated with the decay of the vector bosons that have to be measured in order to gain sensitivity to the largest (interference-level) new physics effects in the production of two bosons with transverse polarizations. This solves a problem that had been previously outlined in the literature, related to a mismatch between the helicity combinations that are sizable in the SM and those that receive large new physics contributions. The problem is solved by getting access, through the measurement of azimuthal decay angles, to the quantum-mechanical density matrix in the space of vector bosons helicities, where the interference between different helicity amplitudes does not cancel. The analytical understanding of the azimuthal decay angle reconstruction for boosted leptonically-decaying W bosons is another important novel result of the paper.

My most recent papers in this area are

On the W&Y interpretation of high-energy Drell-Yan measurements
R. Torre, L. Ricci and A. Wulzer,
JHEP **02** (2021), 144. 56 INSPIRE citations.
High-energy EFT probes with fully differential Drell-Yan measurements
G. Panico, L. Ricci and A. Wulzer,
JHEP **07** (2021), 086. 52 INSPIRE citations.
They offer a complete theory guidance for the experimental exploration of dilepton processes at the LHC, including the complete classification of the possible new physics effects and of the impact of angular distribution measurements, on top of providing the corresponding theory predictions at the adeguate level of accuracy.

These papers are standard references for Effective Filed Theory (EFT) studies at the LHC. They also impacted experimental work especially in diboson final state analyses. Moreover they triggered progress in flavor physics probes by high-PT measurements and led to new perspectives on the possible exploitation of future collider data.

Future Colliders

I established myself as a future collider expert by a number of research articles as well as leadership roles in future collider study groups. My strongest impact results are on muon colliders physics studies and are summarized below

Muon Colliders
J. P. Delahaye *et al.*.
arXiv:1901.06150. 329 INSPIRE citations.
This is the output of a small working group on muon colliders established by CERN in preparation for the 2020 Update of the European Strategy for Particle Physics. At that moment, the study program in the USA had been terminated and there had been very little or no attention to muon colliders in the previous several years. As the only theorist in the working group I was in charge of assessing the physics potential. I found that the obvious virtues of a high energy muon collider had been overlooked (or not satisfactorily spelled out) in the old reports and were not appreciated by the community. My concise overview of the key elements—high mass reach combined with precision—was extremely impactful and it matches very well subsequent assessments resulting from extensive studies. It triggered a new interest of the theory community on muon colliders. Combined with the positive assessment on the feasibility perspectives, this led to the Strategy preocess recommendation- of initiating the IMCC.

I was among the founders of the IMCC and the leader of its Physics working group. In this context I organized several workshops and seminar series aimed at coordinating and collecting the work on muon collider physics that rapidly emerged from the enthusiasm of the community. The outcome was summarized in several many-authors reports, including

Towards a muon collider
C. Accettura, *et al.*.
Eur. Phys. J. C **83** (2023) no.9, 864. 349 INSPIRE citations.
We summarized the status and the recent advances on muon colliders design, physics and detector studies, offering the starting point for the future development of the study program.

The new interest on muon colliders had a very strong impact on the Snowmass 2021 planning process in the USA. The P5 and NAS recommendations outlined the ambition of building a muon collider in the USA and planned investments on the R&D program in the coming decade. The "US Muon Collider Collaboration" was formed in 2025. The ESPPU 2026 recommended the continuation of muon collider technology investments.

I wrote several research articles on muon collider physics. The first ones are

Two Paths Towards Precision at a Very High Energy Lepton Collider
D. Buttazzo, R. Franceschini and A. Wulzer.
JHEP **05** (2021), 219. 82 INSPIRE citations.
We provided a first illustration of the simultaneous availability of two paths for precision physics at a muon collider. One is to exploit high-PT measurements, where the effects of heavy new physics are enhanced. We show in examples that this offers sensitivity to 100 TeV scale new physics (at a 10 TeV muon collider), whose manifestations are on the contrary too tiny (one part per million) to be confidently established even at the best possible future Higgs factory operating at order 100 GeV energy. The second one is to exploit the large rate for production

processes initiated by effective vector bosons scattering, leading to high statistics and precise measurements. The excellent perspectives for the determination of the Higgs trilinear coupling were studied as an illustration.

Learning from radiation at a very high energy lepton collider

S. Chen, A. Glioti, R. Rattazzi, L. Ricci and A. Wulzer.

JHEP **05** (2022), 180. 50 INSPIRE citations.

We studied the interplay between the long-distance (IR) phenomenon of Electroweak radiation and the short-distance new physics effects to be probed by high-PT measurements at a order 10 TeV energy muon collider. First, we established that these effects are sizable and require resummation for sufficiently accurate Standard Model predictions. Second, we extended the resummation techniques based on the IR Evolution Equation to a novel and more useful class of observables. Third, we outlined and demonstrated in examples that studying the pattern of the radiation offers new handles for new physics sensitivity because, at variance with QED and QCD, electroweak radiation connects hard amplitudes with different (Electroweak) gauge color and it is sensitive to the hard particles chirality. The paper outlines new opportunities for high-PT muon collider measurements at the interface between BSM and SM theory calculations.

Machine Learning

The Machine Learning (broadly, AI) revolution was triggered by the widespread availability of hardware and software tools for the practical deployment of Statistical Learning methodologies. This produced innovations in Data Science that are being incorporated in basic science and in particular in high energy physics. The peculiarity of my work in this area is the direct application of the new methodologies to the statistical inference problems that are of relevance for our field. The ambition is to advance Statistical Data Analysis using Statistical Learning techniques, discovering new methods that can possibly lead to new physics discovery. My most impactful results in this area is the development of the New-Physics-Learning Machine (NPLM) method, in the following papers:

Learning New Physics from a Machine

R. T. D'Agnolo and A. Wulzer,

Phys. Rev. D **99** (2019) no.1, 015014. 193 INSPIRE citations.

It is possible (or likely) that the model of new physics that is actually realized in Nature is a one that has not yet been hypothesized. In this case, being unable to foresee its experimental manifestations, it will not be discovered at the LHC even if its signature was indeed present in the data. The problem is that the LHC data are so rich and complex that establishing their incompatibility with the "old" physics model (the SM), rather than searching for the manifestations of a specific "new" model, is a highly non-trivial task. Attempts in this direction are called "model-independent" new physics search strategies. In the paper, we designed an innovative model-independent strategy based on employing neural networks as a flexible unbiased parametrization of the underlying data distribution. The neural network is fitted to the data, and the presence of new physics is detected by how much the best fit distribution departs from the one predicted by the SM. This is possible thanks to the observation that Maximum Likelihood fit and hypothesis testing can be turned to a training problem by employing a Monte Carlo sampling of the reference (SM) hypothesis distribution (together with the observed data) as training data.

After this first paper on the NPLM method, I developed it with a group formed by experimental physicists (M. Pierini and M. Zanetti) and our former doctoral students G. Grosso and others, producing four papers

Learning multivariate new physics
R. T. D'Agnolo, G. Grosso, M. Pierini, A. Wulzer and M. Zanetti.
Eur. Phys. J. C **81** (2021) no.1, 89. 99 INSPIRE citations.
We demonstrated the viability of the NPLM method for realistic multivariate problems of a dimensionality comparable with the one of realistic LHC analyses. The ability of NPLM to identify the new physics effects were demonstrated on simulated data produced with benchmark new physics models.

Learning new physics from an imperfect machine
R. T. d'Agnolo, G. Grosso, M. Pierini, A. Wulzer and M. Zanetti.
Eur. Phys. J. C **82** (2022) no.3, 275. 52 INSPIRE citations.
We devised a strategy to account for the imperfections in the Standard Model data predictions, avoiding that such modeling uncertainties result in false positives.

Learning new physics efficiently with nonparametric methods
M. Letizia, G. Losapio, M. Rando, G. Grosso, A. Wulzer, M. Pierini, M. Zanetti and L. Rosasco.
Eur. Phys. J. C **82** (2022) no.10, 879. 40 INSPIRE citations.
We show that kernel methods can be used in NPLM instead of neural network. The resulting dramatic gain in computational speed expands the potential domain of applicability of the method, as we showed in the following paper:

Fast kernel methods for data quality monitoring as a goodness-of-fit test
G. Grosso, N. Lai, M. Letizia, J. Pazzini, M. Rando, L. Rosasco, A. Wulzer and M. Zanetti.
Mach. Learn. Sci. Tech. **4** (2023) no.3, 035029. 12 INSPIRE citations.
Data quality monitoring is the assessment of the status of a detector (or any apparatus) during operation, to ensure that it is working under proper design conditions. This can be done by NPLM using as reference the data collected off-line under controlled conditions. We demonstrated this possibility using real data collected by a drift-tube chamber.

Further improvements of the NPLM method were achieved later by a group at MIT (including G. Grosso). A first LHC data analysis with the NPLM method, in the dilepton final state, is currently in progress within the CMS collaboration.

Electroweak Physics at Very High Energy

I have been working regularly on Electroweak interactions in the kinematic regime where the collision energy is much above the mass of the vector bosons. The perspective of exploring this regime with future colliders is only one motivation for these investigations, which are of self-standing theoretical interest. My major achievement is a novel formalism for perturbative calculations in massive gauge theory that does not suffer from "gauge cancellations" that invalidate energy power-counting. My interest emerged while working on this paper

Probing the Scattering of Equivalent Electroweak Bosons
P. Borel, R. Franceschini, R. Rattazzi and A. Wulzer,
JHEP **06** (2012), 122. 63 INSPIRE citations.

Here we proved the validity of the "Effective W Approximation", namely the universal factorization of collinear emissions at tree-level, from incoming fermions, of vector bosons that eventually participate to a hard scattering process as if they were on-shell initial particles. Gauge cancellations prevent the proof to be performed in the standard covariant formalism and requires the axial gauge.

This led me to design a Lorentz-covariant formalism where gauge cancellations are avoided and power-counting is manifest:

An Equivalent Gauge and the Equivalence Theorem

A. Wulzer,

Nucl. Phys. B **885** (2014), 97-126. 48 INSPIRE citations.

The approach is based on the innovative idea of exploiting gauge redundancies to modify the representative states of the BRST cohomology operator in the Fock space of the gauge-fixed theory. A byproduct of the paper is a novel all-orders proof of the "Goldstone Boson Equivalence Theorem", as well as the assessment of the conditions for its validity and of the corrections it receives beyond tree-level. However this approach is inherently on-shell and requires the Electroweak bosons to be treated as stable particles.

In this work I completed my program of reformulating massive gauge theories making power-counting manifest, by employing a strategy based on a generalized Ward identity for amputated amplitudes:

Goldstone Equivalence and High Energy Electroweak Physics

G. Cuomo, L. Vecchi and A. Wulzer,

SciPost Phys. **8** (2020) no.5, 078. 31 INSPIRE citations.

We extended my previous results to the (physically relevant) case of unstable massive vectors and we also derived an exact decomposition of low-virtuality vector bosons (and Goldstones) propagators that is essential for the study of factorization. The formalism is set up for a general gauge theory, at all orders in perturbation theory and for arbitrary (linear and Lorentz-preserving) gauge-fixing functionals. It can deal with external unstable gauge bosons on their complex mass-shell, and with low-virtuality off-shell bosons. We outlined the advantages of manifest power-counting in concrete tree-level and loop calculations and we also performed a complete proof of collinear factorization in the SM, of which the Effective W Approximation is a particular case.

The most recent paper on this topic is:

Low-virtuality splitting in the Standard Model

F. Nardi, L. Ricci and A. Wulzer. JHEP **10** (2024), 215. 7 INSPIRE citations.

Based on the "Goldstone Equivalence" formalism we extended the proof of tree-level factorization and the calculation of the corresponding splitting amplitudes in a way that includes the soft splitting regime together with the collinear one in a single "low-virtuality" expansion. A version of the massive spinor helicity formalism developed in the paper provides concise helicity-basis-independent expressions for the amplitudes.