Gruppo IV (SPIF)

Stefano Carrazza, Giancarlo Ferrera, Stefano Forte,
Claudia Frugiuele, **Raoul Röntsch**, Alessandro Vicini,
Ramon Winterhalder, Marco Zaro + postdocs & students

Istituto Nazionale di Fisica Nucleare

Consiglio di Sezione INFN

15/07/2025

Overlap with other INFN groups/initiatives

- Machine learning: Stefano Carrazza, Stefano Forte, Alessandro Vicini, Ramon Winterhalder, Marco Zaro
- Quantum computing: Stefano Carrazza
- JUNO: Vito Antonelli

+ synergies with ATLAS & LHCb groups

The Standard Model of Particle Physics

Theoretical description of elementary particles:

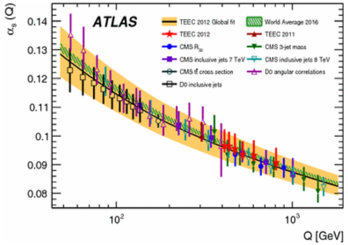
- Quantum mechanics + special relativity + gauge invariance → **Q**uantum **F**ield **T**heory
- Mathematical formulation of high energy particle physics.

→ Quantum Electrodynamics (QED)

$$a_e^{\text{th.}} = 1.15965218188(78) \times 10^{-3}$$

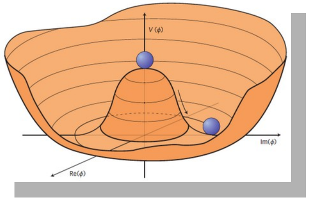
$$a_e^{\text{expt}} = 1.15965218073(28) \times 10^{-3}$$

→ Quantum Chromodynamics (QCD)

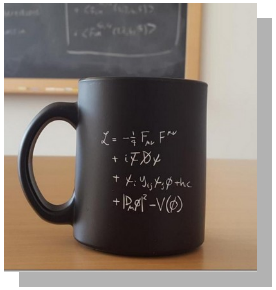


→ Electroweak force (EW)

with spontaneous symmetry breaking of electroweak symmetry (EWSB) through Higgs mechanism.

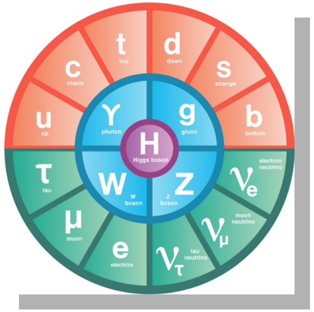


The Standard Model of Particle Physics



QCD + electroweak theory + Higgs mechanism
= **S**tandard **M**odel of Particle Physics:

Mathematically consistent & concise
description of nature at fundamental level.



- New questions:
  - Is it really the *SM Higgs?*
  - What is the *exact form* of the Higgs potential?
  - How does it couple to the rest of the SM?
  - Is it *solely* responsible for EWSB?
  - …
  -

➡ In-depth investigations of the Higgs boson

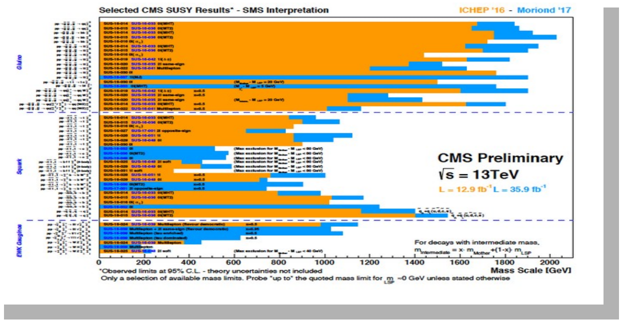
Fundamental properties (mass, spin,…), couplings to other SM particles, self-couplings, high energy behavior, ….

Beyond the Standard Model

- Abundant evidence that SM cannot be complete...

  (Gravity not included in the SM; astrophysical and cosmological evidence for dark matter; neutrinos oscillate and therefore have mass; matter-antimatter asymmetry; hierarchy problem...)

- ...but no evidence for BSM physics at LHC.



- Stress-test SM in search of new physics:
  - ➢ Can we observe traces of BSM physics in SM processes?

    → use **E**ffective **F**ield **T**heory to parametrize BSM physics

    (Analogous to Fermi theory for weak interactions)

  - ➢ Test self-consistency of SM

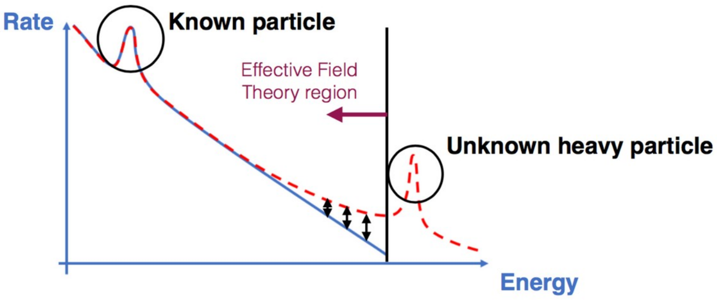


Image: E. Vryonidou

$$m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\alpha}{G_\mu\sqrt{2}m_Z^2}(1+\Delta r)}\right)$$

→ compare predictions and measurements of m_W

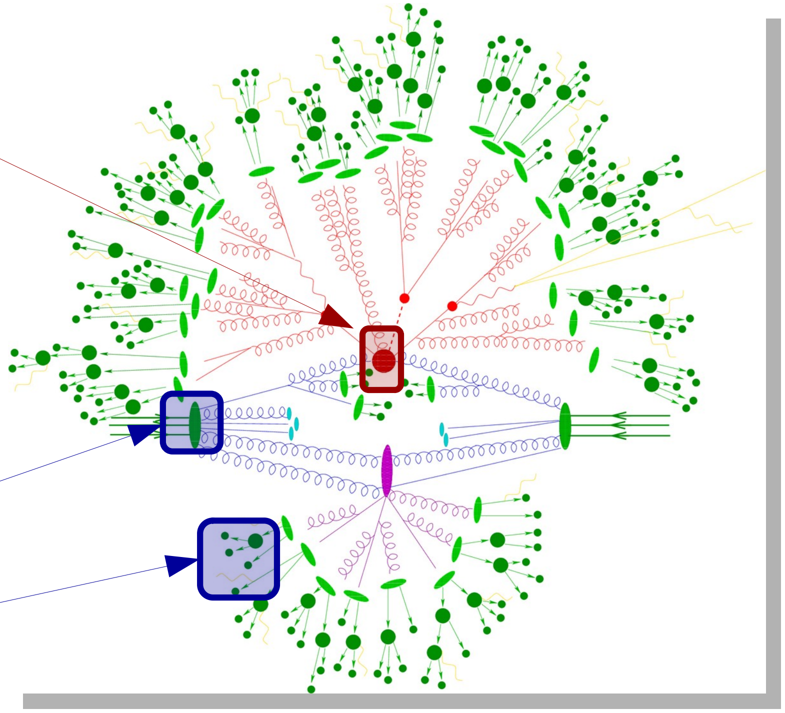
Theoretical Predictions

Schematic view of collision at LHC:

Energy

SM (BSM?) interactions

Q ~ 100 GeV – 1 TeV



Protons in beam

Hadrons in detector

Q ~ 1 GeV

Image: F. Kraus

Theoretical Predictions

Schematic view of collision at LHC:

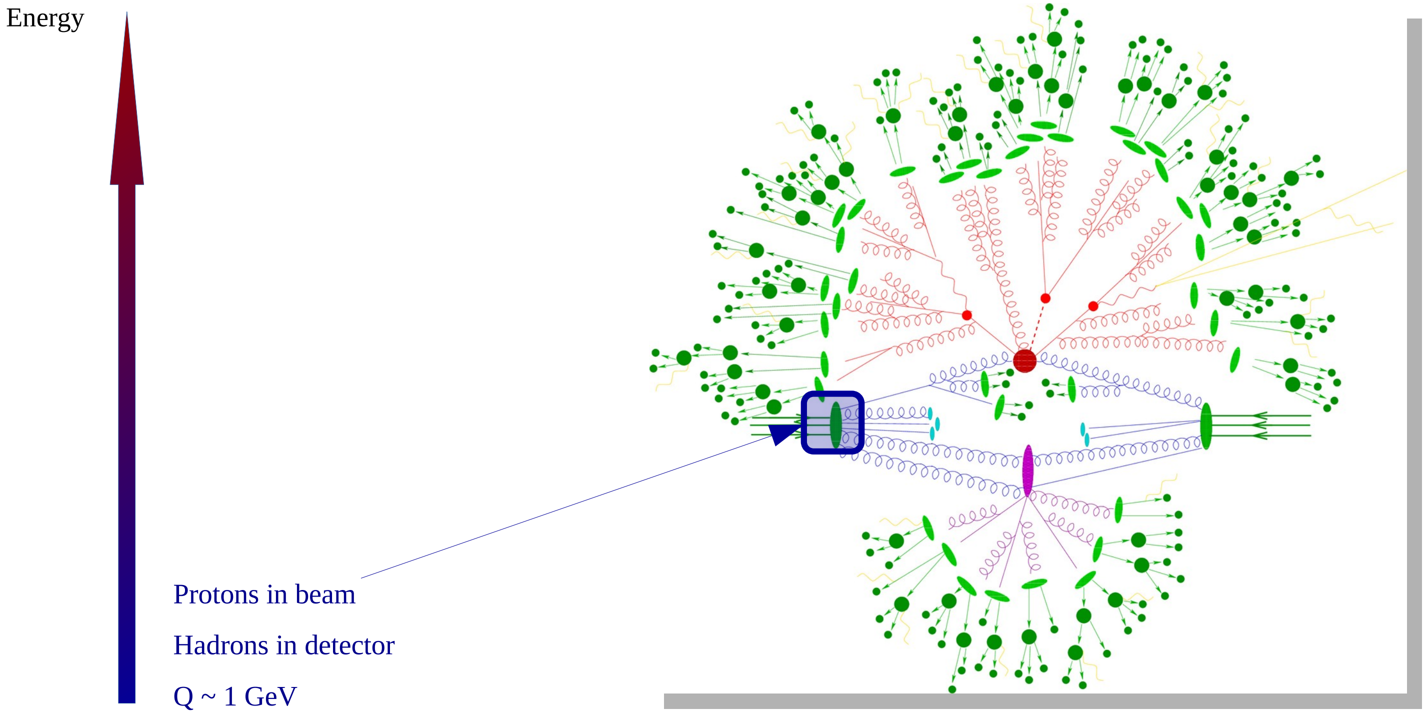


Image: F. Kraus

Challenge #1: understand behavior of partons (=quarks and gluons) inside protons

→ **p**arton **d**istribution **f**unctions

Parton distribution functions

- PDFs not analytically computable (confinement), determined from fits to data.

NNPDF → using neural nets / machine learning to perform fit

(Stefano Carrazza,
Stefano Forte)

- Inclusion of higher order QCD/QED effects in pdfs;
- Photon content of proton;
- Estimating theory uncertainties;
- Faithfulness of fits with inconsistent data;
- Determination of strong coupling;
- ...

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- ...

Evaluating the faithfulness of PDF uncertainties in the presence of inconsistent data

Andrea Barontini,[a] Mark N. Costantini,[c] Giovanni De Crescenzo,[b] Stefano Forte,[a] and Maria Ubiali[c]

in which uncorrected inconsistencies are present. Taken together, these results provide a reassuring indication that as more data are included in global PDF determination, thereby making PDFs more precise, it will be possible to achieve an accuracy that matches the level of precision.

hep-ph/2503.17447

Parton distribution functions

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- Faithfulness of fits with inconsistent data;
- Determination of strong coupling;
  - Impacts every LHC process
  - Significant source of uncertainty for e.g. Higgs investigations.

A Determination of $\alpha_s(m_Z)$ at $\mathrm{aN^3LO_{QCD}} \otimes \mathrm{NLO_{QED}}$ Accuracy from a Global PDF Analysis

The NNPDF Collaboration:
Richard D. Ball[1], Andrea Barontini[2], Juan Cruz-Martinez[3], Stefano Forte[2], Felix Hekhorn[4,5], Emanuele R. Nocera[6], Juan Rojo[7,8], and Roy Stegeman[1]

- Its methodology is validated by a closure test.
- Uncertainties include the MHOUs on the processes used for PDF determination both at NNLO and $\mathrm{aN^3LO}$.
- Effects of mixed QCD⊗QED evolution and the photon PDF are accounted for.

hep-ph/2506.13871

Parton distribution functions

- PDFs not analytically computable (confinement), determined from fits to data.

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(Stefano Carrazza,
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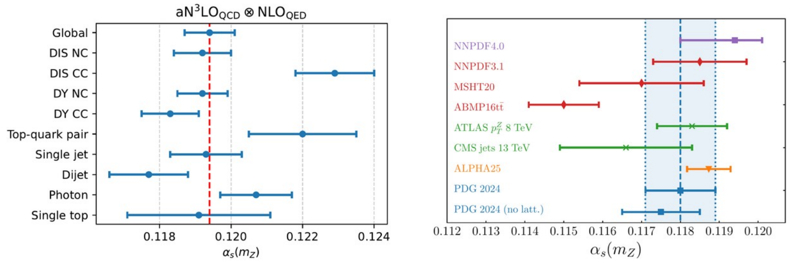

hep-ph/2506.13871

Parton distribution functions

- PDFs assume zero transverse momentum
- Extend to small (but non-zero) transverse momentum → **t**ransverse **m**omentum **d**istribution

JI

A Neural-Network Extraction of Unpolarised Transverse-Momentum-Dependent Distributions

The **MAP** (Multi-dimensional Analyses of Partonic distributions) Collaboration

Alessandro Bacchetta,[1, 2, *] Valerio Bertone,[3, †] Chiara Bissolotti,[4, ‡] Matteo Cerutti,[5, 6, §] Marco Radici,[2, ¶] Simone Rodini,[7, **] and Lorenzo Rossi[8, 9, ††]

hep-ph/2502.04166

Conclusions

In this work, we presented the first extraction of the unpolarised quark TMD PDFs in the proton from a comprehensive set of DY data using a parametrisation for the nonperturbative part based on a NN. Our results employ

Theoretical Predictions

Schematic view of collision at LHC:

Energy

SM (BSM?) interactions

Q ~ 100 GeV – 1 TeV

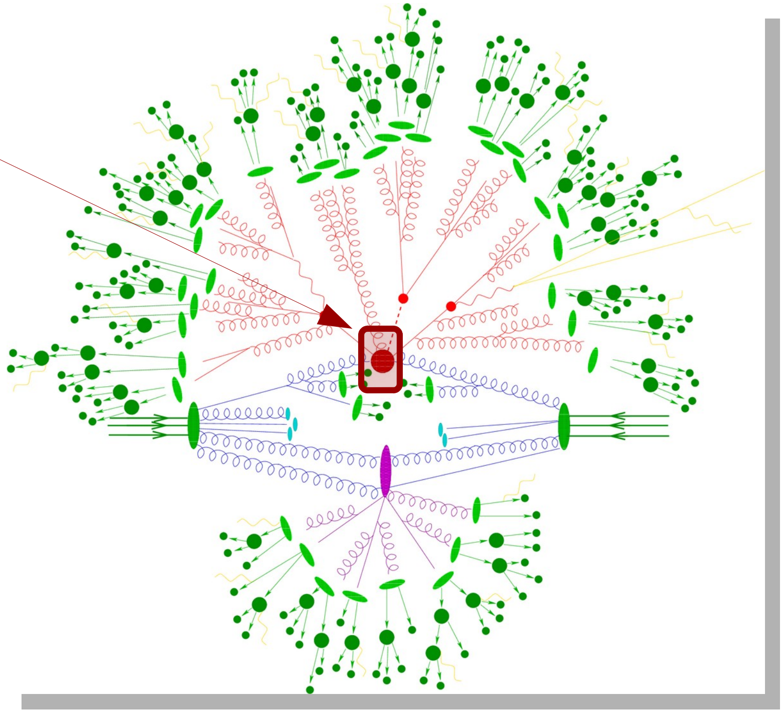

Image: F. Kraus

Challenge #2: compute hard (high-energy) scattering process

Theoretical Predictions

Schematic view of collision at LHC:

Energy

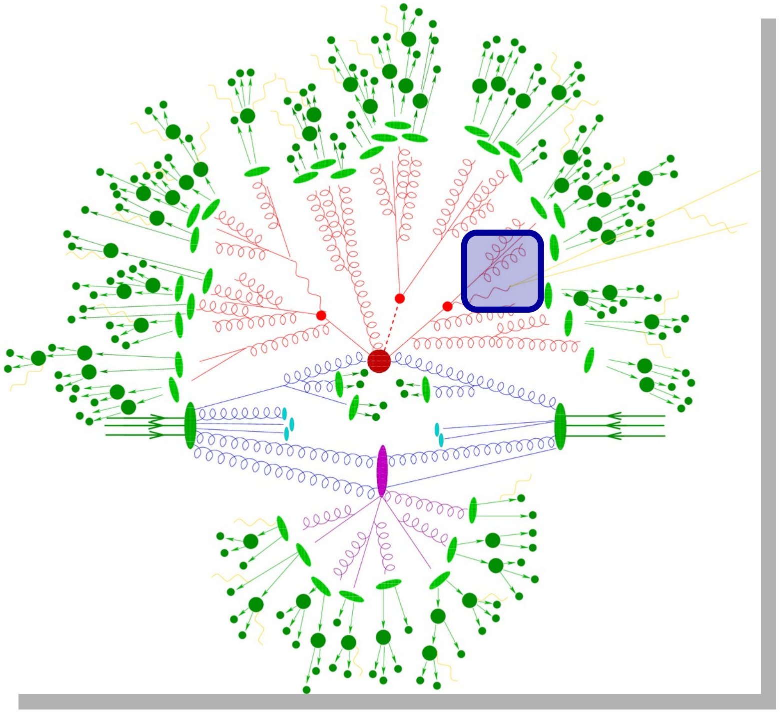

Image: F. Kraus

Challenge #3: account for multiple radiated partons

Theoretical Predictions

- QFTs of SM not analytically solvable – compute perturbatively in strong and EW couplings

$$\mathrm{d}\hat{\sigma} = \mathrm{d}\hat{\sigma}^{(0,0)} + \alpha_s\,\mathrm{d}\hat{\sigma}^{(1,0)} + \alpha_s^2\,\mathrm{d}\hat{\sigma}^{(2,0)} + \alpha_s^3\,\mathrm{d}\hat{\sigma}^{(3,0)} + \alpha\,\mathrm{d}\hat{\sigma}^{(0,1)} + \alpha\alpha_s\,\mathrm{d}\hat{\sigma}^{(1,1)} + \ldots$$

Leading Order (LO)	NLO QCD	NNLO QCD	N3LO QCD	NLO EW	Mixed QCD-EW

- Two major obstacles in computing higher order corrections:

1) Calculating multi-loop amplitudes (Feynman integrals)

2) Treatment of infrared singularities

(Giancarlo Ferrera, Stefano Forte, Raoul Röntsch, Alessandro Vicini, Marco Zaro)

Techniques for higher-order calculations

- Current state-of-the-art: $2 \rightarrow 3$ processes at NNLO QCD
- Often require ~ 10 million CPU hours
- Improvements in calculational techniques is an active field

Towards a general subtraction formula for NNLO QCD corrections to processes at hadron colliders: final states with quarks and gluons

Federica Devoto,[a] Kirill Melnikov,[b] Raoul Röntsch,[c] Chiara Signorile-Signorile,[d] Davide Maria Tagliabue,[b,c] Matteo Tresoldi[b]

hep-ph/2503.15251

Saddle-point method for resummed form factors in QCD

Ugo Giuseppe Aglietti[(a)], Giancarlo Ferrera[(b)] and Wan-Li Ju[(c)]

hep-ph/2506.18707

Theoretical Predictions

- Want calculations to be used by community → efficient, stable, public codes

Hardware acceleration for next-to-leading order event generation within MadGraph5_aMC@NLO

Zenny Wettersten[1,2,*], *Olivier* Mattelaer[3], *Stefan* Roiser[1], *Andrea* Valassi[1], and *Marco* Zaro[4]

(Ramon Winterhalder, Marco Zaro)

hep-ph/2503.07439

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Zenny Wettersten[1,2,*], *Olivier* Mattelaer[3], *Stefan* Roiser[1], *Andrea* Valassi[1], and *Marco* Zaro[4]

(Ramon Winterhalder, Marco Zaro)

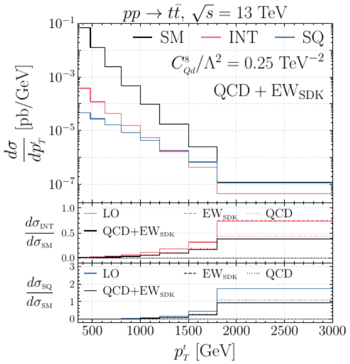
hep-ph/2503.07439

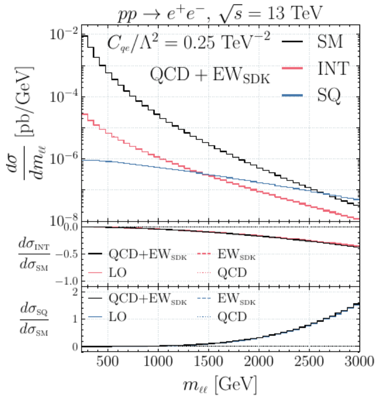
- Interplay of SMEFT effects and higher-order corrections

Electroweak corrections in the SMEFT: four-fermion operators at high energies

Hesham El Faham,[a] Ken Mimasu,[b] Davide Pagani,[c] Claudio Severi,[a] Eleni Vryonidou,[a] Marco Zaro[d,e]

hep-ph/2412.16076





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(Ramon Winterhalder, Marco Zaro)

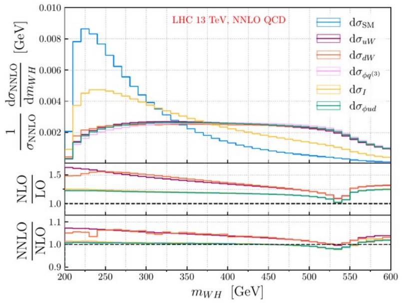
hep-ph/2503.07439

- Interplay of SMEFT effects and higher-order corrections

WH production at the LHC within SMEFT at next-to-next-to-leading order QCD

Marco Bonetti,[1,2,3,*] Robert V. Harlander,[3,†] Dmitrii Korneev,[3,‡] Ming-Ming Long,[4,§] Kirill Melnikov,[4,¶] Raoul Röntsch,[5,6,**] and Davide Maria Tagliabue[4,5,6,††]

hep-ph/2502.12846



Lepton colliders

- Revisiting old LEP data and planning for future e+e- collider

Double neutral-current corrections to NLO electroweak leptonic cross sections

Stefano Frixione,[a] Fabio Maltoni,[b,c,d] Davide Pagani,[d] Marco Zaro[e,f]

hep-ph/2506.10732

Heavy quark mass effects in the Energy-Energy Correlation in the back-to-back region

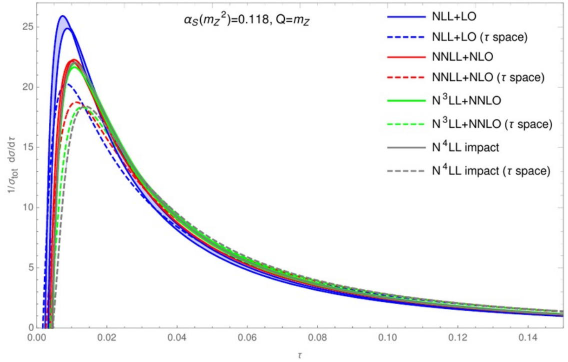
Ugo Giuseppe Aglietti[(a)] and Giancarlo Ferrera[(b)]

hep-ph/2412.02629

Thrust distribution in electron-positron annihilation at full N^{3}LL+NNLO (and beyond) in QCD

Ugo Giuseppe Aglietti[(a)], Giancarlo Ferrera[(b,c)], Wan-Li Ju[(c,d)] and Jiahao Miao[(b)]

hep-ph/2502.01570



Machine Learning

ML becoming ubiquitous in HEP – need to understand its limits as well as opportunities it provides.

- Improving HEP simulations using ML… … while keeping computational costs low

Accurate Surrogate Amplitudes with Calibrated Uncertainties

Henning Bahl[1], Nina Elmer[1], Luigi Favaro[1,2], Manuel Haußmann[3], Tilman Plehn[1,4], and Ramon Winterhalder[5]

hep-ph/2412.12069

BitHEP — The Limits of Low-Precision ML in HEP

Claudius Krause[1], Daohan Wang[1] and Ramon Winterhalder[2]

hep-ph/2504.03387

Quantum Computing

- Quantum sensors for DM searches

Transmon qubit modeling and characterization for Dark Matter search

R. Moretti,[1,2,3] D. Labranca,[1,2,3,4] P. Campana,[1,2,3] R. Carobene,[1,2,3] M. Gobbo,[1,2,3] M. A. Castellanos-Beltran,[4] D. Olaya,[4,5] P. Hopkins,[4] L. Banchi,[6,7] M. Borghesi,[1,2,3] A. Candido,[8] S. Carrazza,[8,9,10,11] H. A. Corti,[1,2,3] A. D'Elia,[12] M. Faverzani,[1,2,3] E. Ferri,[2] A. Nucciotti,[1,2,3] L. Origo,[1,2,3] A. Pasquale,[9,10,11] A. S. Piedjou Komnang,[12] A. Rettaroli,[12] S. Tocci,[12] C. Gatti,[12] and A. Giachero[1,2,3,13]

hep-ph/2409.05988

- ML for QC

AI-Powered Noisy Quantum Emulation: Generalized Gate-Based Protocols for Hardware-Agnostic Simulation

Matthew Ho,[1,*] Jun Yong Khoo,[1,†] Adrian M. Mak,[1] and Stefano Carrazza[2,3,4,5]

hep-ph/2502.19872

- Middleware for quantum computing emulation and calibration (Qibo)

Qibocal: an open-source framework for calibration of self-hosted quantum devices

Andrea Pasquale,[1,2,3] Edoardo Pedicillo,[1,2] Juan Cereijo,[2] Sergi Ramos-Calderer,[2,4] Alessandro Candido,[5] Gabriele Palazzo,[2,6] Rodolfo Carobene,[7,8,9] Marco Gobbo,[7,8,9] Stavros Efthymiou,[2] Yuanzheng Paul Tan,[10] Ingo Roth,[2] Matteo Robbiati,[1,11] Jadwiga Wilkens,[2,12] Alvaro Orgaz-Fuertes,[2] David Fuentes-Ruiz,[2] Andrea Giachero,[7,8,9] Frederico Brito,[13,2] José I. Latorre,[2,14,4] and Stefano Carrazza[5,1,3,2]

hep-ph/2410.00101

Synergy with INFN Gruppo V: QUART&T

Community-wide involvement

State-of-the-art cross sections for $t\bar{t}H$: NNLO predictions matched with NNLL resummation and EW corrections

Roger Balsach[1] Alessandro Broggio[2] Simone Devoto[3] Andrea Ferroglia[4] Rikkert Frederix[5] Massimiliano Grazzini[6] Stefan Kallweit[6] Anna Kulesza[1] Javier Mazzitelli[7] Leszek Motyka[8] Davide Pagani[9] Benjamin D. Pecjak[10] Chiara Savoini[11] Tomasz Stebel[8] Malgorzata Worek[12] Marco Zaro[13]

hep-ph/2503.15043

Theoretical modeling of QCD radiation in off-shell Higgs production through gluon fusion

Rafael Coelho Lopes de Sá[1⋆], Martina Javurkova[1,2†], Matteo Lazzeretti[3‡] and Raoul Röntsch[3,4∘]

hep-ph/2506.17022

Quantum Information meets High-Energy Physics: Input to the update of the European Strategy for Particle Physics

Contact Persons: Yoav Afik [*1], **Federica Fabbri** [†2,3], **Matthew Low** [‡4], **Luca Marzola** [§5,6],
Juan Antonio Aguilar-Saavedra[7], Mohammad Mahdi Altakach[8], Nedaa Alexandra Asbah[9], Yang Bai[10,11], Hannah Banks[12], Alan J. Barr[13], Alexander Bernal[7], Thomas E. Browder[14], Paweł Caban[15], J. Alberto Casas[7], Kun Cheng[4], Frédéric Déliot[16], Regina Demina[17], Antonio Di Domenico[18,19], Michał Eckstein[20], Marco Fabbrichesi[21], Benjamin Fuks[22], Emidio Gabrielli[5,21,23], Dorival Gonçalves[24], Radosław Grabarczyk[25], Michele Grossi[9], Tao Han[4], Timothy J. Hobbs[11], Paweł Horodecki[26,27], James Howarth[28], Shih-Chieh Hsu[29], Stephen Jiggins[30], Eleanor Jones[30], Andreas W. Jung[31], Andrea Helen Knue[32], Steffen Korn[33], Theodota Lagouri[34], Priyanka Lamba[2,3], Gabriel T. Landi[17], Haifeng Li[35], Qiang Li[36], Ian Low[11,37], Fabio Maltoni[2,3,38], Josh McFayden[39], Navin McGinnis[40], Roberto A. Morales[41], Jesús M. Moreno[7], Juan Ramón Muñoz de Nova[42], Giulia Negro[31], Davide Pagani[3], Giovanni Pelliccioli[43,44], Michele Pinamonti[45,46], Laura Pintucci[45,46], Baptiste Ravina[9], Alim Ruzi[36], Kazuki Sakurai[47], Ethan Simpson[48], Maximiliano Sioli[2,3], Shufang Su[40], Sokratis Trifinopoulos[49], Sven E. Vahsen[14], Sofia Vallecorsa[9], Alessandro Vicini[50,51], Marcel Vos[52], Eleni Vryonidou[48], Chris D. White[53], Martin J. White[54], Andrew J. Wildridge[31], Tong Arthur Wu[4], Laura Zani[55], Yulei Zhang[29], and Knut Zoch[56]

hep-ph/2504.00086

Les Houches 2023 - Physics at TeV Colliders: Report on the Standard Model Precision Wishlist

Alexander Huss[1], Joey Huston[2], Stephen Jones[3], Mathieu Pellen[4], Raoul Röntsch[5]

hep-ph/2504.06689

Community-wide involvement

Looking to the future:

Precision phenomenology at multi-TeV muon colliders

Stefano Frixione,[a] Fabio Maltoni,[b,c,d] Davide Pagani,[d] Marco Zaro[e,f]

hep-ph/2506.10733

ECFA Higgs, electroweak, and top factory study

hep-ph/2506.15390

Future Circular Collider Feasibility Study Report

hep-ph/2505.00274

Summary

Group is extremely active:

- Covers most areas of perturbative QCD & precision collider physics:
  - PDFs
  - Fixed-order perturbative calculation
  - Resummation
  - Public availability of codes
- Different aspects of collider phenomenology: Drell-Yan, Higgs physics, top physics, jets, …
- BSM physics through SMEFT, ML in HEP, quantum computing, …
- Strong involvement across HEP community

THANK YOU FOR YOUR ATTENTION