Machine Learning Application for HEP community

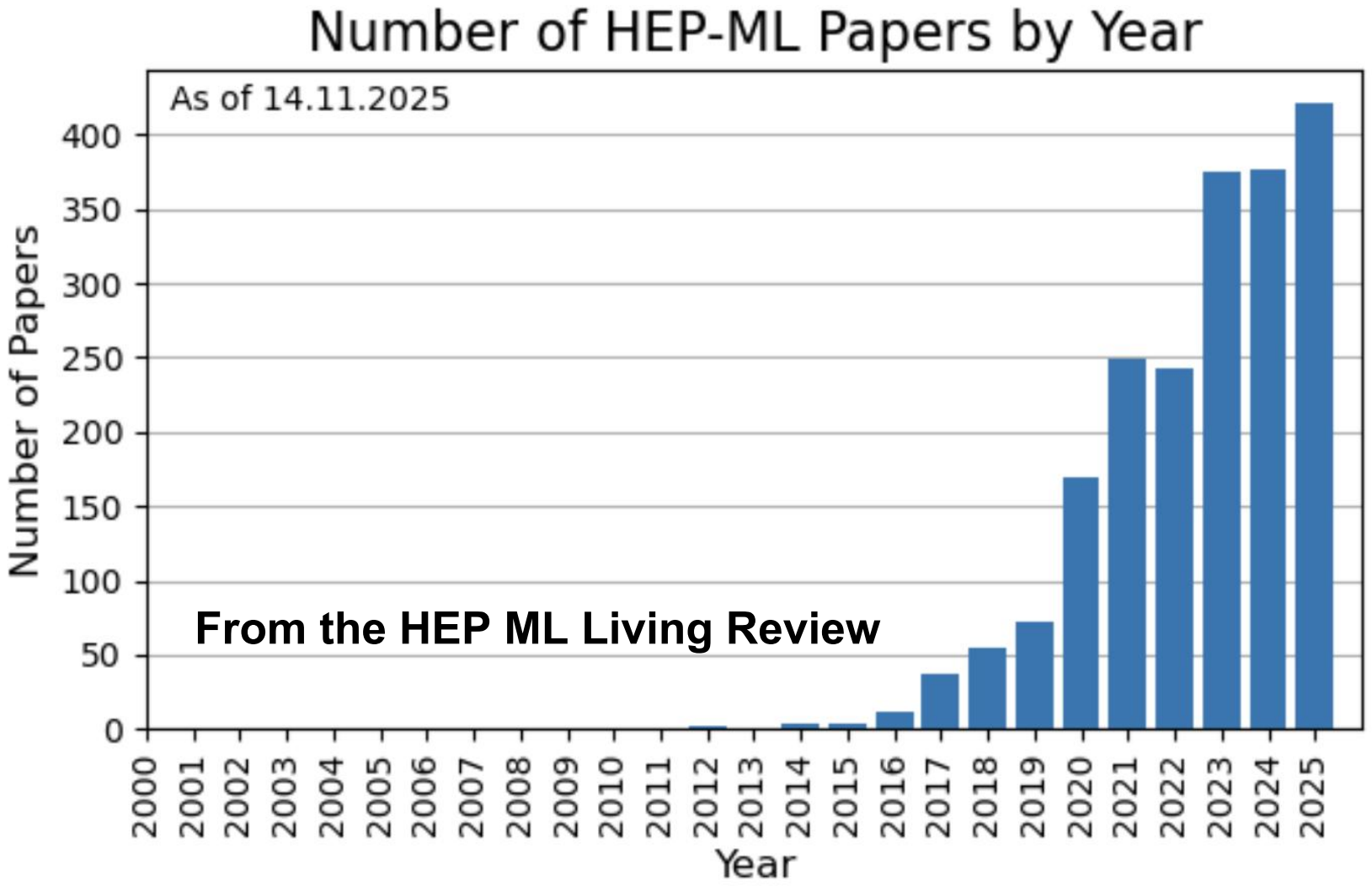
Teng Li
On behalf of Tianji Cai, Ke Li and Teng Li

Outline

1. **International AI+HEP Community**
2. **Proposal for the Chinese AI-HEP White Paper**
   - **Selected Physics Topics**
   - **Preparations and the Community Survey**

1. International AI+HEP Community

Evolving Landscape of AI+HEP



https://iml-wg.github.io/HEPML-LivingReview/

Major Research Fields:

- High Energy Experiment (hep-ex)
- High Energy Phenomenology (hep-ph)
- High Energy Theory (hep-th)
- Lattice Field Theory (hep-lat)
- Astroparticle Physics (astro-ph.CO)
- …

Global Vision for AI+HEP

arXiv > physics > arXiv:2209.07559

Search... Help | Ac

USA

Physics > Computational Physics

[Submitted on 15 Sep 2022]

Snowmass 2021 Computational Frontier CompF03 Topical Group Report: Machine Learning

Phiala Shanahan, Kazuhiro Terao, Daniel Whiteson

The rapidly-developing intersection of machine learning (ML) with high-energy physics (HEP) presents both opportunities and challenges to our community. Far beyond applications of standard ML tools to HEP problems, genuinely new and potentially revolutionary approaches are being developed by a generation of talent literate in both fields. There is an urgent need to support the needs of the interdisciplinary community driving these developments, including funding dedicated research at the intersection of the two fields, investing in high-performance computing at universities and tailoring allocation policies to support this work, developing of community tools and standards, and providing education and career paths for young researchers attracted by the intellectual vitality of machine learning for high energy physics.

A global community is rapidly taking shape — uniting to define its goals, set priorities, and mobilize the resources to realize them.

It's time for us to organize our own community!

arXiv > astro-ph > arXiv:2503.14192

Search... Help | Advar

Europe

Astrophysics > Instrumentation and Methods for Astrophysics

[Submitted on 18 Mar 2025]

Strategic White Paper on AI Infrastructure for Particle, Nuclear, and Astroparticle Physics: Insights from JENA and EuCAIF

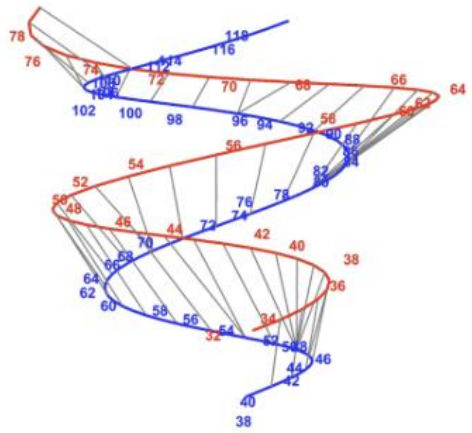
Sascha Caron, Andreas Ipp, Gert Aarts, Gábor Bíró, Daniele Bonacorsi, Elena Cuoco, Caterina Doglioni, Tommaso Dorigo, Julián García Pardiñas, Stefano Giagu, Tobias Golling, Lukas Heinrich, Ik Siong Heng, Paula Gina Isar, Karolos Potamianos, Liliana Teodorescu, John Veitch, Pietro Vischia, Christoph Weniger

Artificial intelligence (AI) is transforming scientific research, with deep learning methods playing a central role in data analysis, simulations, and signal detection across particle, nuclear, and astroparticle physics. Within the JENA communities-ECFA, NuPECC, and APPEC-and as part of the EuCAIF initiative, AI integration is advancing steadily. However, broader adoption remains constrained by challenges such as limited computational resources, a lack of expertise, and difficulties in transitioning from research and development (R&D) to production. This white paper provides a strategic roadmap, informed by a community survey, to address these barriers. It outlines critical infrastructure requirements, prioritizes training initiatives, and proposes funding strategies to scale AI capabilities across fundamental physics over the next five years.

Major Collaboration in USA

The NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI)

Deep Learning (AI) + Deep Thinking (Physics) = Deeper Understanding



RESEARCH

TALENT

COMMUNITY

Website:

https://iaifi.org/

Major Collaboration in Europe

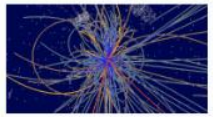
EuCAIF

European Coalition for AI in Fundamental Physics

Advancing AI and fundamental physics: A European cross-disciplinary research and training network

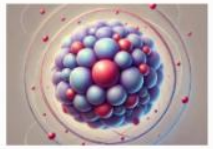
Theoretical physics

Crafting mathematical frameworks to predict and explain the fundamental laws of nature.



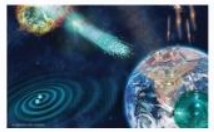
Particle physics

Unlocking the secrets of the tiniest building blocks of the universe.



Nuclear physics

Studying atomic nuclei to understand the forces that power stars and shape the elements around us.

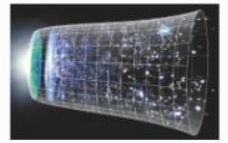


Astroparticle physics

Exploring cosmic rays, neutrinos, and dark matter to reveal the universe's mysteries.

Gravitational waves

Listening to the ripples in spacetime to witness the most violent cosmic events.



Cosmology

Investigating the origins, evolution, and ultimate fate of the universe on the grandest scales.

Accelerator physics

Pushing the frontiers of technology to accelerate particles and probe the structure of matter.

Website:

https://eucaif.org

JENAA

Joint ECFA-NuPECC-APPEC Activities

Major Collaboration in Japan

Resolution of fundamental problems in physics
via unification of theoretical methods of
Machine learning and Physics

MLPhYs Foundation of "Machine Learning Physics"
Grant-in-Aid for Transformative Research Areas (A)

Physics

The most precise testing ground in natural science
Multi-hierarchical problems and collaborative mathematics

Machine Learning

Explosive field of computational science
Social and technological innovation

"Discovering new laws, pioneering new materials, solving fundamental problems in physics by integrating theoretical methods in machine learning and in physics."

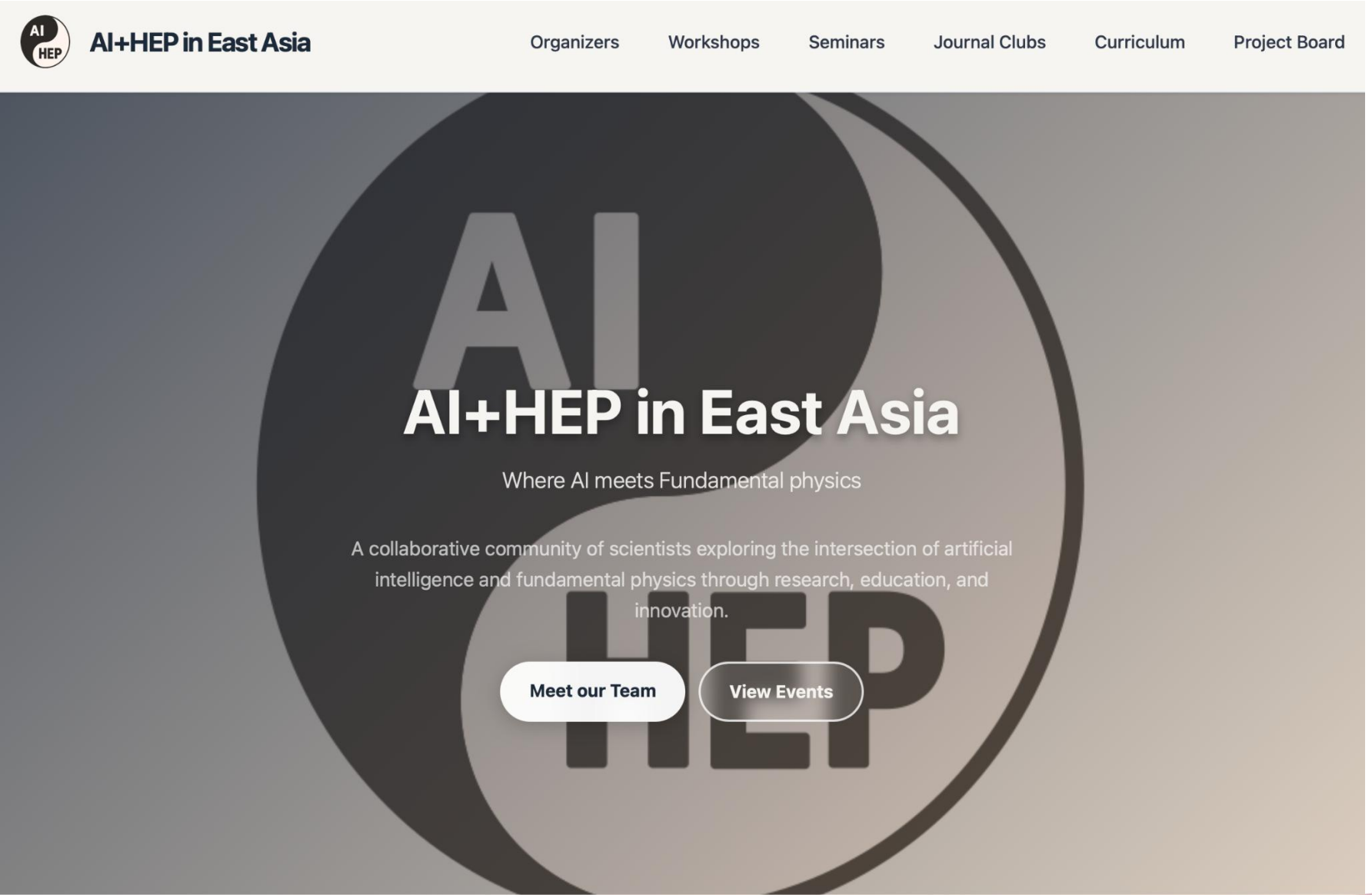
Website:
https://mlphys.scphys.kyoto-u.ac.jp/en/

Machine Learning Physics

New Collaboration in East Asia

Website:

https://ai-hep.github.io



Organizers:

- Tianji Cai (Tongji)
- Sung Hak Lim (IBS)
- Vinicius Mikuni (KMI)
- Huilin Qu (CERN)
- Ahmed Hammad (KEK)
- Lingxiao Wang (RIKEN/Tokyo)

Advisory Committee:

- Matthew R Buckley (Rutgers)
- Koji Hashimoto (Kyoto)
- Satoshi Iso (RIKEN/KEK)
- Gregor Kasieczka (Hamburg)
- Yanqing Ma (Peking)
- Benjamin Nachman (Stanford)
- Mihoko M. Nojiri (KEK)
- David Shih (Rutgers)
- Hua Xing Zhu (Peking)

2. Chinese White Paper
- Selected Physics Topics

Roadmap of AI+HEP in China

- The "AI+" action is a National Strategy for the next decade
- Challenge: HEP facilities, e.g. BESIII, LHC, STCF, are generating massive data
- AI as one of the most promising solutions: to enhance, accelerate and improve physics studies
- We need a stragetic plan for "AI+HEP" now !
  - Develop & Apply AI for core HEP tasks
  - Stengthen collaboration between AI and HEP fields
  - Build a sustainable ecosystem for continuous AI development
  - Align with national funding & policy

Main Topics in AI+HEP

- Classification
  - Parameterized classifiers
  - Representations
  - Targets
  - Learning strategies
  - Fast inference / deployment
- Regression
  - Pileup
  - Calibration
  - Recasting
  - Matrix elements
  - Parameter estimation
  - Parton Distribution Functions (and related)
  - Lattice Gauge Theory
  - Function Approximation
  - Symbolic Regression
  - Monitoring
- Equivariant networks.
- Physics-informed neural networks (PINNs).
- Decorrelation methods.
- Generative models / density estimation
  - GANs
  - (Variational) Autoencoders
  - (Continuous) Normalizing flows
  - Diffusion Models
  - Transformer Models
  - Physics-inspired
  - Mixture Models
  - Phase space generation
  - Gaussian processes
  - Other/hybrid
- Anomaly detection.
- Foundation Models, LLMs.
- Kolmogorov-Arnold Networks (KANs).
- Simulation-based (`likelihood-free') Inference
  - Parameter estimation
  - Unfolding
  - Domain adaptation
  - BSM
  - Differentiable Simulation
- Uncertainty Quantification
  - Interpretability
  - Estimation
  - Mitigation
  - Uncertainty- and inference-aware learning
- Formal Theory and ML
  - Theory and physics for ML
  - ML for theory

Technique-wise

Analyze huge data / solution space.

Automate labor / computation intensive procedures.

More Fundamentally

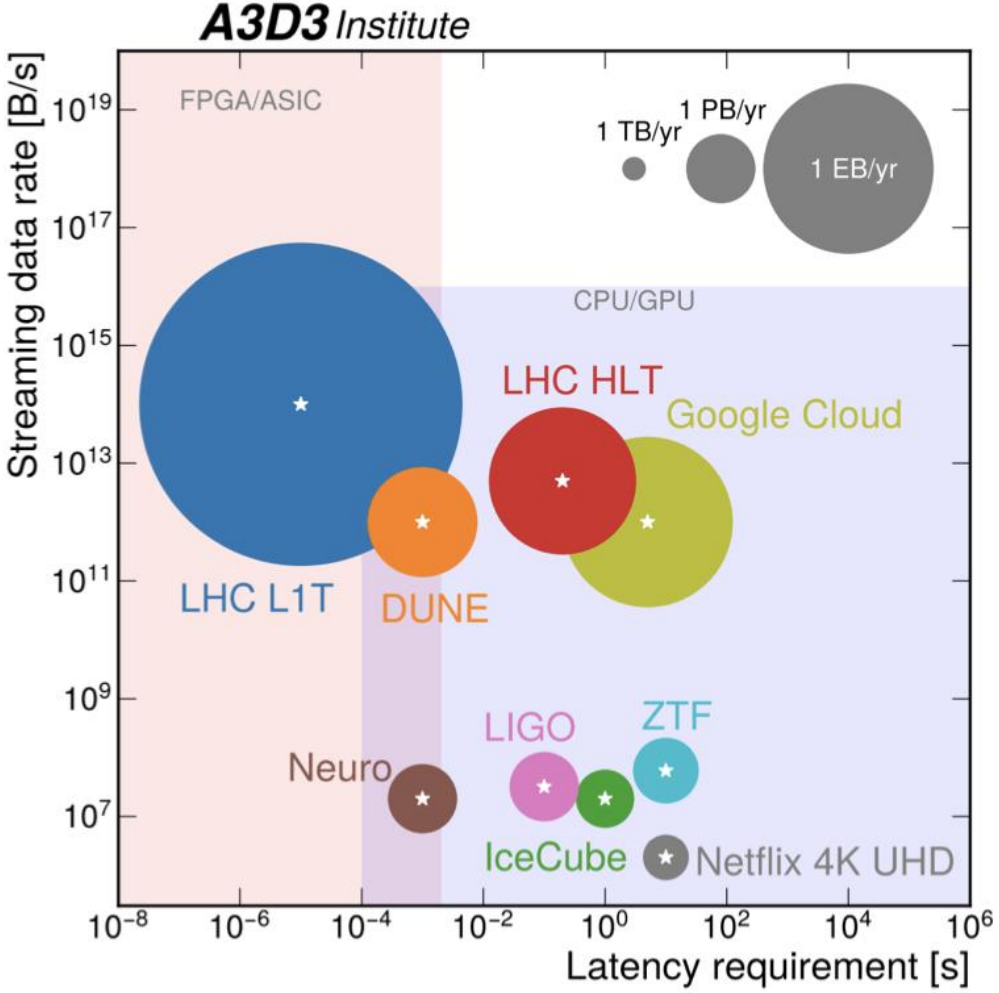
Extract hidden laws from data.

Uncover the underlying theory thoroughly and systematically.

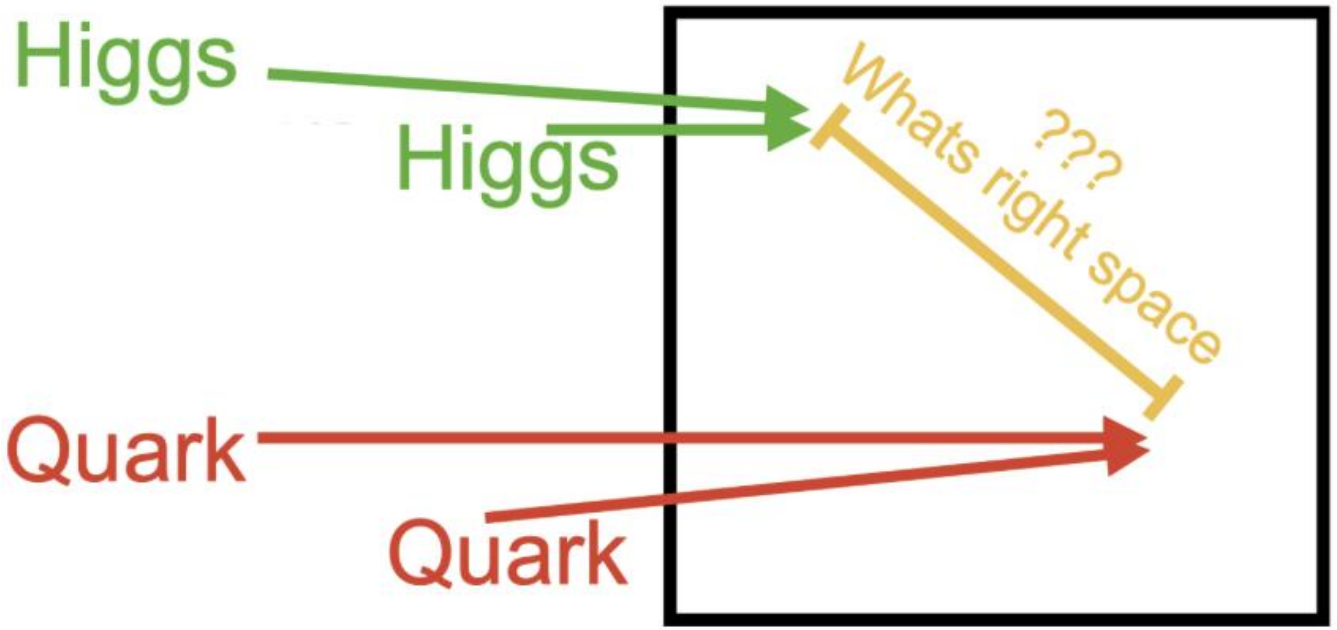
AI for HEP Phenomenology

The majority of AI applications is in HEP Pheno.

1. To address the big data challenge:



2. To extract/infuse more physics from/into the models:



AI for HEP Theory

- Data-Driven Einstein-Dilaton Model for Pure Yang-Mills Thermodynamics and Glueball Spectrum (2025)
- Transforming Calabi-Yau Constructions: Generating New Calabi-Yau Manifolds with Transformers (2025)
- Solving inverse problems of Type IIB flux vacua with conditional generative models (2025)
- Approximate Ricci-flat Metrics for Calabi-Yau Manifolds (2025)
- Improved Ground State Estimation in Quantum Field Theories via Normalising Flow-Assisted Neural Quantum States (2025)
- Machine Learning the 6d Supergravity Landscape (2025)
- Reinforcement Learning and Metaheuristics for Feynman Integral Reduction (2025)
- Machine Learning Calabi-Yau Three-Folds, Four-Folds, and Five-Folds (2025)
- Unraveling particle dark matter with Physics-Informed Neural Networks [DOI] (2025)
- AInstein: Numerical Einstein Metrics via Machine Learning (2025)
- Generating particle physics Lagrangians with transformers (2025)
- Recurrent Features of Amplitudes in Planar $\mathcal{N} [DOI] (2025)
- Machine Learning Gravity Compactifications on Negatively Curved Manifolds (2025)
- Symbolic Approximations to Ricci-flat Metrics Via Extrinsic Symmetries of Calabi-Yau Hypersurfaces (2024)
- The S-matrix bootstrap with neural optimizers I: zero double discontinuity (2024)
- Generative AI for Brane Configurations, Tropical Coamoeba and 4d N [DOI] (2024)
- Comparative Study of Neural Network Methods for Solving Topological Solitons (2024)
- Generating particle physics Lagrangians with transformers (2025)
- Emergent field theories from neural networks (2024)
- Truth, beauty, and goodness in grand unification: a machine learning approach [DOI] (2024)
- cymyc -- Calabi-Yau Metrics, Yukawas, and Curvature [DOI] (2024)
- Calabi-Yau metrics through Grassmannian learning and Donaldson's algorithm (2024)
- Bootstrapping string models with entanglement minimization and Machine-Learning [DOI] (2024)
- Machine Learning Toric Duality in Brane Tilings (2024)

Topics Attempted:

Scattering Amplitudes, Feynman Integrals, Lattice Field Theory, String Theory, Gravity, Lagrangian Construction, Standard Model Rediscovery, New Physics Model Building……

AI for HEP Experiment

- Many HEP experiments operating or being planned
  - BESIII, LHC, JUNO, LHAASO, STCF, CEPC, and many others
  - AI is playing vital role promoting physics results (Jet tagging, PID, fast simulation, reconstruction, data analysis, ...)
  - Faced with common AI-related challenges by all these experiments
- Topcis to be discussed:
  - Targeted Models for Specific Technical Challenges
  - General-Purposed Models as Foundational Tools for HEP Experimental Applications
    - AI agents for Q&A in the special domain
    - AI agents to automate the experimental analysis pipeline, e.g. Dr.Sai
  - Combining Targeted Models and General-Purposed Models

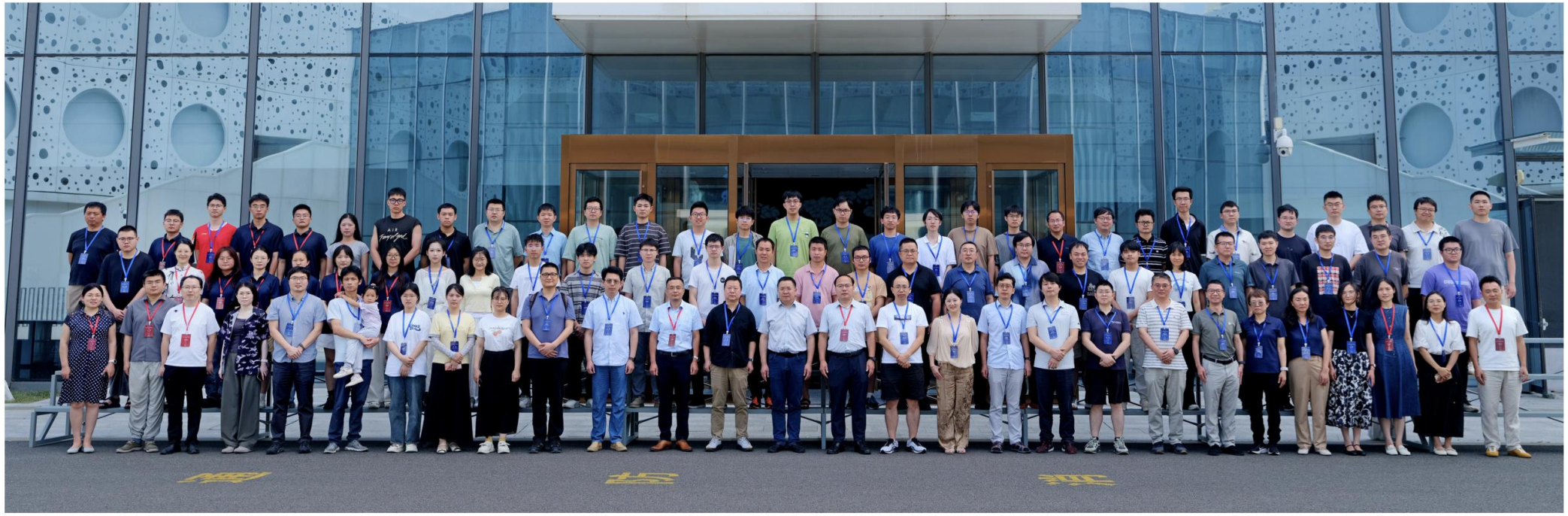
Other Topics

- Infrastructure needed for AI+HEP research
  - Open data
  - Workflow platform
  - Computing infrastructure
  - Environment impact (green AI)
- Community needs, research organization, scientific collaboration
  - Funding strategies (make proposals)
  - Organization structures
  - Interdisciplinary collaboration
  - Training and education
  - Others

2. Chinese White Paper
- Preparations and Community Survey

3rd Quantum Computing and Machine Learning Workshop

- The third workshop in the series, held in Qingdao from Aug. 19 to Aug. 23 2025
  - First two held in Qingdao (2023) and Jilin (2024)
  - ~100 participants from ~40 institutes and companies (online include) joined
  - 47 talks are presented in 12 sessions with very diversed topics
    - LLM (8), Quantum AI/Algorithm/Hardware/Simulation (10)
    - AI for online (3), AI for offline (20), AI for theory (5), and others



3rd Quantum Computing and Machine Learning Workshop

- **In addition to the academic presentations, we also discussed the preparation of the community white paper**

第三届量子计算与机器学习研讨会

Discussion Sessions

Dates: 8.21 & 8.22, 2025
Moderators: Tianji Cai, Teng Li, Ke Li
Qingdao, Shandong, China

Purpose of the paper, its targeted audience, and what we want to achieve by writing this paper.

Major Concerns:

- Balance the Chinese specific discussions and the general physics discussions as part of the international community.
- What's novel about our paper that set us apart from other white papers already written?

Suggestions:

- To advance the high energy & AI ecosystem in China, while at the same time contributing to the international community.
- To survey on the many open questions of interest to the entire community and set a **flexible framework** both boosting targetted and structured research in key resource-intensive areas and leaving enough room for free explorations in yet unforeseeable domains.
- To demonstrate the community needs and serve as a reference when advocating for our community.

Current Paper Organization

CONTENTS

Mainly just placeholders. Contents to be modified.

May delete & distributed in each section

After a lively discussion, we reached a basic consensus

- Written materials like white papers are vital
- White papers must reflect shared vision, so we will design surveys to gather broad community feedback firstly.
- Open community platforms for roadmap iteration are needed, and we should keep white papers updated to track rapid progress.
- Establishing fair and efficient structures for sharing resources

Goals & Structure

Welcome to the AI+HEP Community Survey! This survey aims to gather insights from researchers working at the intersection of Artificial Intelligence (AI) and High-Energy Physics (HEP). Your responses will help us better understand the current research landscape, identify key challenges, and inform strategies for future collaborations, infrastructure development, and educational initiatives.

The collected results will serve as the foundation for a community white paper and as a critical input to forthcoming national-level decisions that will shape the future of this research field.

Part A

multiple-choice; essential questions; mandatory; 20 mins to complete.

Part B

open-ended questions; additional perspectives & ideas; optional.

All responses will be kept confidential. Individual responses will not be shared, and any quotes used in later reports will be anonymized.

Survey Part A

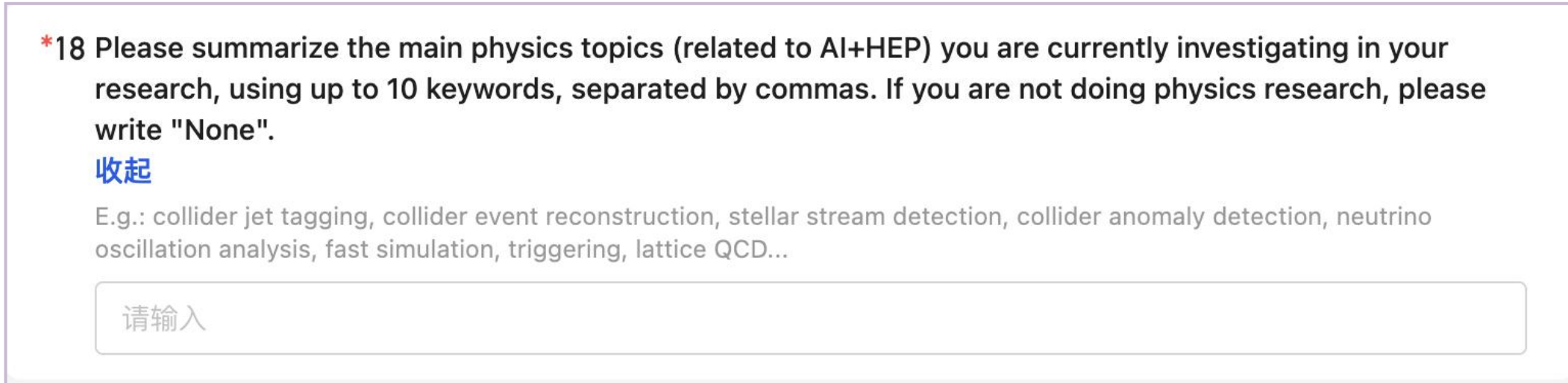
Section 1: General Information

In this section, we will collect some basic information about you and your research in general, so as to help us form a better understanding of the community. This section takes about 5 mins to finish.

Section 2: AI+HEP Research Topics

In this section, we focus on concrete research topics at the intersection of AI and High Energy Physics (AI+HEP). Your insights are essential for shaping the future direction of this emerging field and guiding its development within China and beyond. This section takes about 5-10 mins to finish.

Sample Question:



Survey Part A

Section 3: Research Ecosystem & Community Building

In this section, we focus on the aspect of community building and research ecosystem for AI+HEP. Your input plays a critical role in informing the future development of the field and the trajectory of this research area in China. Please take a moment to answer the following questions thoughtfully and responsibly. This section takes about 10-15 mins to finish.

A. Funding & Collaborative Entities; **B.** Career & Supports; **C.** Computing & Data Ecosystem; **D.** Teaching & Mentoring

Sample Question:

Survey Part B

Section 2 Extra: AI+HEP Research Topics

This section gathers additional feedback on AI+HEP research topics, complementing Section 2 of Part A. Please answer the following questions carefully and with as much detail as you can. Your responses will directly inform our understanding of the community's priorities, challenges, and opportunities.

Sample Question:

01 **Please describe each physics problem you are currently addressing—or plan to address—using AI-related methods. Provide one paragraph per problem (approximately 200 words each), and number your entries accordingly.**

收起

You are encouraged to follow this suggested template when writing your description:

- Physics problem: What is the specific problem you are studying?
- Traditional approach: What challenges does the conventional method face?
- AI approach: What AI method(s) are you applying or plan to apply to address the problem?
- Observations: What successes or preliminary results have you seen, and what obstacles remain?
- Future direction: What are your goals or wishlist for applying AI to this problem in the future?"

请输入

Survey Part B

Section 3 Extra: Research Ecosystem & Community Building

This section gathers additional feedback on Research Ecosystem & Community Building, complementing Section 3 of Part A. Please answer the following questions carefully and with as much detail as you can. Your responses will directly inform our understanding of the community's priorities, challenges, and opportunities.

Section 4: Others

Sample Question:

09 Please describe your vision for a sustainable and effective open data and data-sharing ecosystem for the AI+HEP community. You may include aspects such as data standards, accessibility, storage and computing integration, collaboration mechanisms, and incentives for sharing.

收起

Consider both technical and organizational aspects that would make the ecosystem useful, equitable, and sustainable. You may suggest innovative or non-traditional models.

请输入

Survey Statistics so far...

Reach 100-150 responses ideally.

查看人数	查看次数	填写平均耗时	填写完成率
85	240	1221.7s	23.53%

填写情况

Part A

正在收集

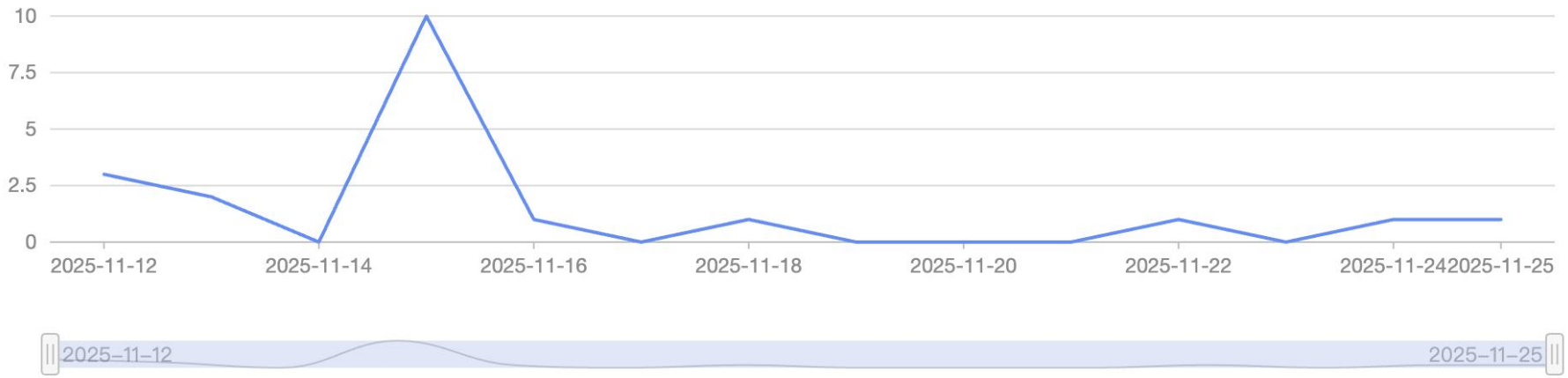
20	20	66
填写人数	填写结果	未填写人数

关联结果到表格 ···

Part B: 1 person submitted.

地域位置

填写趋势



Please submit your survey responses!

Part A

Part B

Deadline: 12.31.2025

Organizers & Advisors

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Tongji Univ

Ke Li 李科
IHEP, CAS

Teng Li 李腾
Shandong Univ

Great Thanks to Our Advisors

Cheng-Wei Chiang 蒋正伟 (NTU), **Xingtao Huang 黄性涛** (Shandong Univ),
Liang Li 李亮 (SJTU), **Tao Liu 刘滔** (HKUST),
Yanqing Ma 马滟青 (Peking Univ), **Manqi Ruan 阮曼奇** (IHEP, CAS).

As well as all the experts attended the discussions!

Nothing would be possible without the time & effort everyone volunteered!

Thank you for your attention!