

Fun Physics

Tilman Plehn

LHC physics

Complexity fun

Physics fun

Useful fun

Agentic fun

Doing Particle Physics because It's Fun

Tilman Plehn

Universität Heidelberg

TaoFest, May 2026



Tao's LHC program

Driven by curiosity

- dark matter?
- matter vs antimatter?
- origin of Higgs boson?

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MADPH-08-1002
FERMILAB-PUB-08/364
hep-ph/9811350

On Kaluza-Klein States from Large Extra Dimensions

Tao Han^(a), Joseph D. Lykken^(b) and Ren-Jie Zhang^(a)

^(a)Department of Physics, University of Wisconsin, Madison, WI 53706

^(b)Theory Group, Fermi National Accelerator Laboratory, Batavia, IL 60510

hep-ph/9811350 v2 29 Jan 1999

Abstract

We consider the novel Kaluza-Klein (KK) scenario where gravity propagates in the $4 + n$ dimensional bulk of spacetime, while gauge and matter fields are confined to the $3 + 1$ dimensional world-volume of a brane configuration. For simplicity we assume compactification of the extra n dimensions on a torus with a common scale R , and identify the massive KK states in the four-dimensional spacetime. For a given KK level n there are one spin-2 state, $(n-1)$ spin-1 states and $n(n-1)/2$ spin-0 states, all mass-degenerate. We construct the effective interactions between these KK states and ordinary matter fields (fermions, gauge bosons and scalars). We find that the spin-1 states decouple and that the spin-0 states only couple through the dilaton mode. We then derive the interacting Lagrangian for the KK states and Standard Model fields, and present the complete Feynman rules. We discuss some low energy phenomenology for these new interactions for the case when $1/R$ is small compared to the electroweak scale, and the ultraviolet cutoff of the effective KK theory is on the order of 1 TeV.



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Precision-LHC physics

- fundamental questions
- huge data set
- first-principle simulations
- answers hidden in complexity

FERMILAB-PUB-91/70-T

BNL-45990

March 1991

QCD Correction to the $pp \rightarrow WH$ and ZH Total Cross Sections

T. Han

*Fermi National Accelerator Laboratory**P.O. Box 500, Batavia, IL 60510*

and

S. Willenbrock

*Brookhaven National Laboratory**Upton, NY 11973*

Abstract

We calculate the QCD correction to the total cross section for the production of a Higgs boson in association with a W or Z boson at the LHC/SSC. The QCD-corrected cross section is insensitive to the choice of factorization and renormalization scales. Setting these scales to the invariant mass of the VH final state, the QCD correction increases the lowest-order cross section by about 17/15 percent in the DIS factorization scheme, and 12/10 percent in the $\overline{MS}$ scheme, at the LHC/SSC.



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Events in hypothetical theory worlds

- calculate scattering
- simulate QCD [do not 'model QCD data']
- much more than total rates

PHYSICAL REVIEW D **97**, 113004 (2018)

Higgs boson pair production at future hadron colliders: From kinematics to dynamics

Dorival Gonçalves,¹ Tao Han,¹ Felix Kling,² Tilman Plehn,³ and Michihisa Takeuchi⁴

¹*PITT PACC, Department of Physics and Astronomy, University of Pittsburgh,
Pittsburgh, Pennsylvania 15260, USA*

²*Department of Physics and Astronomy, University of California, Irvine, California 92697, USA*

³*Institut für Theoretische Physik, Universität Heidelberg, ITP Heidelberg 69120, Germany*

⁴*Kavli IPMU (WPI), UTIAS, Kashiwa, Chiba 277-8583, Japan*



(Received 15 April 2018; published 20 June 2018)

The measurement of triple Higgs coupling is a key benchmark for the Large Hadron Collider (LHC) and future colliders. It directly probes the Higgs potential and its fundamental properties in connection to new physics beyond the Standard Model. There exist two phase space regions with an enhanced sensitivity to the Higgs self-coupling, the Higgs pair production threshold, and an intermediate top pair threshold. We show how the invariant mass distribution of the Higgs pair offers a systematic way to extract the Higgs self-coupling, focusing on the leading channel $pp \rightarrow hh + X \rightarrow b\bar{b}\gamma\gamma + X$. We utilize new features of the signal events at higher energies and estimate the potential of a high-energy upgrade of the LHC and a future hadron collider with realistic simulations. We find that the high-energy upgrade of the LHC to 27 TeV would reach a 5σ observation with an integrated luminosity of 2.5 ab^{-1} . It would have the potential to reach 15% (30%) accuracy at the 68% (95%) confidence level to determine the Standard Model (SM) Higgs boson self-coupling. A future 100 TeV collider could improve the self-coupling measurement to better than 5% (10%) at the 68% (95%) confidence level.



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Future analyses

- compare simulations and data
 - discover exciting physics!
- **Make a difference — to us all!**



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- compare simulations and data
 - discover exciting physics!
- **Enjoy shaping the future**



Fits → machine learning

Complex data and analyses

- imagine SUSY (★)
with CP-phases (★★)
at an e^+e^- collider (★★★)

- 1 global analysis
- 2 optimal observables

→ Now called 'modern LHC physics'

hep-ph/0101106

MADPH-00-1207

TPI-00164

UPR-916-T

CP-Violating Phases in SUSY, Electric Dipole Moments, and Linear Colliders

V. Barger, T. Falk,¹ T. Han, J. Jiang,
T. Li,² and T. Plehn

Department of Physics, University of Wisconsin, Madison, WI 53706, USA

Abstract

We reexamine large CP-violating phases in the general Minimal Supersymmetric Standard Model, as well as more restricted models. We perform a detailed scan over parameter space to find solutions which satisfy the current experimental limits on the electric dipole moments of the electron, neutron and ^{199}Hg atom, exploring the allowed configurations of phases and masses, and we attempt to quantify the level of tuning of the parameters necessary to populate the regions of cancellations. We then consider the measurement of CP-violating phases at a future linear collider. We find that measurements of chargino and neutralino masses and production cross-sections allow for a determination of ϕ_1 (the phase of M_1) to a precision of $\pi/30$, while the EDM constraints require that θ_μ be too small to be measured. Using the EDM constraints we find that the CP-even model parameters and the phase ϕ_1 can be determined at a Linear Collider with 400 GeV c.m. energy. As long as some information on the size of $|\mu|$ is included in the observables, a measurement of ϕ_1 is guaranteed for $\phi_1 > \pi/10$. To unambiguously identify CP violation, we construct CP-odd kinematical variables at a linear collider. However, the CP asymmetries are rather small, typically about 0.1 – 1.5%, and it will be challenging to experimentally observe the predicted asymmetries.



Fits $\rightarrow$ machine learning

Complex data and analyses

- imagine SUSY ($\star$)
with CP-phases ($\star\star$)
at an e^+e^- collider ($\star\star\star$)

- 1 global analysis
- 2 optimal observables

$\rightarrow$ Now called 'modern LHC physics'

15 years later: fit $\rightarrow$ neural network

- approximate $d\sigma_\theta(x) \approx d\sigma(x)$
- learning $\phi \in \theta$

$\rightarrow$ θ data representation

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15 years later: fit $\rightarrow$ neural network

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$\rightarrow$ θ data representation

Phase space probabilities

- regression $x \rightarrow A_\theta(x)$
- classification $x \rightarrow p_\theta(x)$
- generation $r \sim \mathcal{N} \rightarrow x \sim p_\theta(x)$
- conditional generation $r \sim \mathcal{N} \rightarrow x \sim p_\theta(x|y)$

What to encode in θ ?

1. known symmetries
2. uncertainties
3. explainable structures

$\rightarrow$ New toy: physics representation learning



ATLAS, because it's fun!

NN-calorimeter calibration with uncertainties

- learned calibration w/ calibrated uncertainties
- systematics: noise
detector engineering
reality → clearly theorists' job!

$$\mathcal{R}_{\text{NN}}(x) \pm \Delta \mathcal{R}_{\text{NN}}(x) \approx \frac{E^{\text{obs}}(x)}{E^{\text{dep}}(x)}$$



ATLAS, because it's fun!

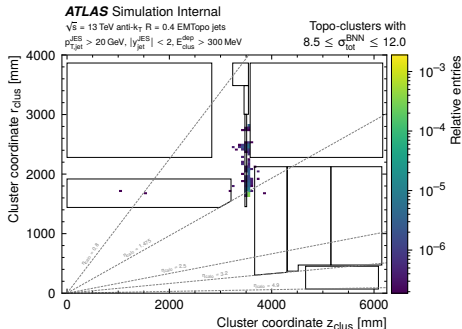
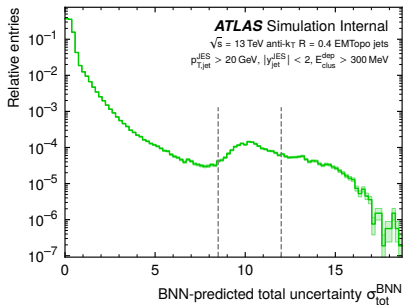
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$\rightarrow$ Understand ATLAS



hanlib → ML-MadGraph

Theory day job

- tools drive progress
- ideas need to come true

→ Perfect: fun projects paying the bills



hanlib $\rightarrow$ ML-MadGraph

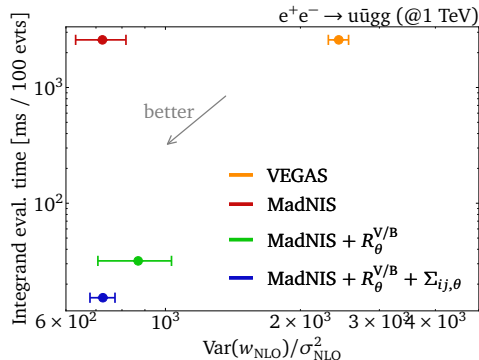
Theory day job

- tools drive progress
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Former Madison people: accelerate event generators

- virtual NN-amplitudes with uncertainties
- real NN-amplitudes with uncertainties
- neural importance sampling
- learned channel weights
- conditional on FKS sectors



hanlib → ML-MadGraph

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Former Madison people: accelerate event gener

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→ How close to 'NLO as fast as LO?'



hanlib → MadAgents

Agentic systems

- 1– autonomously solving problems, replacing researchers, producing knowledge, but...
...who will read that next paper?
...who cares about λ_{HHH} ?
 - 2– solving problems with domain tools
domain-specific standards
workflow acceleration
 - 3– interacting with researchers
designed to support humans
tutors, trainers, advisors
- Universities are not just research



hanlib → MadAgents

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Agents for users

1. install MadGraph-Pythia-Delphes-ROOT
2. train students
3. support experts
4. generate events autonomously



MadAgents at work

#3 Simulation support

· introduction

User

I am a PhD student working on precision simulations for top-quark processes at colliders.
I currently have a baseline leading-order, on-shell simulation for a given process and observable.

Task:

Critically assess the limitations of such a setup and propose systematic and conceptually distinct ways to improve its theoretical precision.

For each proposed improvement:

- Explain which physical effects are being captured that are missing at baseline level.
- Clarify when and why this improvement becomes important for realistic analyses.
- Indicate, at a high level, how such an improvement is typically implemented in modern Monte-Carlo simulations.

Reason from first principles and standard practice in collider phenomenology. The goal is to identify the dominant axes along which precision is improved, not to enumerate tools.



MadAgents at work

#3 Simulation support

- introduction
- improvements

MadAgents (shortened)

[...]

Dominant and conceptually distinct precision axes

Starting from a leading-order, on-shell baseline for top-quark processes, the main orthogonal directions along which theoretical predictions can be systematically improved are:

1. **Perturbative QCD accuracy in production and decay:** fixed-order calculations at NLO or NNLO, matching to parton showers (NLO+PS), and higher-order resummation at NNLO accuracy.
2. **Description of additional hard radiation:** inclusion of multi-jet matrix elements and their consistent merging with parton showers at LO or NLO accuracy.
3. **Finite-width and off-shell effects:** treatment beyond the narrow-width approximation, including the full resonance structure, non-resonant contributions, and interference effects.
4. **Electroweak and QED corrections:** NLO electroweak effects and photon radiation, which become increasingly relevant for high-scale observables and leptonic final states.
5. **All-order logarithmic structure:** higher-logarithmic resummation and improved parton-shower descriptions for observables sensitive to large scale hierarchies.
6. **Non-perturbative, PDF, and scheme uncertainties:** effects from hadronisation, the underlying event, colour reconnection, parton distribution functions and α_s , as well as choices of mass and renormalisation schemes.

In realistic precision top-quark analyses, several of these axes are typically combined. The appropriate level of sophistication is guided by which physical effects dominate the theoretical uncertainties for the observables and phase-space regions under consideration.



MadAgents at work

#3 Simulation support

- introduction
- improvements
- generate events

User (shortened)

Based on the precision-improvement axes identified above, the task is to construct and compare concrete simulation setups.

Simulation task: For each of the following strategies:

1. Higher-order QCD corrections (NLO+PS),
2. Finite-width and off-shell effects beyond the narrow-width approximation,
3. Hard additional radiation via matrix-element multi-jet merging,

do the following:

- Define a representative simulation setup implementing the respective strategy.
- Generate 50000 events for each setup using reasonable, standard choices.
- Clearly state all assumptions and simplifications, such as on-shell versus off-shell decays, jet multiplicities, or matching and merging schemes.

You may choose suitable tools, schemes, and defaults where needed, but avoid unnecessary over-optimisation.
[...]



MadAgents at work

#3 Simulation support

- introduction
- improvements
- generate events
- compare events

MadAgents (shortened)

Concrete setups and files

Common to all three:

- Collider: pp at $\sqrt{s} = 13$ TeV.
- $m_t = 172.5$ GeV, $\Gamma_t \approx 1.32$ GeV.
- PDFs: NNPDF3.1 NLO (LHAPDF ID 303400).
- Final state used in the comparison: **only** $t\bar{t} \rightarrow be^+ \nu_e \bar{b} \mu^- \bar{\nu}_\mu$ (no $e^- \mu^+$).
- Fiducial selection (analysis level): exactly 1 e and 1 μ (OS), $p_T > 25$ GeV, $|\eta| < 2.5$, isolated; at least 2 jets with $p_T > 25$ GeV, $|\eta| < 2.5$ and at least 1 truth b-tag.

Samples and locations:

1. NLO+PS on-shell (higher-order QCD axis)

- Process: $pp \rightarrow t\bar{t}$ [QCD] at NLO QCD, on-shell tops.
- Decays: LO MadSpin, $t \rightarrow be^+ \nu_e$, $\bar{t} \rightarrow \bar{b} \mu^- \bar{\nu}_\mu$.
- Matching: aMC@NLO to Pythia8, hadronisation+UE on. [...]

2. LO+PS off-shell 2 $\rightarrow$ 6 (off-shell axis)

- Process: $pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b}$ at LO QCD, with complex-mass scheme and all doubly-, singly- and non-resonant diagrams (full $W^+ W^- b \bar{b}$ structure).
- No separate decay step: leptons and b's appear directly from the ME, with finite widths.
- Shower: Pythia8, hadronisation+UE on. [...]

3. LO MLM-merged $t\bar{t}$ (+0,1j)+PS (hard-radiation axis)

- Processes: $pp \rightarrow t\bar{t}$, $pp \rightarrow t\bar{t}j$ at LO QCD (0 and 1 extra parton; 2-jet MEs were dropped due to a technical issue).
- Merging: MLM k_T with Pythia8, $x_{\text{cut}} \approx 30$ GeV, dynamic scale $\sim H_T/4$.
- Decays: LO MadSpin to the same $e^+ \mu^-$ channel as in NLO+PS. [...]

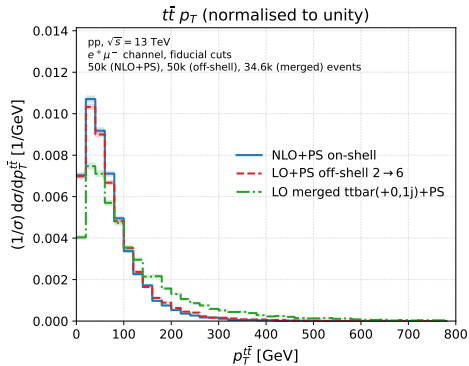


MadAgents at work

#3 Simulation support

- introduction
- improvements
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- compare events

→ [Explained set of plots](#)



MadAgents at work

#3 Simulation support

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→ [Explained set of plots](#)

#4 Autonomous generation

- reproduce a dataset

User

Please implement and execute the workflow described in the paper. As a final deliverable, I want the generated events, a histogram of the resonance reconstruction, and a bash script that can execute the end-to-end workflow (including creation of the resonance histogram). All deliverables must be saved, you may create suitable subdirectories.

Constraint: Your generated events and reconstructions must match the paper as closely as possible.

Persistence: Do not present partial or simplified results. Present the final results only if you believe you have recreated the workflow to the best of your ability and that the outputs match the paper as closely as reasonably possible.

Assumptions & Decisions: If any part of the paper is unclear or ambiguous, do not ask me. Instead, make a reasonable decision. In your final reply, list every unclear or ambiguous point you encountered and, for each one, state the decision you made and briefly explain your reasoning.



MadAgents at work

#3 Simulation support

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→ Explained set of plots

#4 Autonomous generation

- reproduce a dataset
- provide analysis note
- know your limits

MadAgents (shortened)

Simulation and analysis setup

The signal under study is a simplified scalar leptoquark S_1 with quantum numbers $S_1 \sim (\bar{3}, 1, 1/3)$, pair-produced in proton–proton collisions, followed by the decay chain

$$pp \rightarrow S_1 S_1^\dagger \rightarrow (\ell^+ j)(\ell^- j) \Rightarrow 2\ell + 2j \text{ final state,} \quad (5)$$

closely following the workflow outlined in the HEPTAPOD [51] short note and the MC4BSM-style tutorials.

Event generation.

Events are generated with MadGraph5_aMC@NLO v3.7.0 [5] interfaced to Pythia 8.3 [1] for parton showering and hadronisation. We use an existing public leptoquark UFO model, LQn1o_5FNS_v5_UFO, originally constructed in the FeynRules framework [54], and identify the HEPTAPOD scalar S_1 with the particle LQ1d

[...]

All non-trivial choices that are not fixed by the HEPTAPOD note (collider energy, PDF set, specific UFO model, Yukawa pattern, use of hadron-level rather than detector-level objects, exact cuts and binning) are documented in a separate “ambiguities and decisions” note that accompanies this analysis.



MadAgents at work

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#4 Autonomous generation

- reproduce a dataset

→ Find better ways to spend your time...



Thank you, Tao...

...for showing me how to enjoy physics and that...

...it is not about knowing answers

...it is not about solving problems

...it is about asking questions

...and working on them as a team

→ (Your) curiosity and excitement driving our field!

