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 PLENARY TALKS

Colloquium at LPSC, Grenoble.	**2023**
ACAT 2022 conference, Bari.	**2022**
"Hammers & Nails 2022", Weizmann Institute of Science, Israel.	**2022**
The "28th IFT Xmas Workshop", Madrid.	**2022**
Workshop "PHYSTAT-Anomalies", CERN.	**2022**
Workshop "Multi-Boson Interactions 2022", Shanghai.	**2022**
Workshop "Muon Collider Collaboration Meeting", CERN.	**2022**
EP-IT Data Science Seminars, CERN.	**2021**
Colloquium at IFAE, Barcelona.	**2021**
Colloquium at IFIC, Valencia.	**2021**
14th International Workshop on Top Quark Physics (TOP2021)	**2021**
The First Muon Collider Collaboration (kickoff) meeting	**2020**
4th FCC Physics and Experiments workshop.	**2020**
PITT PACC Workshop: "Muon Collider Physics".	**2020**
Open Symposium — Update of the Europ. Strat. for Part. Phys., Granada.	**2019**
"Hammers & Nails 2019", Weizmann Institute of Science, Israel	**2019**
Rencontres du Vietnam	**2019**
The LHC Physics Conference, Puebla, Mexico	**2019**
"Higgs and Effective Field Theory " workshop, Louvain	**2019**
SUSY 2018, Barcelona	**2018**
"Multi-Boson Interactions", University of Michigan	**2018**

“Beyond Standard Model: Where do we go from here?” GGI, Florence	**2018**
Zurich Phenomenology Workshop	**2017**
“Pushing the Frontiers of Particle Physics During the LHC Run II Era”, Hong-Kong	**2017**
“Multi-Boson Interaction Workshop”, Karlsruhe	**2017**
FCC Week, CERN	**2017**
The 2017 CERN-CKC Workshop, Jeju, South Korea	**2017**
“Beyond the Standard Model – Exploring the Frontier”, Johns Hopkins Workshop	**2017**
“ATLAS Beyond the Standard Higgs Model Higgs and Exotics Joint Workshop”	**2016**
28th Rencontres de Blois on Particle Physics and Cosmology	**2016**
“PP@LHC” Workshop	**2016**
EPS Conference on High Energy Physics	**2015**
Pascos 2015	**2015**
“Higgs Effective Field Theory 2015” conference, Chicago	**2015**
Aspen workshop “Exploring the Physics Frontier with Circular Colliders”	**2015**
CERN workshop on “Neutral Naturalness”	**2015**
Web seminar for the “Invisibles” project	**2015**
X ATLAS Italia Workshop	**2015**
CERN workshop “The top-charm frontier at the LHC”	**2014**
KEK workshop on Beyond the Standard Model	**2014**
“MC4BSM” workshop, Daejeon, Korea	**2014**
“BSM Higgs Workshop @ LPC”, Fermilab	**2014**
“Naturalness 2014” conference, Tel Aviv	**2014**

PHDS STUDENTS SUPERVISION AND MENTORING

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

Additionally, 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

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 steered several working groups and committees contributing shaping the future of particle physics. In particular:

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

I was part of the "Muon Collider Working Group", a small group that provided a preliminary 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 has now been created.

I am 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.

In my capacity of CERN Staff member I participate to the selection committee of CERN Fellows and Limited Duration Staff. I lead the postdocs and students selection processes in Padova and EPFL, especially for the several openings that could be created by the external funds I collected in the course of the years.

CONFERENCES, WORKSHOPS AND LECTURE PROGRAMS ORGANIZATION

I am organizing a workshop "Muon Collider Workshop" at the Kavli Institute for Theoretical Physics (KITP), to be held in 2023.

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 “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**

REGULAR TEACHING

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 χ_{PT}.

From 2012 to 2015 I taught “Theory of Fundamental Interactions” at the Master’s Program in Padova, and more specialistic 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 and on several aspects of LHC collider phenomenology including direct and indirect manifestations of new physics through precision physics. I am playing a leading role in the development and assessment of the physics potential of future collider projects. My ambition of a theoretical research that extents its breadth towards experiments allowed me to have a real impact on LHC experimental practice. Recently, I started establishing myself as a major actor in the growing field of Machine Learning for high energy physics phenomenology.

I authored 45 publications on international peer-reviewed journals, 21 working group reports (5 of which published), 1 book chapter and 5 talks and lectures proceedings. 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 8875 citations on INSPIRE (3419 of which in the last five years) with 115 average citations per paper and an h-index of 42. Of my 28(9) papers with more than 100(250) citations, 15(5) are published articles (and the book) with less than 10 authors, the others from working group reports (on, e.g., the HL-LHC and FCC physics potential) to which I contributed with specific results. The reports of working groups where I played a leading role as convener and/or editor collected 1062 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 potential 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. 92 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. 89 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). 281 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). 200 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. 253 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). 137 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). 454 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). 330 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). 335 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, as well as

On the Interpretation of Top Partners Searches
O. Matsedonskyi, G. Panico and A. Wulzer.
JHEP **12** (2014), 097. 133 INSPIRE citations,
where 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

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). 165 INSPIRE citations.
We assessed the potentiality 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. 142 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. The paper shows how to build, based on this simple observation, 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. 85 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. The development of the program outlined in this paper has been and is being continued also by other groups.

Diboson Interference Resurrection

G. Panico, F. Riva and A. Wulzer,
Phys. Lett. B **776** (2018), 473-480. 73 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 (plus or minus) 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.

Future Colliders

I contributed, with multiple roles, to future colliders physics in the context of the European Particle Physics Strategy Update 2020 process. At the purely scientific level, I contributed with several studies on Top Partners, Heavy Vector Triplets and high-PT probes of new physics at the hadron-hadron FCC and to the corresponding working group reports. However below I will outline the reports to which I also gave a major organizational contribution.

The CLIC Potential for New Physics

J. de Blas *et al.*.

CERN Yellow Rep. Monogr. Vol. 3 (2018). 178 INSPIRE citations.

In my capacity of convener of the "Physics Potential" Working Group within the CLICdp collaboration I had a major responsibility in collecting, organizing and presenting this extensive summary of the potential of the CLIC linear collider project to probe new physics. It mostly consists of invited contributions that review, adapt, and in some cases significantly extend, recent papers on CLIC physics. A number of these papers were actually initiated in the context of the Working Group activities, and a good fraction of the material is fully original.

The Compact Linear e^+e^- Collider (CLIC): Physics Potential

P. Roloff *et al.* [CLIC and CLICdp Collaborations].

arXiv:1812.07986 [hep-ex]. 86 INSPIRE citations.

This is the short summary document we submitted on behalf of the CLIC collaboration to the Physics Preparatory Group (PPG) on the physics potential of CLIC.

Muon Colliders

J. P. Delahaye *et al.*.

arXiv:1901.06150 [physics.acc-ph]. 175 INSPIRE citations.

The output (for the PPG) of the CERN Working Group on muon colliders, in which I was responsible for giving a first assessment of the physics potential. My results had significant impact inside and outside the muon colliders community. Our assessment, and our suggestion to create an international collaboration on muon colliders, have been endorsed in the Strategy Document. The collaboration has now been created.

Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020

Richard Keith Ellis *et al.*.

arXiv:1910.11775 [hep-ex]. arXiv:1901.06150 [physics.acc-ph]. 213 INSPIRE citations.

The "Briefing Book" summarizing the input submitted to the PPG, to be used as scientific input for the Update Process. It follows the Open Symposium in Granada and summarizes the review talks we gave in that context.

Machine Learning

Recently, I found myself interested in Machine Learning, for three reasons. First, because the present-day widespread availability of hardware and software tools for Machine Learning applications has the potential to impact theoretical research practice as much as the availability of computer algebra and Monte Carlo tools did in the past. Actually even the mere observation that Machine Learning techniques are already extensively employed by experimental physicists would be enough to conclude that (at least) some competence in this domain will soon become an "entry-level" requirement for theoretical research in phenomenology. Second, Machine Learning triggers developments in disciplines like data analysis that constitute the universal language of Science. Activity in this area thus stimulates cross-field contamination and mutual development, fighting against the fragmentation of Science that is a particularly severe problem for hyper-specialized disciplines like high energy physics. I daily discover new opportunities from cross-field cooperation with my involvement as convener of the Inter-experimental Machine Learning CERN Working Group. Third, I am interested in Machine Learning because I found evident directions for progress in my own research mission, triggered by a thoughtful and conceptual approach to the problem that is unique of theoretical physics. My results on the design of Machine Learning techniques to search for new physics are:

Learning New Physics from a Machine

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

Phys. Rev. D **99** (2019) no.1, 015014. 110 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 (made here for the first time, as far as I can tell, in the vast literature on Computer Science) 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. Several developments of the method have been presented in another publication, written in collaboration with experimentalists colleagues, and more results will appear soon. The CMS collaboration started working on the application of the method to LHC data.

Parametrized classifiers for optimal EFT sensitivity

S. Chen, A. Glioti, G. Panico and A. Wulzer,

JHEP 05 (2021), 247. 23 INSPIRE citations.

The purpose of this paper is the opposite of the previous one. Rather than searching for new physics of unspecified nature, we search for very specific effects that we want to probe with precision. Specifically, the aim is to improve the sensitivity to new physics effects encapsulated in higher-dimensional Effective Field Theory (EFT) operators, making direct progress on the LHC precision program previously outlined. In this case, the idea is to train a neural network to make it approximate as accurately as possible the likelihood ratio between the SM and the new physics distributions of the data. The neural network will then be used as a surrogate of the exact likelihood ratio (which is obviously not known) for a nearly "optimal" statistical inference on the presence of new physics. The paper makes an important methodological progress through the idea of "parametrization", quantifies the sensitivity improvement in a realistic physically relevant process (WZ production at high-energy, exploiting the decay angle informations whose potential I had identified in a previous paper), compares with other methods and assesses robustly the level of "optimality" of the Machine Learning strategy.