# ADVANCED CALCULUS FOR PRECISION PHYSICS

## Flagship Usecase Proposal

HPC/CN1/Spoke2/WP1/

b) Theoretical Research Projects
b.2) Collider Phenomenology

Pierpaolo Mastrolia (UNIPD)
06.03.2023

In collaboration with:
S. Alioli, N. Bartolo, R. Gröber, M. Liguori, F, Maltoni, P. Mastrolia, C. Oleari, A. Papa, T. Peraro, A. Raccanelli, E. Re, E. Salvioni, F. Tramontano, M. Zanetti

# OUTLINE

- Introduction: Nodes, Objective, Methodology, Impact
- Usecase Description
- Networking
- Conclusions

# INTRODUCTION & TEAM

**NODES**

U. Bologna
U. della Calabria
U. Milano Bicocca
U. Napoli
U. Padova

| Staff | RTDA | PhD students |
|---|---|---|
| 14 | 0 **+ 2** | 5 **+ 3** |

**Introduction**

Supporting the phenomenology analyses for prospects, for detection and observations of new physics events or weaker signals that require an enhancement of sensitivity within advanced collider physics programs (CERN, FermiLab, etc.), as well as within current and future GW detectors (LIGO-VIRGO-KAGRA, ET, LISA, etc.), in the next three decades

Understanding the fundamental laws of Nature at the most extreme conditions.

# OBJECTIVES & METHODOLOGY

**Objectives**

- Developing software and tools for the efficient, automatic evaluation of multi-loop scattering amplitudes, making use of advanced analytic and numerical methods;

- Exploring new computational architectures to improve the events generation, the evaluation of hadronic cross, and the data fits for collider phenomenology;

- Developing codes for describing hadronic production and decay of new particles, as well as to include new physics effects in the study of Higgs boson and top-quark phenomenology;

- Developing softwares that combine new methods and advanced computing techniques of particle physics and cosmology.

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- Developing softwares that combine new methods and advanced computing techniques of particle physics and cosmology.

## Methodology

- Smart combination of existing software packages
- Improvement of existing algorithms
- Development of novel computational strategies
- Development of novel mathematical methods

# IMPACT

The software developed in this research program will have a major impact on Collider Phenomenology, as well as on Cosmology and Mathematics.

- Standard Model Physics
- Beyond Standard Model Physics
- Parton Distributions Functions
- Higgs boson and Heavy Particles Physics
- Anomalous magnetic moment (g-2) of muon and electron
- Effective Field Theories for Quantum and Classical Physics
- Scattering Amplitudes
- Physics of the Universe and Gravitational Waves Physics
- Computational Algebraic Geometry

# Proposal: ADVANCED CALCULUS for PRECISION PHYSICS

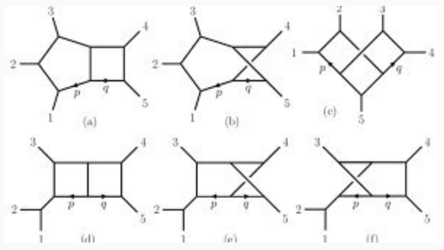
## @ UNIBO

**Participants:** Maltoni, Peraro

**Recruitment:** 1 PhD

**Task 1: Fast and accurate predictions for Collider Phenomenology**

**Description:** We would like to explore analytical, numerical methods and new computational architectures to bring predictions for collider phenomenology up to the challenges of future experiments, in terms of accuracy (two-loop) and speed. At the loop level, we apply new mathematical methods for integrand reduction implemented over finite fields. For order of magnitude improvements in speed we work on the parallelization of MadGraph on GPU's also using Maching Learning methods.



**Links:** WP 2|(3)|4 ; **timing:** 0,5 - 1 MCore-hours/yr

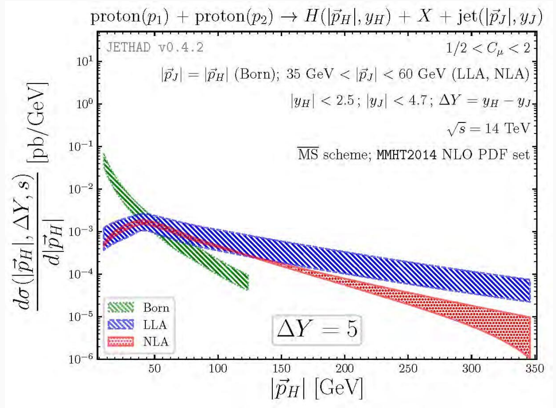
## @ UNICAL

**Participants:** Papa

**Recruitment:** 1 RTDA (or 1 PhD)

**Task 2: Cross Sections and Partonic Distributions**

**Description:** Implementation of numerical techniques for the evaluation of integrals entering the cross section of elementary particle collisions; implementation of global fits of collision data for the extraction of partonic distributions within hadrons.
Deliverables: Fortran and/or Python codes for (1) numerical evaluation of hadronic cross sections in hadronic processes (2) global fits of partonic distributions in hadrons, with special reference to the (unintegrated in the transverse momentum) gluon distribution (UGD) in the proton.



**Links:** WP2; **timing:** ~1 MCore-hours/yr

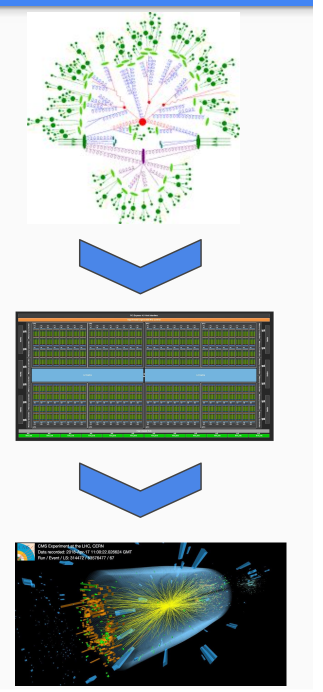
## @ UNIMIB

**Participants:** Alioli, Oleari, Re

**Recruitment:** 1 PhD

**Task 3: Accelerating Event Generation**

**Description:** Improve the parallelization of existing event generators (POWHEG BOX, GENEVA) to take advantage of modern computing infrastructure and accelerators (GPU) and heterogeneous architectures, in preparation for the computing challenges of the LHC high-luminosity upgrade and other future colliders.



**Links:** WP 2|4 ; **timing:** ~ 3 MCore-hours/yr

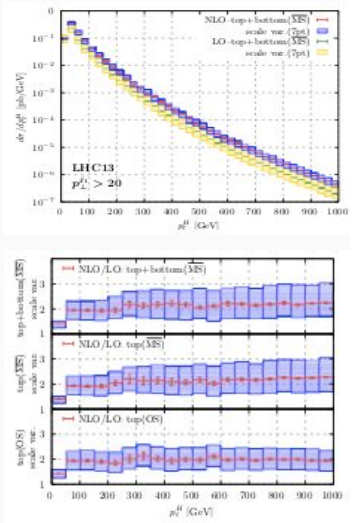
## @ UNINA

**Participants:** Tramontano

**Recruitment:** (1 PhD)

**Task 4: Scalable numerical evaluation of Feynman integrals**

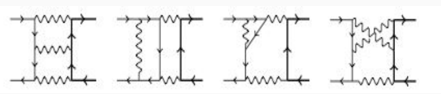
**Description:** Convert and optimize algorithms for the numerical evaluation of Feynman integrals, that have been designed and developed to run with a well-known proprietary software. Such a software is an excellent tool for the exploration phase of novel techniques, but is not suitable for the production mode with parallelization and run on clusters of cpu's or gpu's. The target of Task 4 is to deliver public libraries written with a low level language and making use of open source facilities so to make facible any computation at the second order in perturbation theory by means of exploitation of the computer power.



**Links:** WP 2|(3)|4 ; **timing:** ~ 3 MCore-hours/yr

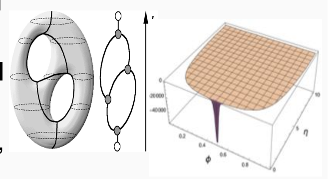
## @ UNIPD

**Participants:** Gröber, Mastrolia, Salvioni, Zanetti
**Recruitment:** 1 RTDA

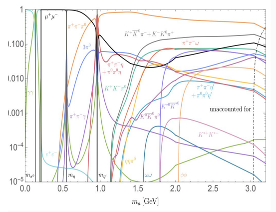


**Task 5: Advanced Computational Tools for Scattering Amplitudes**

**Description:** Developments of methods and tools for analytic and numerical calculation of Feynman Diagrams and Scattering Amplitudes, in gauge theories and EFTs, based on innovative mathematical and computer science methods (Integration by parts, Differential Equations, Intersection Theory, Finite Fields Reconstruction, Tropical Monte Carlo Integration, Machine Learning and Neural Networks), for applications to Particle Physics, General Relativity, and Mathematics (Differential and Algebraic Topology, Theory of Special Functions, Statistics)

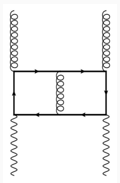


**Links:** WP 2|3|4|(6) ; **timing:** ~ 0,3 – 1 MCore-hours/yr



**Task 6: Optimized Strategies for new Particles and Couplings**

**Description:** Codes describing hadronic production and decay of new GeV-scale particles at intensity- and energy-frontier experiments, optimized to enable fast evaluation for arbitrary input parameters. Inclusion of higher-order effects as well as SMEFT effects in existing codes for Higgs and top physics, allowing to access less constrained couplings through virtual corrections.



**Links:** WP 2|3|4; **timing:** ~ 0,3 – 1 MCore-hours/yr

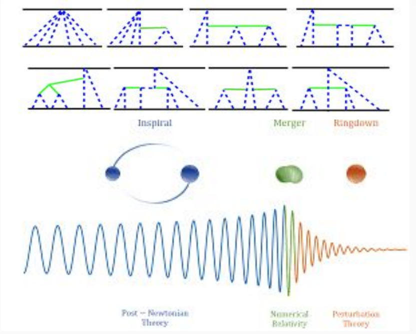
## @ UNIPD

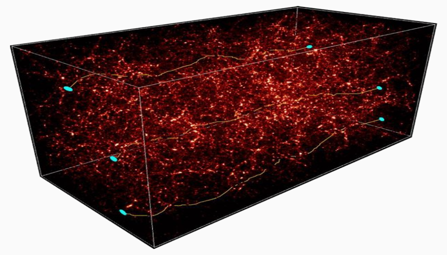
**Participants:** Bartolo, Mastrolia, Raccanelli, Salvioni
**Recruitment:** 1 RTDA (same as before)

**Task 7: EFT Diagrammatic Approach to Gravitational Wave Physics**

**Description:** Combination of existing tools for analytic and numerical evaluation of Feynman Integrals and Scattering Amplitudes, for applications to Gravitational Wave Physics

**Links:** WP3; **timing:** ~0,1-0,5 MCore-hours/yr





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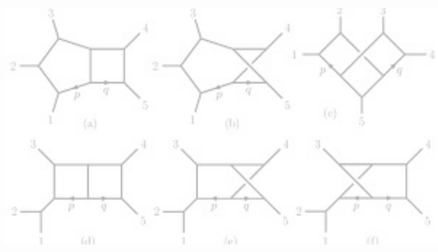

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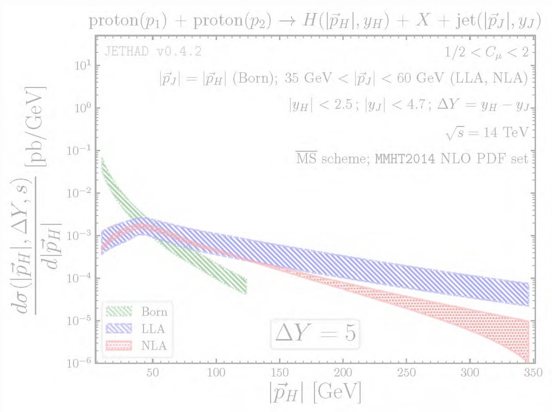

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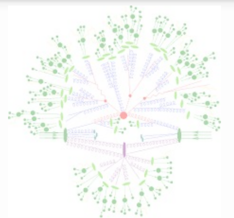

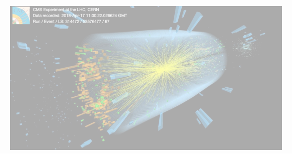

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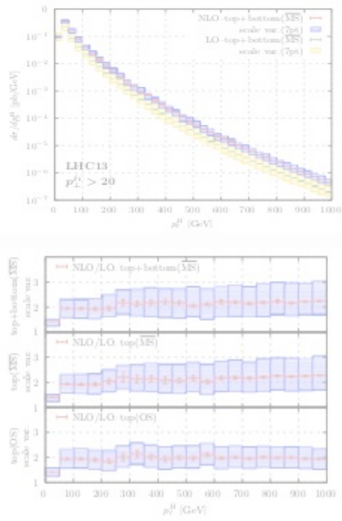

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**Participants:** Gröber, Mastrolia, Salvioni, Zanetti
**Recruitment:** 1 RTDA

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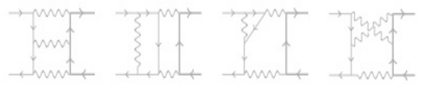

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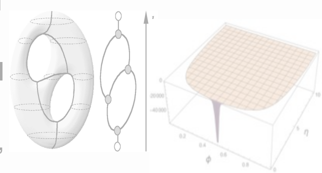

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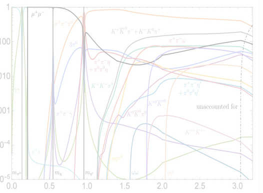

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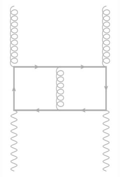

**Links:** WP 2|3|4; **timing:** ~ 0,3 – 1 MCore-hours/yr

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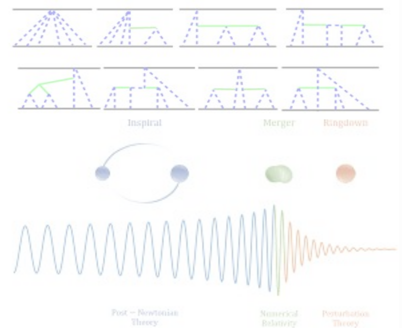

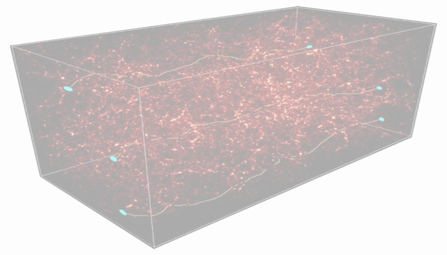

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**Description:** Adaptation of existing codes that calculate Large Scale Structure observables in standard cosmology, to allow for new physics effects, including integration with Markov Chain Monte Carlo packages. Development of user interface taking the linear cosmology evolution as input.

**Links:** WP3; **timing:** ~ 1 - 2 MCore-hours/yr

## Usecase Work Packages

1. Models & Diagrams
2. Amplitudes & Integrals
3. Cross Sections & Events
4. Physics at Colliders
5. Physics beyond Colliders

# WP1. Models & Diagrams

| Task T.1.1 | Title: Automatic Diagram Generation and Multi-Core Computing |
|---|---|
| **Contributors** | • nodes: UNIBO, UNINA, UNIPD<br>• staff: 4 : Maltoni, Peraro (UNIBO), Tramontano (UNINA), Mastrolia (UNIPD)<br>• new personnel: 1 RTDA (UNIPD), 1 PhD (UNIBO) |
| **Description** | Combination of existing tools for the evaluation of Feynman Integrals and Scattering Amplitudes, for applications to Particle Physics, with special relevance to the automatic calculation of two-loop virtual corrections of 2-to-2 and 2-to-3 scattering reactions, following the strategy applied to [1], based on the automatic generation of Feynman diagrams, on the simplification of the integrand [2], and on the minimization of the number of basic functions [3], appearing in the amplitude. |
| **Pilot projects/ References** | [1] M.~K.~Mandal, P.~Mastrolia, J.~Ronca and W.~J.~Bobadilla Torres,``Two-loop scattering amplitude for heavy-quark pair production through light-quark annihilation in QCD," JHEP \textbf{09} (2022), 129 [arXiv:2204.03466 [hep-ph]].<br>[2] P.~Mastrolia, T.~Peraro, A.~Primo and W.~J.~Torres Bobadilla, ``Adaptive Integrand Decomposition," PoS \textbf{LL2016} (2016), 007 [arXiv:1607.05156 [hep-ph]].<br>[3] A.~V.~Smirnov, ``Algorithm FIRE -- Feynman Integral REduction," JHEP \textbf{10} (2008), 107 [arXiv:0807.3243 [hep-ph]]. |
| **Computing Resources** | • CPU/time: 1MCore-hours/yr<br>• Disk Space : 10 TB |
| **Milestones** | • **M.1.1.1:** Interfacing diagram generators, algebraic manipulators, and softwares for integrands and integrals decomposition.<br>• **M.1.1.2**: Development of a software for multi-process amplitudes decomposition and multi-core/parallel computing |
| **Code name:** | **FeynCalc/FeynArt, AIDA (inhouse)** |
| **Progress monitoring** | • Interfacing: automatic generator, algebraic manipulators, decomposition lib., numerical evaluation lib. in AIDA<br>• Testing: phase-1 on massless amplitudes; phase-2 on massive amplitudes;<br>• User interface, sample calculations, and documentation for distribution |

# WP2. Amplitudes & Integrals

| Task T.2.1 | Title: Integrals Decomposition over Finite Fields |
|---|---|
| **Contributors** | • nodes: UNIBO, UNINA, UNIPD<br>• staff: 3 : Peraro (UNIBO), Tramontano (UNINA), Mastrolia (UNIPD)<br>• new personnel: 1 RTDA (UNIPD), 1 PhD (UNIBO) |
| **Description** | Developments of methods and tools for analytic and numerical calculation of Feynman Diagrams and Scattering Amplitudes, in gauge theories and EFTs, based on innovative mathematical and computer science methods, based on the reconstruction of rational functions over finite fields [1]. |
| **Pilot projects/ References** | [1] T.~Peraro, ``FiniteFlow: multivariate functional reconstruction using finite fields and dataflow graphs,'' JHEP \textbf{07} (2019), 031 [arXiv:1905.08019 [hep-ph]].<br>[2] R.~N.~Lee, ``LiteRed 1.4: a powerful tool for reduction of multiloop integrals,'' J. Phys. Conf. Ser. \textbf{523} (2014), 012059 [arXiv:1310.1145 [hep-ph]]. |
| **Computing Resources** | • CPU/time: 1MCore-hours/yr<br>• Disk Space : 15 TB |
| **Milestones** | • **M.2.1.1**: Efficient linear system solving via finite field reconstruction<br>• **M.2.1.2**: Automatic generation and solution of integration-by-parts identities |
| **Code name:** | **FiniteFlow, AIDA (inhouse)** |
| **Progress monitoring** | • Interfacing FiniteFlow, and integration-by-parts identity generators within AIDA<br>• Testing: phase-1 on one-loop 2-to-3 amplitudes; phase-2, on two-loop 2-to-3 amplitudes<br>• User interface, data flow graphics and documentation |

# WP2. Amplitudes & Integrals

| **Task T.2.2** | **Title: Integrals Evaluation** |
| --- | --- |
| **Contributors** | • nodes: UNIBO, UNINA, UNIPD<br>• staff: 4 : Peraro (UNIBO), Tramontano (UNINA), Gröber, Mastrolia (UNIPD)<br>• new personnel: 1 RTDA (UNIPD), 1 PhD (UNIBO) |
| **Description** | Developments of methods and tools for analytic and numerical calculation of Feynman Integrals based on the solutions of linear systems of 1st order partial differential equations (SPDE).<br>The SPDE are analytically derived, by means of integration-by-parts identities[1], and then solved numerically, following the strategy suggested in [2]. |
| **Pilot projects/ References** | [1] S.Laporta, High precision calculation of multiloop Feynman integrals by difference equations, Int. J. Mod. Phys. A 15 (2000)<br>[2] R.N. Lee, A.V. Smirnov and V.A. Smirnov, Solving differential equations for Feynman integrals by expansions near singular points, JHEP 03 (2018) 008 |
| **Computing Resources** | • CPU/time: 3 MCore-horse/yr<br>• Disk Space: 15 TB |
| **Milestones** | • **M.2.2.1**: Automatic generation of systems of differential equations for Feynman integrals<br>• **M.2.2.2**: Numerical solution of systems of differential equations for Feynman integrals |
| **Code name:** | **new library** |
| **Progress monitoring** | • Automatic generation and solution of SPDE for one- and two-loop integrals<br>• Comparison against the results of libraries dedicated to the direct numerical integration<br>• Testing: phase-1, in non-physical (Euclidean) region; phase-2, in physical (Minkowskian) region<br>• User interface, sample calculations, and documentation for distribution |

# WP3. Cross Sections & Events

| Task T.3.1 | Title: Accelerating Events Generation |
|---|---|
| **Contributors** | • node(s): UNIMIB<br>• staff: 3 : Alioli, Oleari, Re (UNIMIB)<br>• new personnel: – |
| **Description** | Improve the parallelization of existing event generators (POWHEG BOX, GENEVA) to take advantage of modern computing infrastructure and accelerators (GPU) and heterogeneous architectures, in preparation for the computing challenges of the LHC high-luminosity upgrade and other future colliders. |
| **Pilot projects/ References** | [1] S. Alioli, P. Nason, C. Oleari and E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, *JHEP* 06 (2010) 043<br>[2] S. Alioli, C. Bauer, C. Berggren, F. Tackmann et al., Matching Fully Differential NNLO Calculations and Parton Showers, *JHEP* 06 (2014) 089 |
| **Computing Resources** | • CPU/time: 3 MCore-hours/yr<br>• Disk Space: 10 TB |
| **Milestones** | • **M.3.1.1:** Improved parallelization and efficiency for event generation |
| **Code name:** | POWHEG BOX, GENEVA |
| **Progress monitoring** | • check the new phase-space parallel GPU generator against the existing serial CPU one<br>• test the performances of the new phase-space generator<br>• check the parallel computation of matrix elements on GPU against the existing CPU one<br>• perform tests on the efficiency of the parallel generation and speed up of the integration procedure |

# WP3. Cross Sections & Events

| **Task T.3.2** | **Title: Deconstruction of signals of new physics, Cross Sections and PDFs** |
|---|---|
| **Contributors** | • node(s): UNICAL<br>• staff: 1 : A. Papa (UNICAL)<br>• new personnel: 1 RTDA : L. Panizzi (UNICAL) |
| **Description** | Implementation of a modular and collaborative framework for model-independent analyses of signatures of new physics at colliders (DeSigN). Generation of public databases with simulated samples categorized by independent and new-physics-induced kinematics features. Implementation of software tools to select and combine database elements through weighted sums to describe the predictions of different classes of models, and to perform parametric fits of experimental data. Extension of the framework to address the numerical evaluation of hadronic cross sections in hadronic processes and global fits of partonic distributions in hadrons, with special reference to the (unintegrated in the transverse momentum) gluon distribution (UGD) in the proton.<br><br>Deliverables: public portal with user interface to access, integrate and expand the databases of simulated samples; software tools to perform analyses and fits; codes for the extension of the framework to hadronic cross-sections and PDFs. |
| **Pilot projects/ References** | [1] S. Moretti, L. Panizzi, J. Sjölin and H. Waltari, ``Deconstructing squark contributions to di-Higgs production at the LHC,'' arXiv:2302.03401 [hep-ph]<br>[2] A. Deandrea, T. Flacke, B. Fuks, L. Panizzi and H. S. Shao, ``Single production of vector-like quarks: the effects of large width, interference and NLO corrections,'' JHEP 08 (2021), 107 [erratum: JHEP 11 (2022), 028]<br>[3] A.D. Bolognino, F.G. Celiberto, D.Yu. Ivanov and A. Papa, ``Unintegrated gluon distribution from forward polarized \rho-electroproduction,'' Eur. Phys. J. C \textbf{78} (2018) no.12, 1023. |
| **Computing Resources** | • CPU-time: 2MCore-hours/yr<br>• Disk Space: 5TB |
| **Milestones** | • **M.3.2.1:** Public portal and database collections<br>• **M.3.2.2:** Software tools for phenomenological studies and experimental data analyses<br>• **M.3.2.3:** Automatisation of database expansion<br>• **M.3.2.4:** Hadronic cross-sections and PDFs |

# WP4. Physics at Collider

| Task T.4.1 | Title: Accurate Predictions for Collider Phenomenology |
|---|---|
| **Contributors** | • nodes: UNIBO, UNINA, UNIPD<br>• staff: 5 Maltoni, Peraro (UNIBO), Tramontano (UNINA), Gröber, Mastrolia, Zanetti (UNIPD)<br>• new personnel: 1PhD |
| **Description** | Exploring analytical, numerical methods and new computational architectures to bring predictions for collider phenomenology up to the challenges of future experiments, in terms of accuracy (two-loop) and speed. For order of magnitude improvements in speed we plan to work on the parallelization of MadGraph on GPU's also using Machine Learning methods. |
| **Pilot projects/ References** | [1] A.~Butter, T.~Plehn, S.~Schumann, S.~Badger, S.~Caron, K.~Cranmer, F.~A.~Di Bello, E.~Dreyer, S.~Forte and S.~Ganguly, \textit{et al.} ``Machine Learning and LHC Event Generation,'' [arXiv:2203.07460 [hep-ph]].<br>[2] L.~Alasfar, R.~Gr\"ober, C.~Grojean, A.~Paul and Z.~Qian, ``Machine learning the trilinear and light-quark Yukawa couplings from Higgs pair kinematic shapes,'' JHEP \textbf{11} (2022), 045 [arXiv:2207.04157 [hep-ph]].<br>[3]. M.~Migliorini, R.~Castellotti, L.~Canali and M.~Zanetti, ``Machine Learning Pipelines with Modern Big Data Tools for High Energy Physics,'' Comput. Softw. Big Sci. \textbf{4} (2020) no.1, 8 [arXiv:1909.10389 [cs.DC]]. |
| **Computing Resources** | • CPU/time: 1 MCore-hours/yr<br>• Disk Space : 10 TB |
| **Milestones** | • **M.4.1.1:** Developing parallelization on GPU for MadGraph<br>• **M.4.1.2:** Machine Learning techniques for collider phenomenology<br>• **M.4.1.2:** Multi-loop calculus for collider phenomenology |
| **Code name:** | MadGraph, Aida, FiniteFlow + inhouse |
| **Progress monitoring** | • Testing: Performance of GPU in comparison to the existing CPU based computation;<br>• Optimization of two-loop 2-to-2 and 2-to-3 amplitudes' evaluation<br>• User interface, sample calculations, and documentation for distribution |

# WP4. Physics at Collider

| Task T.4.2 | Title: Optimized Strategies for New Particles and Coupling |
|---|---|
| **Contributors** | • nodes: UNIPD<br>• staff: 2 : Gröber, Salvioni (UNIPD)<br>• new personnel: – |
| **Description** | [1] Inclusion of higher-order effects as well as SMEFT effects in existing codes for Higgs and top physics, allowing access to less constrained couplings through virtual corrections. [2] Development of a code describing hadronic production and decay of new GeV-scale particles at intensity- and energy-frontier experiments, optimized to enable fast evaluation for arbitrary input parameters. |
| **Pilot projects/ References** | [1] R. Bonciani, G. Degrassi, P. Giardino, R. Gröber “Analytic method for Next-To-Leading Order QCD corrections to Double-Higgs production”, Phys. Rev. Lett. 121 (2018) 016.<br>[2] H.-C. Cheng, L. Li, E. Salvioni “A theory of dark pions”, JHEP 01 (2022) 122. |
| **Computing Resources** | • CPU/time: 1 MCore-hours/yr<br>• Disk Space : 5 TB |
| **Milestones** | • **M.4.2.1:** Ameliorated software for Double Higgs Production at NLO QCD including new-physics effects<br>• **M.4.2.2:** Software for evaluation of ALP decay widths, extended to arbitrary EFT parameter inputs |
| **Code name:** | **TBD** |
| **Progress monitoring** | [1]<br>• performance checks in various kinematic limits<br>• cross-check with existing tools in SM limit<br>• benchmarking new physics effects for when existing tools can be used<br>• inclusion of higher-order SMEFT effects<br>[2]<br>• extension to general EFT parametrization<br>• cross-check against existing results<br>• optimization of amplitude evaluation and integration, to reduce running time |

# WP5. Physics beyond Colliders

| Task T.5.1 | Title: Scattering Amplitudes and Gravitational Waves |
|---|---|
| **Contributors** | • nodes: UNIPD<br>• staff: 2 : Bartolo, Mastrolia (UNIPD)<br>• new personnel: 1 RTDA (UNIPD) |
| **Description** | Combination of existing tools for analytic and numerical evaluation of Feynman Integrals and Scattering Amplitudes, for applications to Gravitational Wave Physics, with special relevance to the Post-Newtonian corrections to the gravitational potential of a coalescing binary system of compact objects. |
| **Pilot projects/ References** | [1] S.~Foffa, P.~Mastrolia, R.~Sturani, C.~Sturm and W.~J.~Torres Bobadilla,``Static two-body potential at fifth post-Newtonian order,'' Phys. Rev. Lett. \textbf{122} (2019) no.24, 241605 [arXiv:1902.10571 [gr-qc]].<br>[2] M.~K.~Mandal, P.~Mastrolia, R.~Patil and J.~Steinhoff, ``Gravitational Spin-Orbit Hamiltonian at NNNLO in the post-Newtonian framework,'', accepted by JHEP [arXiv:2209.00611 [hep-th]]. |
| **Computing Resources** | • CPU/time: 0,5 MCore-hours/yr<br>• Disk Space : 5 TB |
| **Milestones** | • **M.5.1.1**: EFT Diagrammatic Approach to Gravitational Wave Physics |
| **Code name:** | EFTtoPNG + in house code |
| **Progress monitoring** | • Interfacing: automatic generator, algebraic manipulators, decomposition lib.<br>• Compatibility with AIDA<br>• Testing: phase-1 static corrections; phase-2 non-static corrections; phase-3, spin-dependent corrections.<br>• User interface, sample calculations, and documentation for distribution |

# WP5. Physics beyond Colliders

| Task T.5.2 | Title: New Physics and Large Scale Structure |
|---|---|
| **Contributors** | • nodes: UNIPD<br>• staff: 4: Bartolo, Liguori, Raccanelli, Salvioni (UNIPD)<br>• new personnel: – |
| **Description** | Extension of codes that calculate Large Scale Structure observables in standard cosmology, to allow for new physics effects, including integration with Markov Chain Monte Carlo packages. Development of user interface taking the linear cosmology evolution as input. |
| **Pilot projects/ References** | [1] G. D'Amico, L. Senatore, P. Zhang, "Limits on wCDM from the EFTofLSS with the PyBird code", JCAP 01 (2021) 066, arXiv:2003.07956 [astro-ph.CO].<br>[2] J. Lesgourgues, "The Cosmic Linear Anisotropy Solving System (CLASS) I: overview", arXiv:1104.2932 [astro-ph.IM]. |
| **Computing Resources** | • CPU/time: 2 MCore-hours/yr<br>• Disk Space : 5 TB |
| **Milestones** | • **M.5.2.1**: Enhancement of existing software evaluating LSS observables to include New Physics effects<br>• **M.5.2.2**: Integration with Markov chain MonteCarlo for parameter space exploration |
| **Code name:** | PyBird (https://github.com/pierrexyz/pybird) [1] |
| **Progress monitoring** | • for given model, cross-checks of linear cosmology with CLASS [2]<br>• implementation of power spectrum of biased tracers by extending PyBird<br>• MCMC analysis |

# NETWORKING

**Network activities**

- Regular meetings (remotely and in presence) among nodes members, to monitor the evolution of the various research lines

- Regular participation to and organization of international workshops on Advanced Computing and Analysis Techniques in Physics Research, such as the ACAT workshop series

- Training activities: training weeks, and school organization

- Meetings dedicated to the development of cross-disciplinary projects

- Fostering the interest of researchers and softwares developers for the update and the continuous maintenance and update of existing valuable tools, preventing the risk of their obsolescence.

# CONCLUSIONS

***Deliverables***

**Software** relevant for Particle Phenomenology (.and. GW Physics .and. Math)
@ LHC upgrade and future colliders and experiments
[c++, phython, fortran, mathematica/maple]-libraries
– multi-purpose/process (broad-brush) tools .and. specific target oriented packages
– publically available in dedicated repository / website
– high-confidence level / feasibility and high-impact for precision physics
– testbed available

***Resources Requests***

**Human resources:** 2 RTDA's, 3 (+1) PhD's
**CPU timing allocation:** O(MCore-hours/yr/use case) in production mode; fewer in R&D and tests
**Disk Space allocation:** O(100 TB)
**Software Licences:** Mathematica, Maple, others.

***Cross-links***

**w/ WP2 + WP3:** (R&D) exploit/share common computational techniques
**w/ WP4:** (R&D.and.Production mode) scalability and GPU/GPU multi-cores clusters
**w/ WP5:** (R&D.and.Production mode) long-term data preservation
**w/ WP6:** (R&D) computational topology for Data Science