Several applications of machine learning and quantum computing in jet reconstruction and identification

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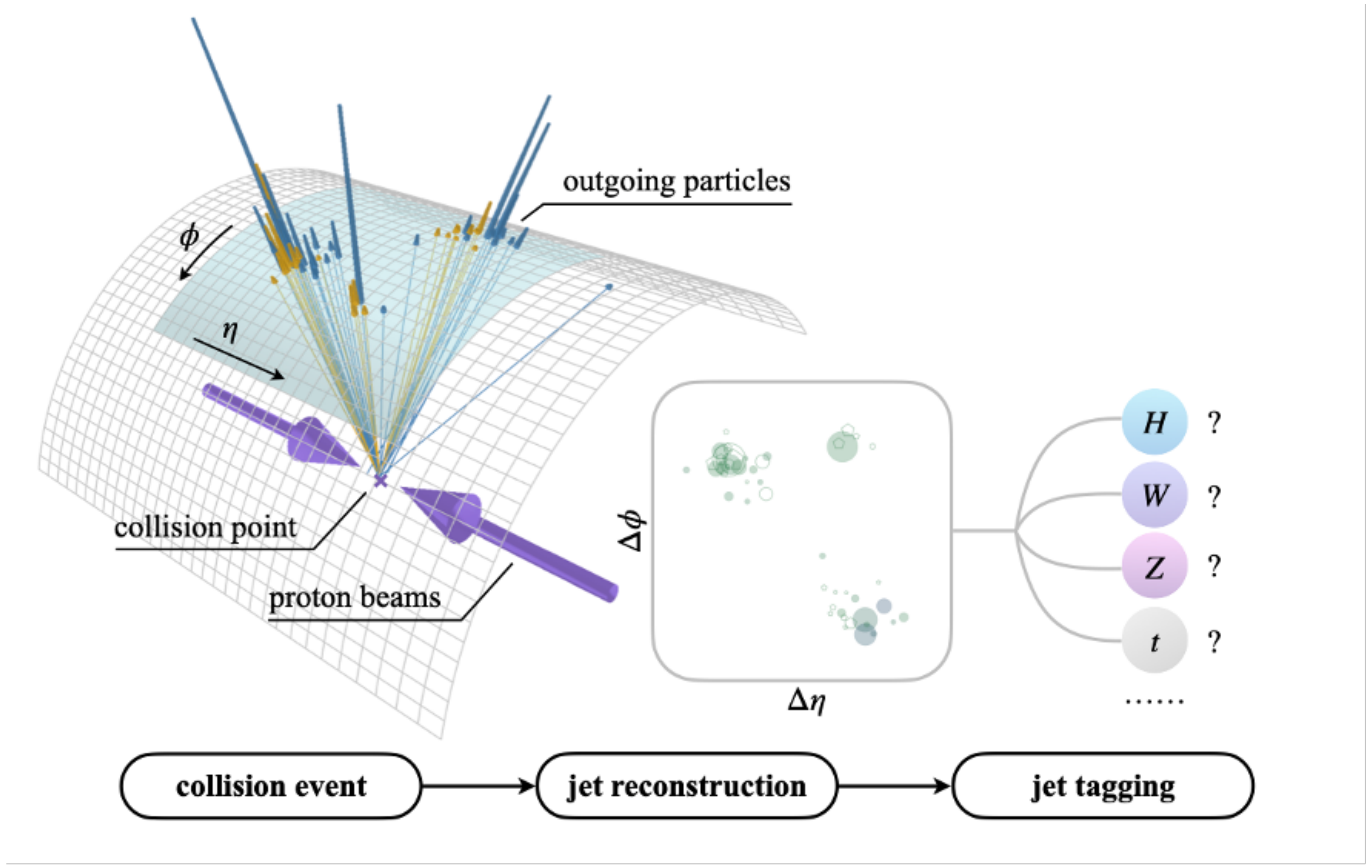
Introduction

- Jet reconstruction and identification are important for physics studies. How to improve?
- Use quickly developing techniques of machine learning and quantum computing



1. A novel quantum realization of jet clustering in high-energy physics experiments

Science Bulletin 70 (2025) 460

In collaboration with Dong Liu (Tsinghua/BAQIS), Manqi Ruan (IHEP), and others

A novel quantum realization of jet clustering

- Exploring the application of quantum technologies to fundamental sciences holds the key to fostering innovation for both sides
- Accurate jet clustering is crucial as it retains the information of the originating quark or gluon and forms the basis for many physics studies
- Quantum Approximate Optimization Algorithm (QAOA) is a hybrid quantum-classical algorithm for addressing classical combinatorial optimization problems with available quantum resources
- For the first time, by mapping collision events into graphs—with particles as nodes and their angular separations as edges—we realize jet clustering using QAOA

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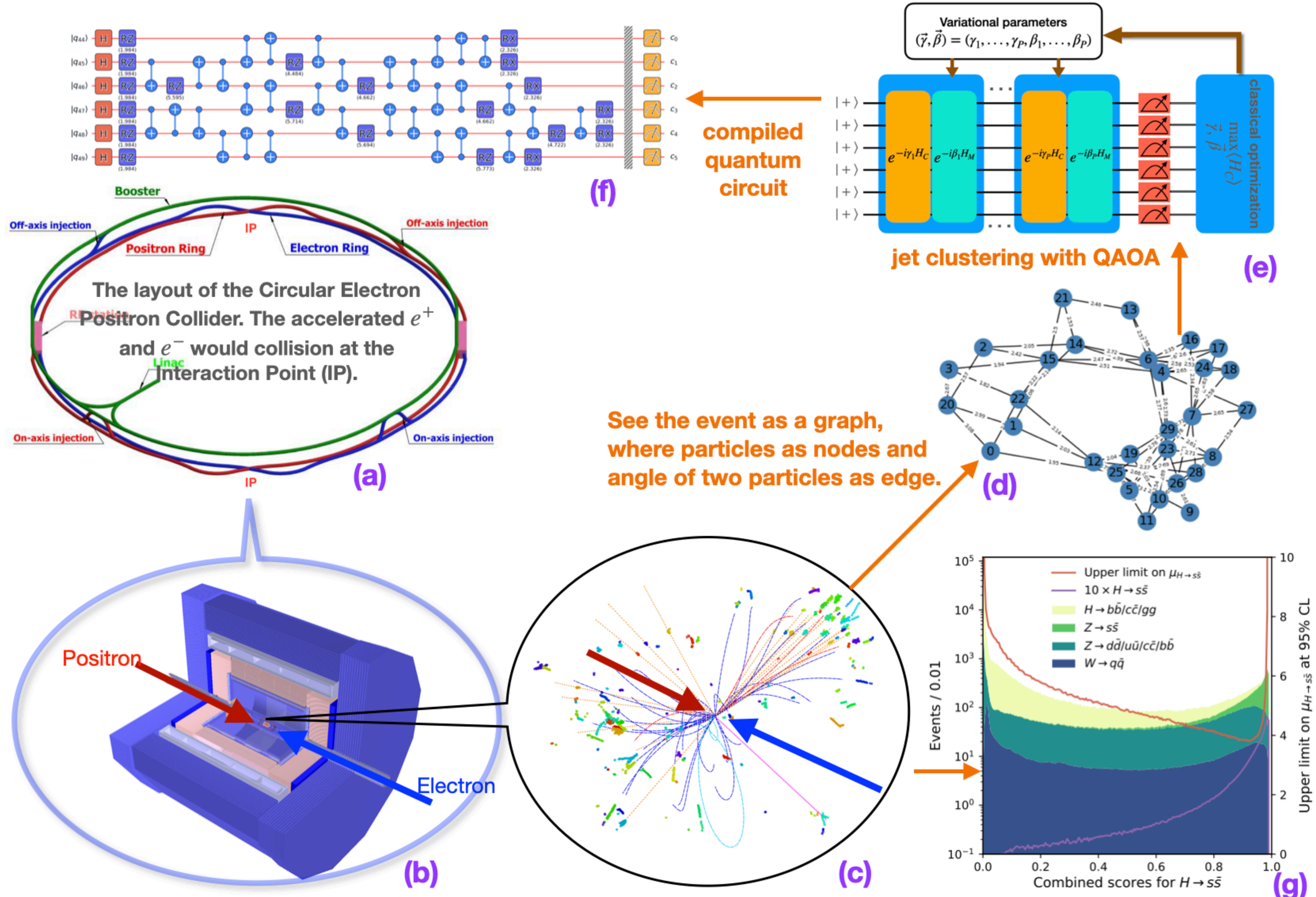

$$\widehat{H}_C = \frac{1}{2}\sum_{(i,j)\in E} W_{ij}\left(I - \sigma_i^z \sigma_j^z\right)$$

$$\widehat{H}_M = \sum_{j=1}^{n} \sigma_j^x$$

$$C(x) = \sum_{i,j=1}^{|v|} w_{ij} x_i (1 - x_j)$$

The collision of e^+ and e^- can generate quarks, gluons, and leptons.

The quarks and gluons would immediately transform into collimated particle sprays known as jets.

With jet clustering and other techniques, the related physics analyses can be performed.

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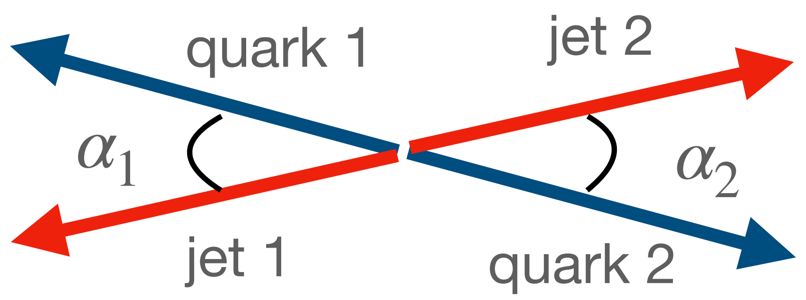
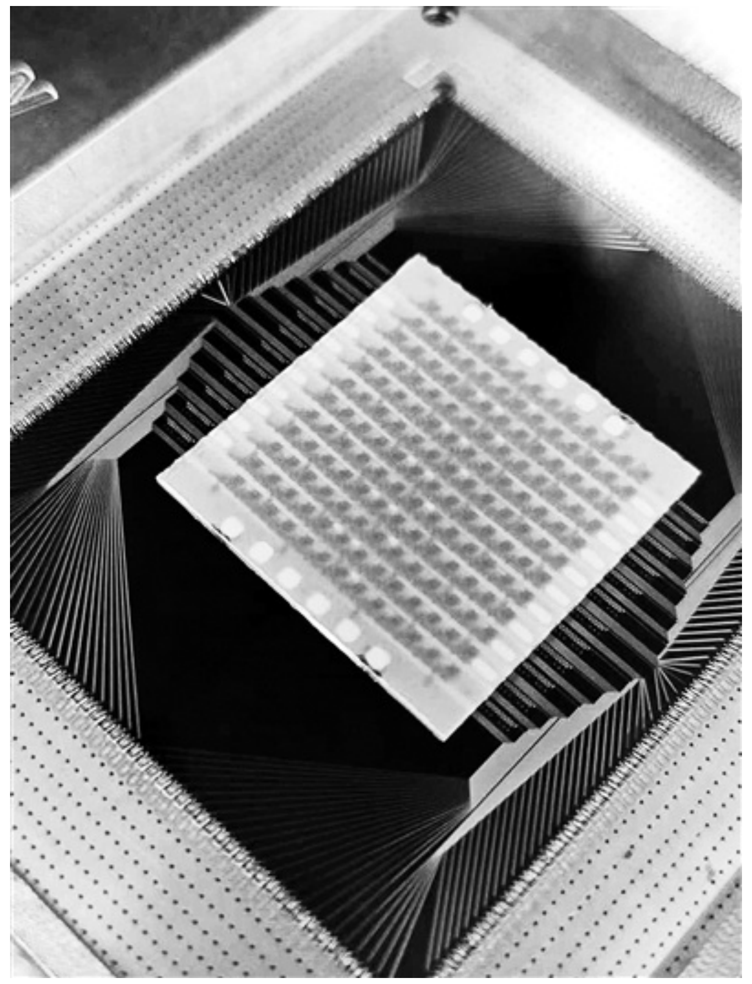
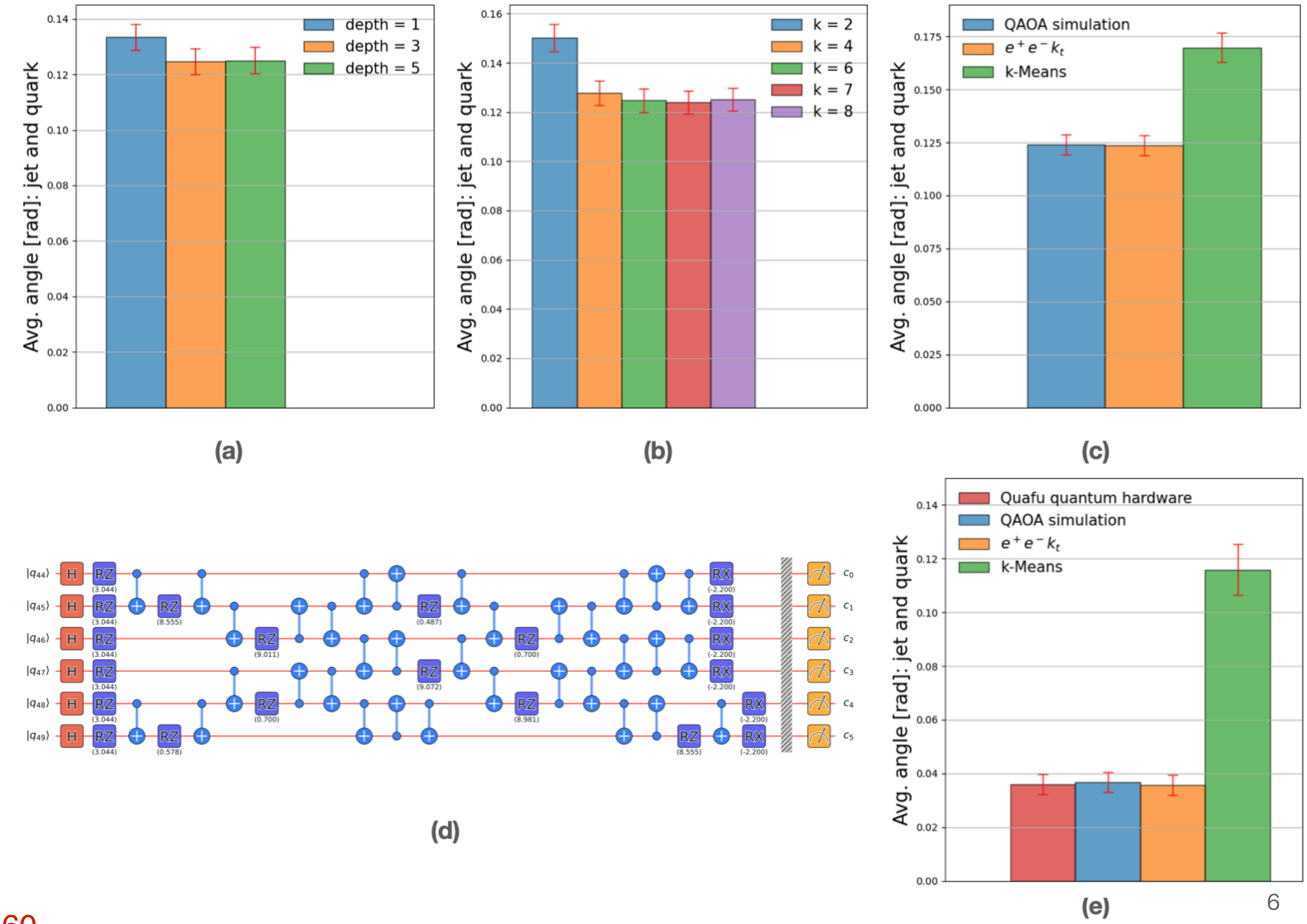

quark 1
jet 2
α_1
α_2
jet 1
quark 2




Avg. angle [rad]: jet and quark
depth = 1
depth = 3
depth = 5
(a)
k = 2
k = 4
k = 6
k = 7
k = 8
(b)
QAOA simulation
$e^+e^-k_t$
k-Means
(c)
(d)
Quafu quantum hardware
QAOA simulation
$e^+e^-k_t$
k-Means
(e)

A novel quantum realization of jet clustering

- Our results, derived from 30 qubits on quantum computer simulator and 6 qubits on quantum computer hardware, demonstrate that jet clustering performance with QAOA is comparable with classical algorithms for a small-sized problem
- This study highlights the feasibility of quantum computing to revolutionize jet clustering, bringing the practical application of quantum computing in high-energy physics experiments one step closer

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2. Machine learning-based jet-origin identification and its application at an e^-e^+ Higgs factory

Phys. Rev. Lett. 132 (2024) 221802

In collaboration with Manqi Ruan (IHEP), Huilin Qu (CERN), and others

Machine learning-based jet-origin identification

- We propose and realize the concept of jet-origin identification using state-of-the-art machine learning algorithms, such as ParticleNet

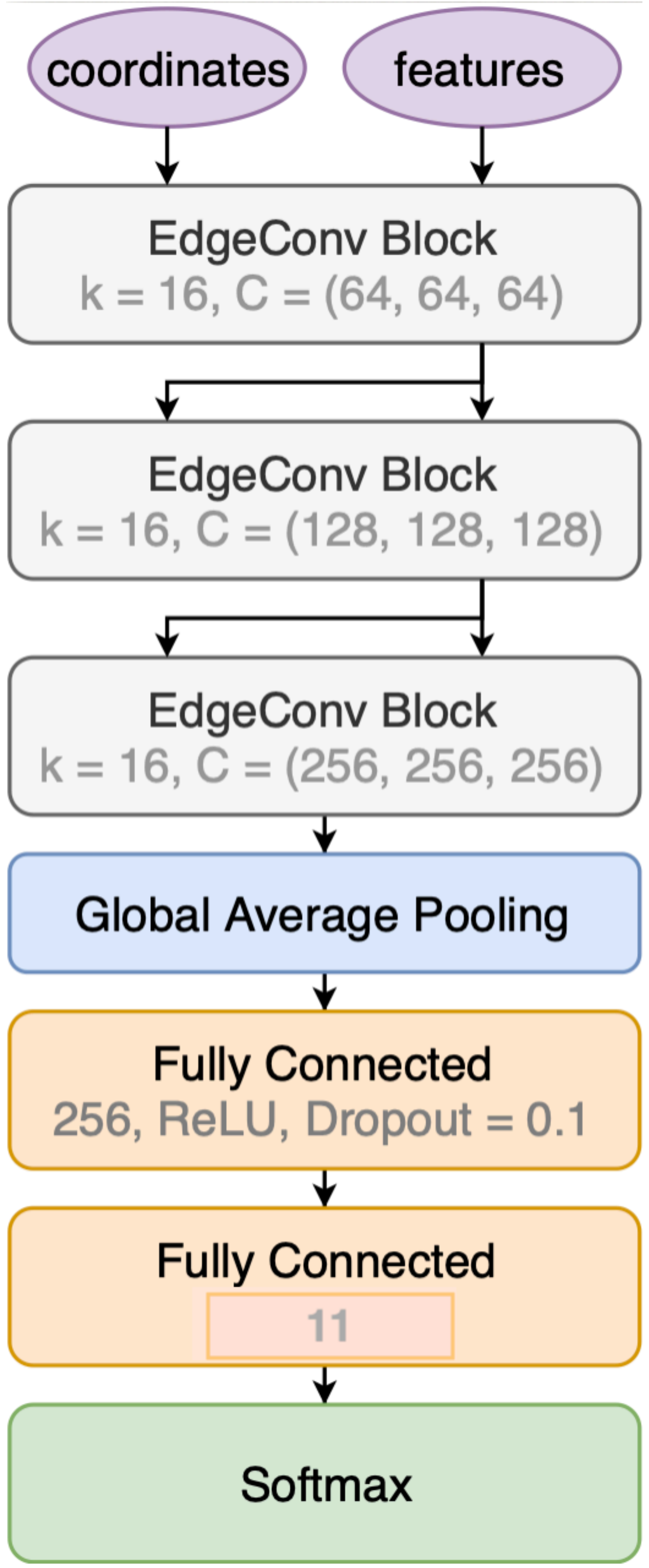
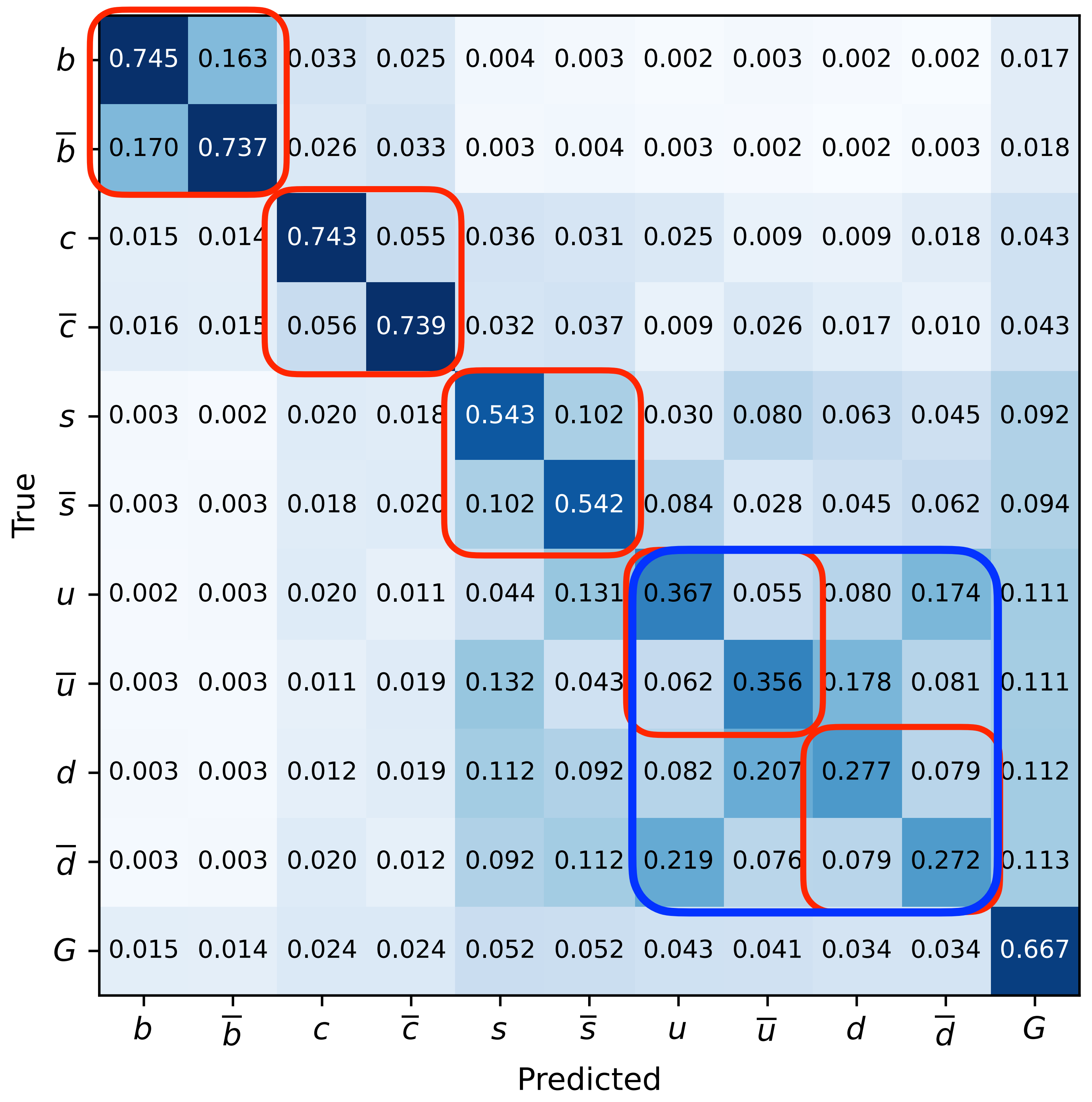
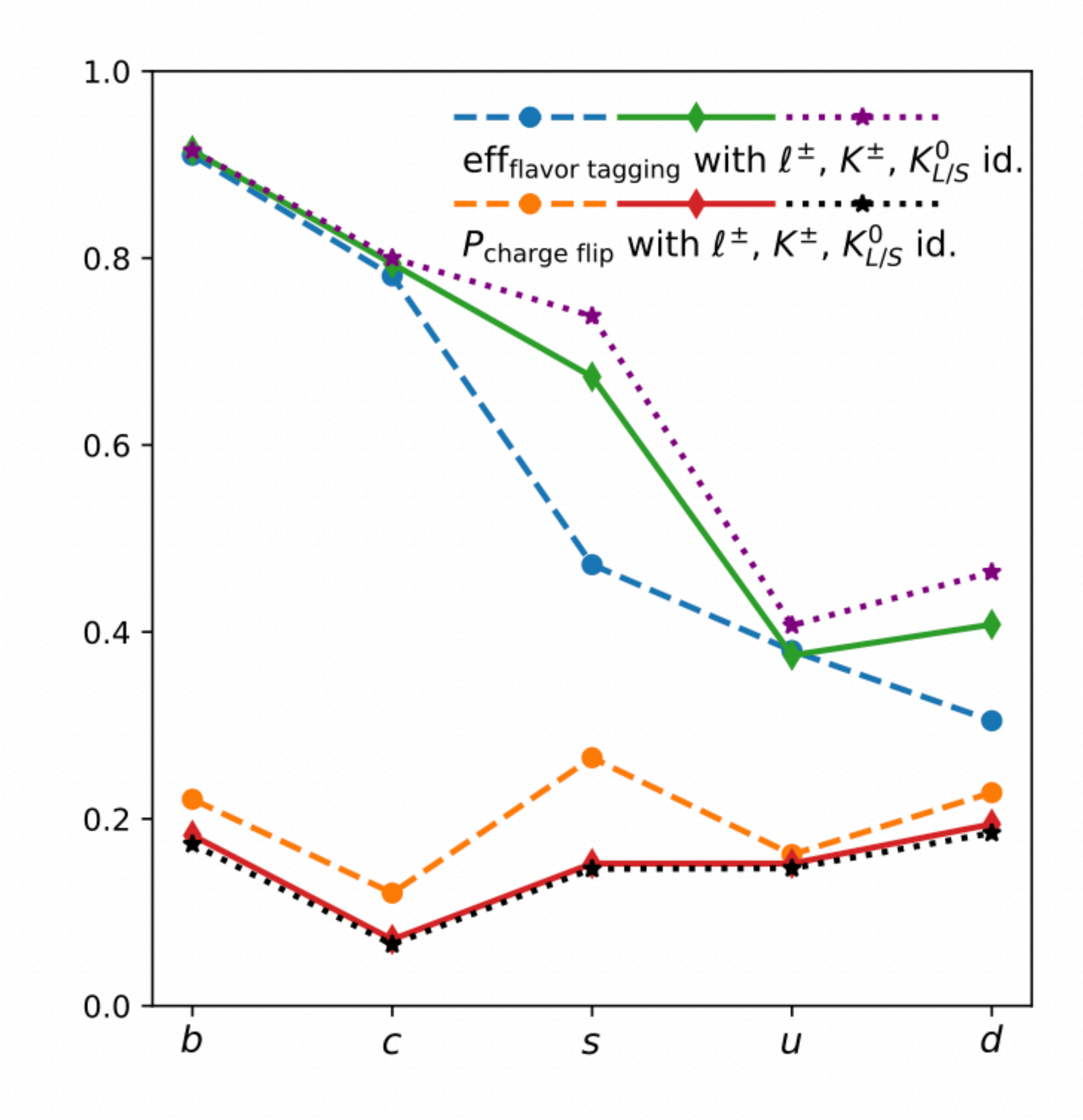


Table 3 The input variables used in ParticleNet for jet flavor tagging at the CEPC

Variable	Definition
$\Delta\,\eta$	Difference in pseudorapidity between the particle and the jet axis
$\Delta\,\phi$	Difference in azimuthal angle between the particle and the jet axis
$\log P_t$	Logarithm of the particle's P_t
logE	Logarithm of the particle's energy
$\log \frac{P_t}{P_t(jet)}$	Logarithm of the particle's P_t relative to the jet P_t
$\log \frac{E}{E(jet)}$	Logarithm of the particle's energy relative to the jet energy
ΔR	Angular separation between the particle and the jet axis
d_0	Transverse impact parameter of the track
$d_0$err	Uncertainty associated with the measurement of the d_0
z_0	Longitudinal impact parameter of the track
$z_0$err	Uncertainty associated with the measurement of the z_0
Charge	Electric charge of the particle
isElectron	Whether the particle is an electron
isMuon	Whether the particle is a muon
isChargedKaon	Whether the particle is a charged Kaon
isChargedPion	Whether the particle is a charged Pion
isProton	Whether the particle is a proton
isNeutralHadron	Whether the particle is a neutral hadron
isPhoton	Whether the particle is a photon

Machine learning-based jet-origin identification





- Our jet-origin identification categorizes jets into five quark species (b, c, s, u, d), five antiquarks, and the gluon
- It reaches jet flavor tagging efficiencies ranging from 67% to 92% for b, c, and s quarks and jet charge flip rates of 7%–24% for all quark species

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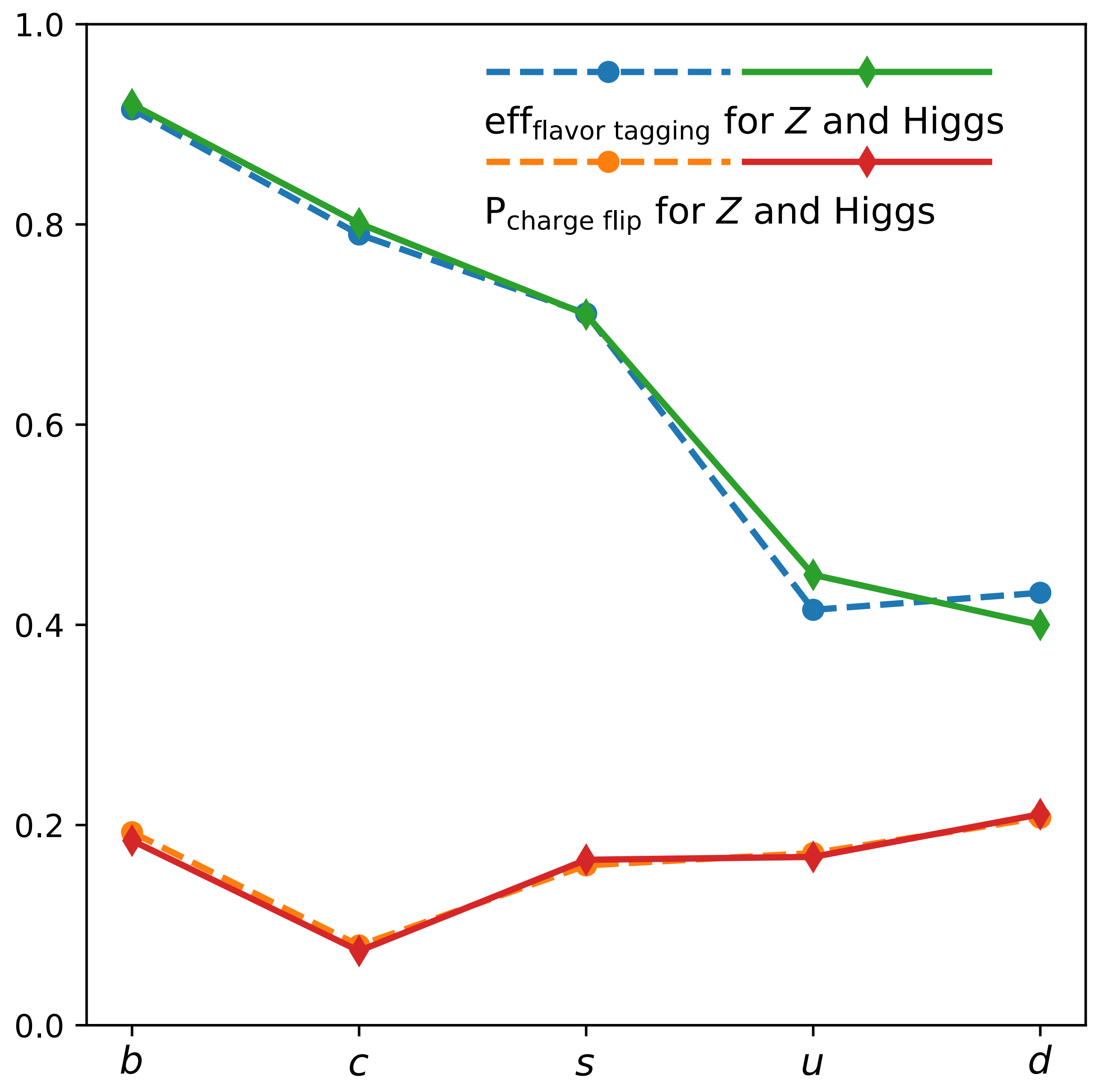
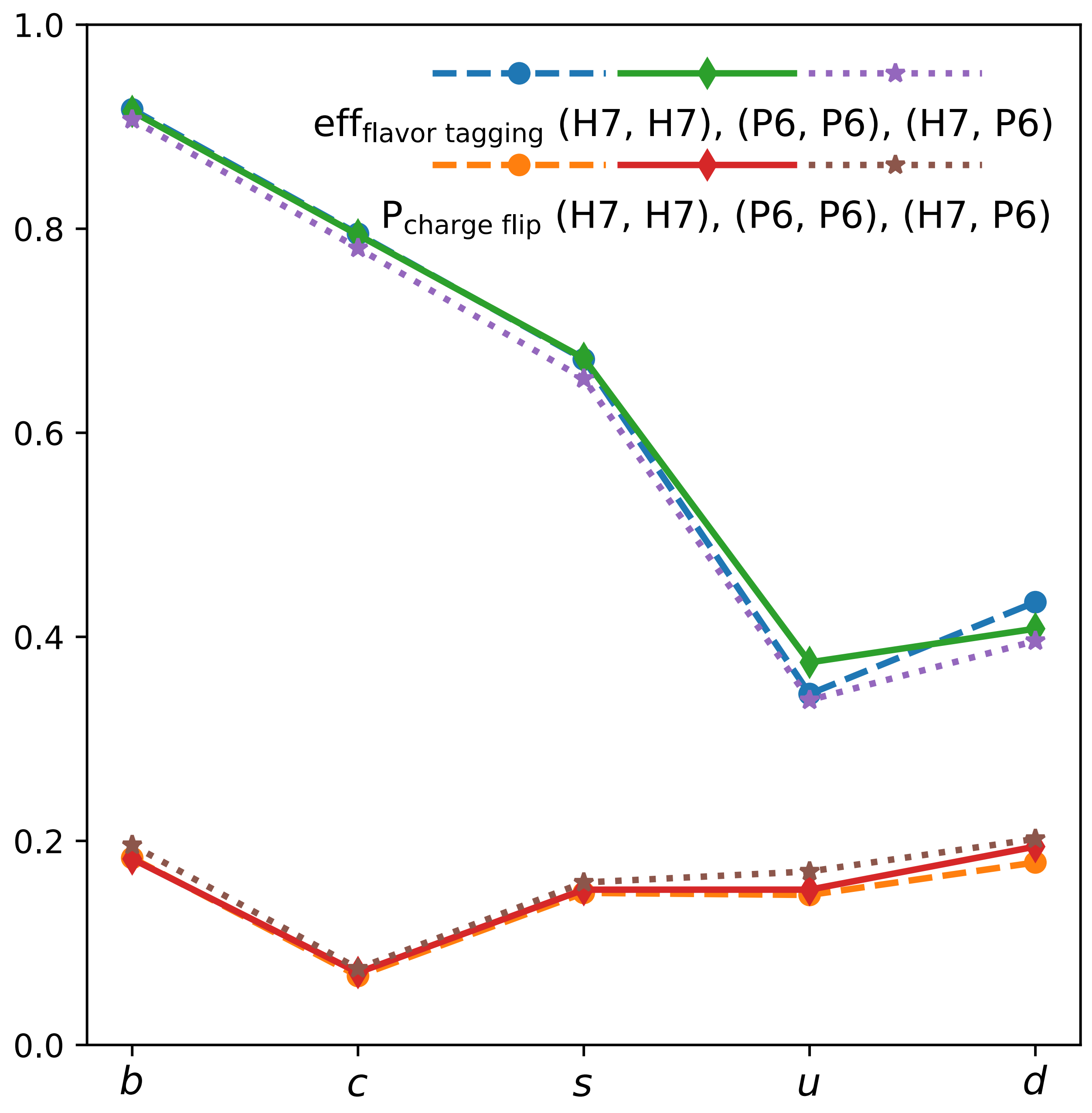
Machine learning-based jet-origin identification

- We perform a series of comparison studies to understand the systematic uncertainties for jet-origin identification
- We found the performance are consistent between different physics processes (left) and comparable between different hadronization models (right)





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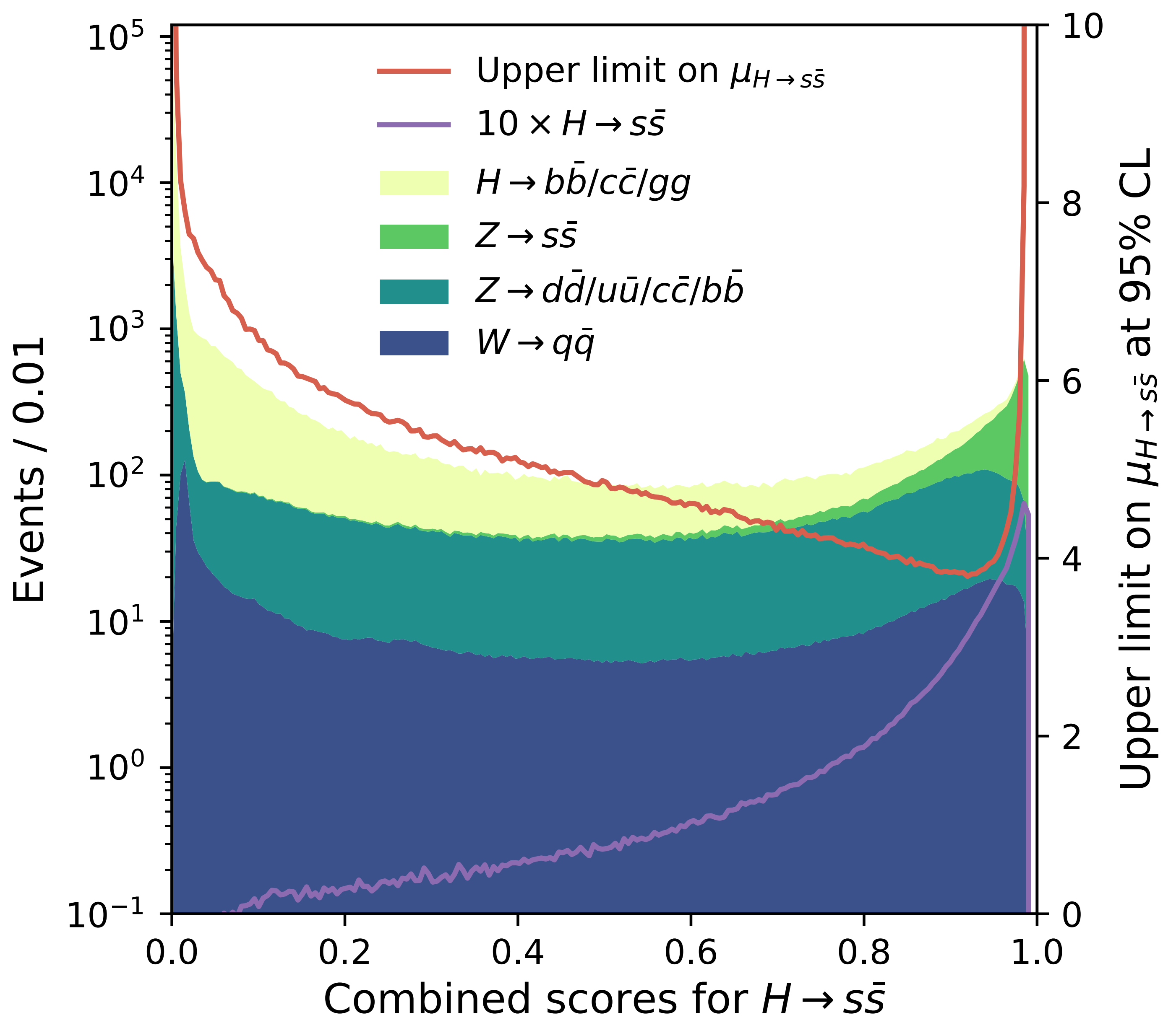
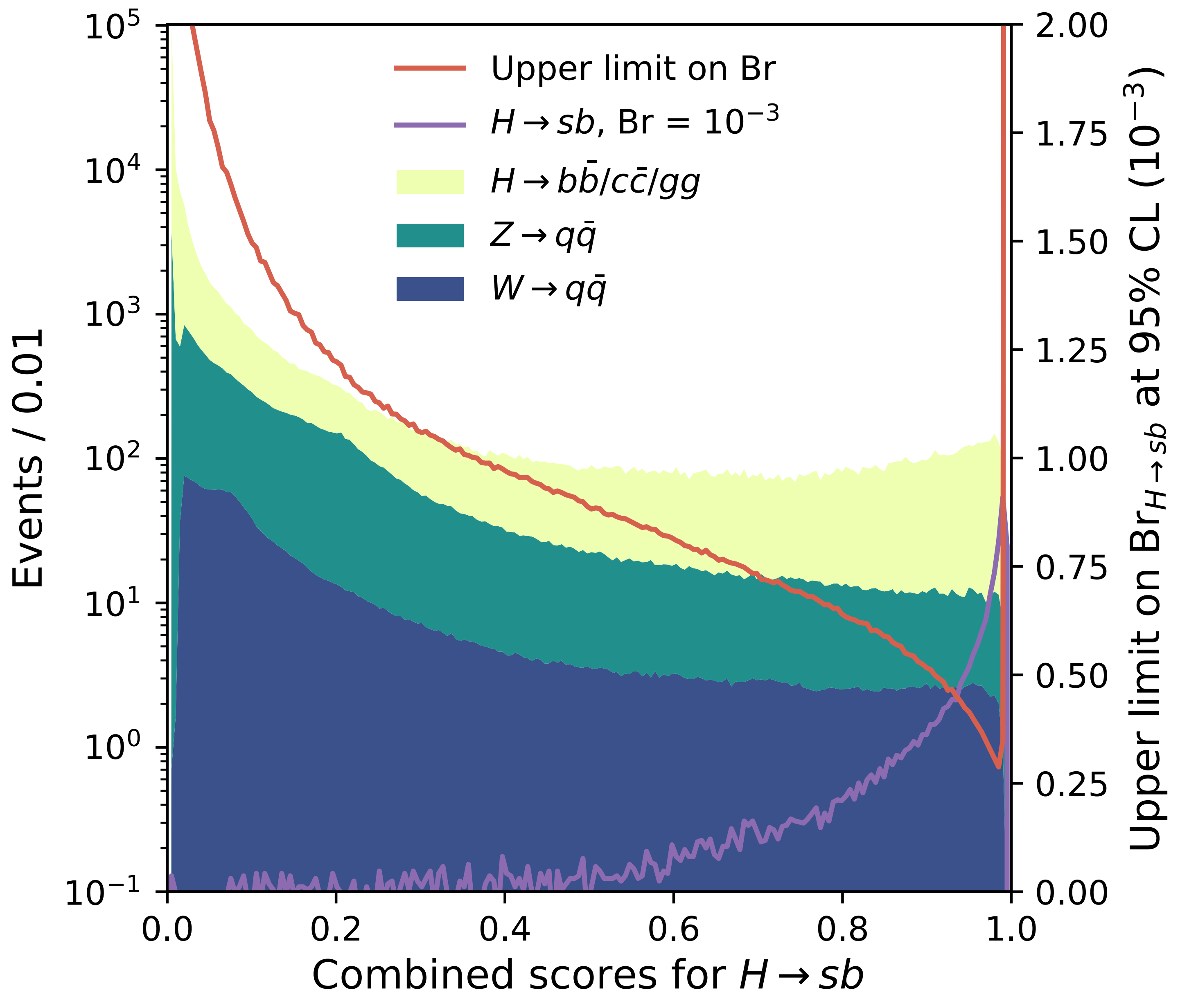
JOI’s application at an electron-positron Higgs factory

- We apply the jet-origin identification to Higgs rare and exotic decay measurements at CEPC





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JOI’s application at an electron-positron Higgs factory

- The upper limits at 95% confidence level on the branching ratios of H → ss, uu, dd and H → sb, db, uc, ds can be determined to 2 × 10^{-4} to 1 × 10^{-3}, which are greatly improved upon previous studies

TABLE I. Summary of background yields from $H \to b\bar{b}/c\bar{c}/gg$, Z, and W prior to the flavor-based event selection, along with the expected upper limits on Higgs decay branching ratios at 95% CL under the background-only hypothesis.

	Bkg (10^3)			Upper limits on Br (10^{-3})						
	H	Z	W	$s\bar{s}$	$u\bar{u}$	$d\bar{d}$	sb	db	uc	ds
$\nu\bar{\nu}H$	151	20	2.1	0.81	0.95	0.99	0.26	0.27	0.46	0.93
$\mu^+\mu^-H$	50	25	0	2.6	3.0	3.2	0.5	0.6	1.0	3.0
e^+e^-H	26	16	0	4.1	4.6	4.8	0.7	0.9	1.6	4.3
Comb.	⋯	⋯	⋯	0.75	0.91	0.95	0.22	0.23	0.39	0.86

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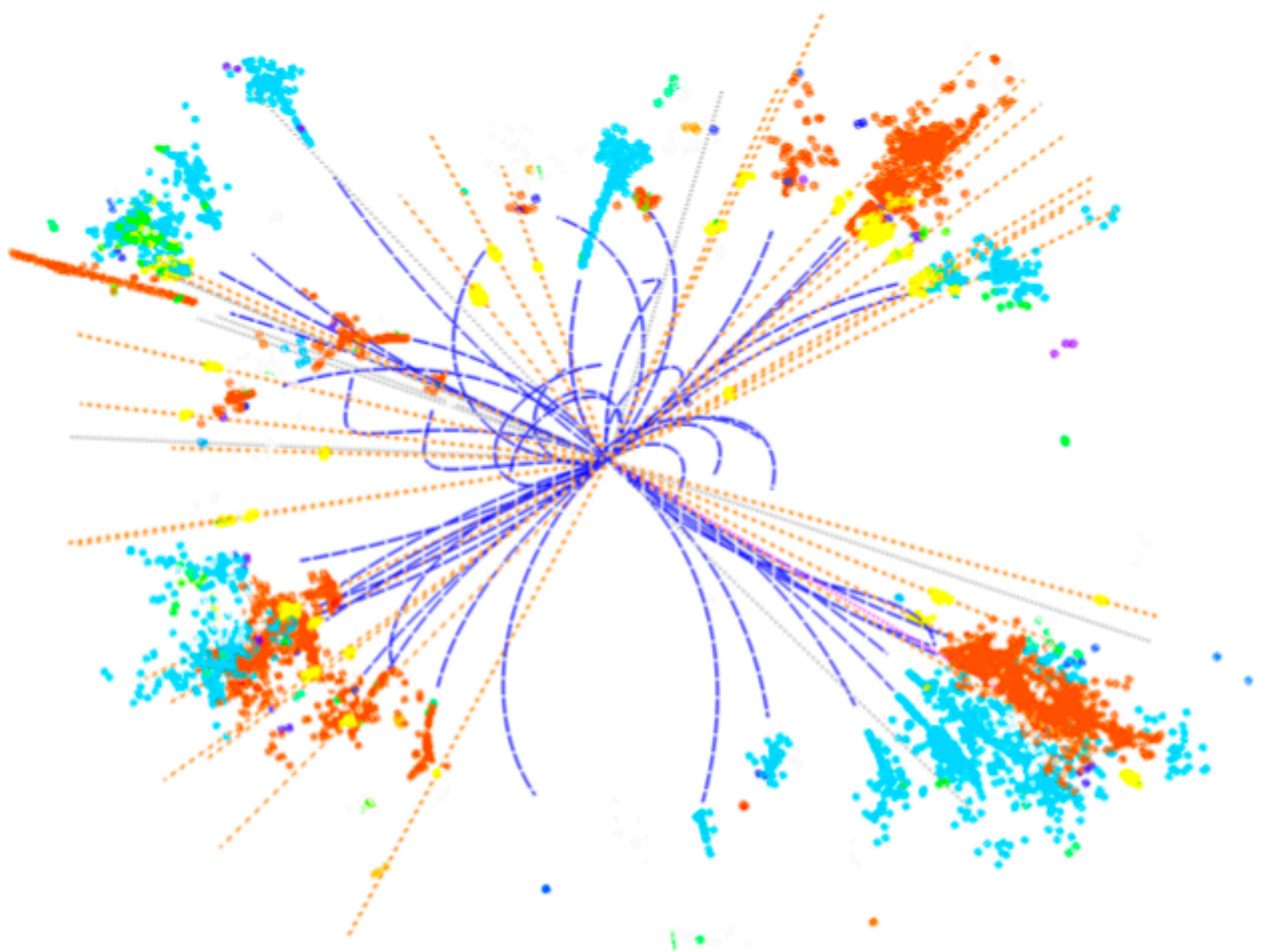
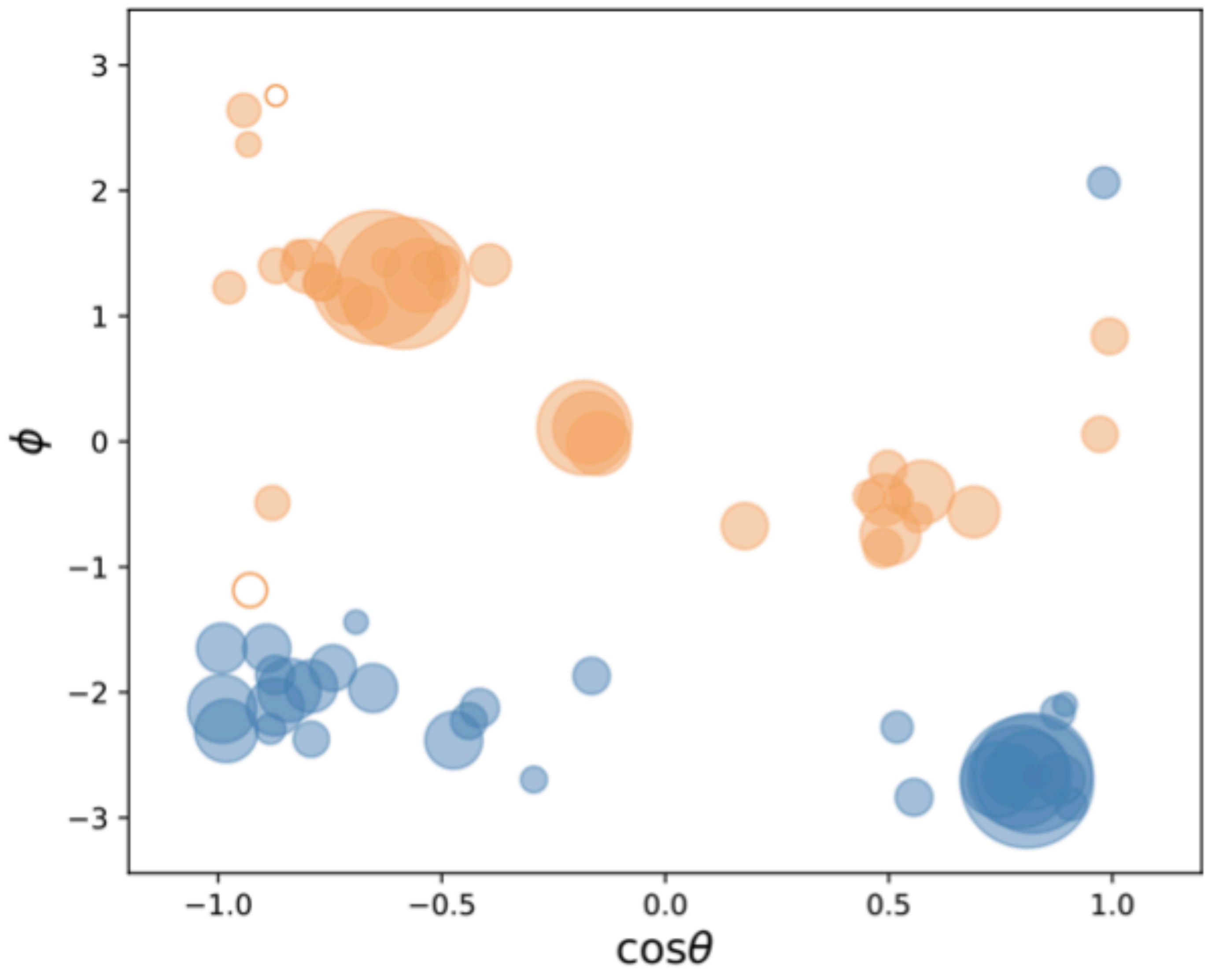
3. Holistic approach and Advanced Color Singlet Identification based on Machine Learning

arxiv:2506.11783

In collaboration with Manqi Ruan (IHEP), Huilin Qu (CERN), and others

Holistic approach and Advanced Color Singlet Identification





- We propose a holistic approach and Advanced Color Singlet Identification (ACSI), both of which utilize inclusive reconstructed information and ML techniques
  - Holistic approach is designed to simultaneously classify physics events
  - ACSI focuses on associating final-state particles with their parent massive bosons

arxiv:2506.11783

Holistic approach and Advanced Color Singlet Identification

TABLE II: When the CEPC operates as a Higgs factory and collects an integrated luminosity of 20 ab^{-1}, the signal strength precisions for the decay channels $H \to b\bar{b}/c\bar{c}/gg/s\bar{s}$ and $q\bar{q}H(j\bar{j})$ are evaluated under five different scenarios. The bottom four rows present results assuming only irreducible backgrounds—specifically, Higgs decays themselves in the $\nu\bar{\nu}H$ channel, and fully hadronic WW and ZZ events in the $q\bar{q}H$ channel. For comparison, the conventional approach refers to cut-flow followed by BDT for event classification.

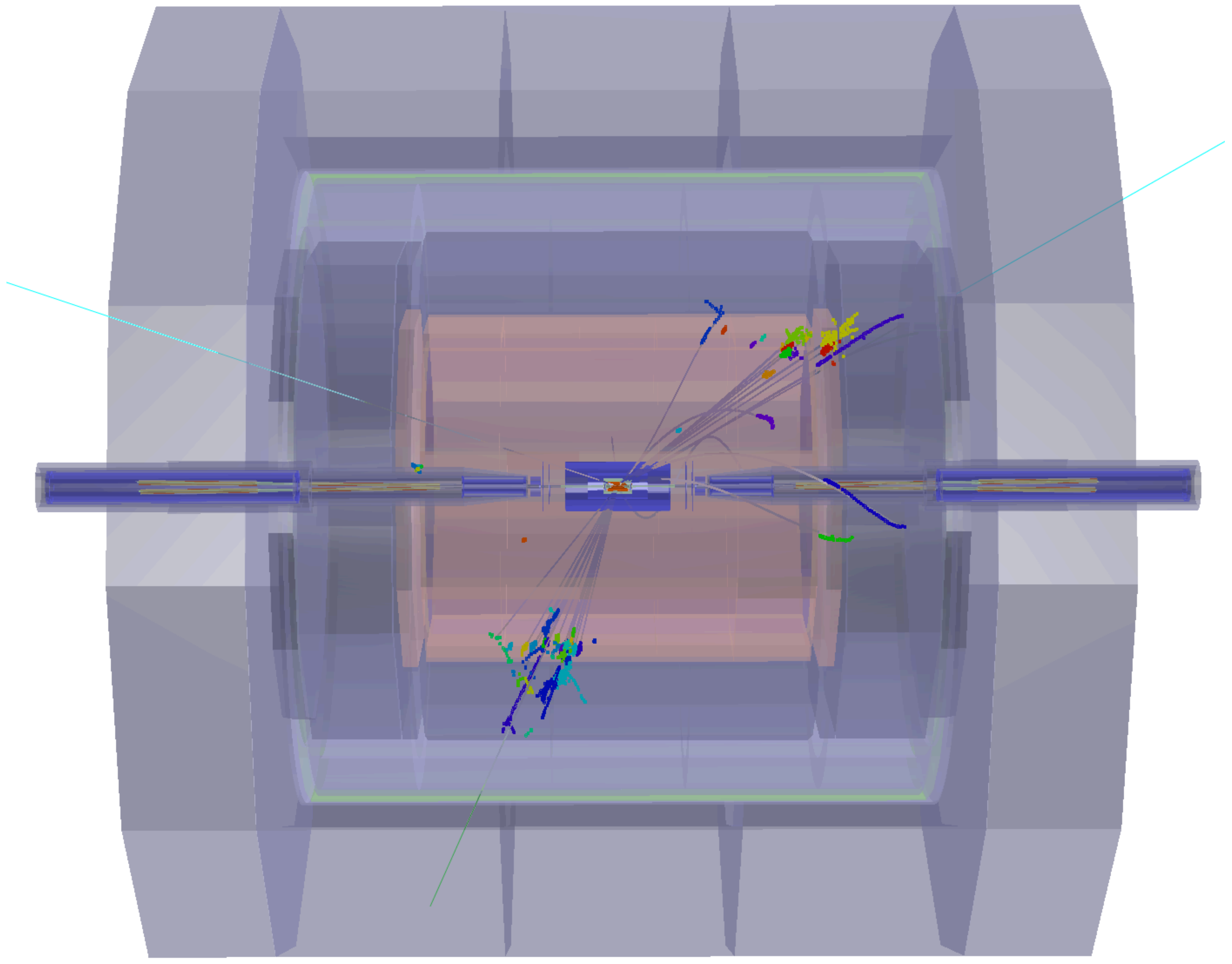
	$\nu\bar{\nu}H$				$q\bar{q}H(j\bar{j})$	$q\bar{q}H$			
	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$	$H \to s\bar{s}$		$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$	$H \to s\bar{s}$
cut + BDT	0.26%[21]	3.04%[21]	0.96%[21]	190.00%[19]	0.27%	0.19%[21]	4.10%[21]	2.10%[21]	-
holistic	0.14%	0.72%	0.46%	29.34%	0.097%	0.11%	1.96%	1.05%	279%
holistic with CSI	-	-	-	-	0.087%	0.09%	1.03%	0.73%	114%
holistic with ideal CSI	-	-	-	-	0.072%	0.08%	0.41%	0.24%	14.32%
statistical limit	0.14%	0.61%	0.36%	6.91%	0.072%	0.08%	0.35%	0.21%	4.02%

- Applied to the physics benchmarks of vvH and qqH processes with H → bb, cc, ss, and gg decays
  - these concepts improve the expected precisions by factors of two to six
  - enable the potential observation of the rare H → ss decay at future electron-positron Higgs factories

arxiv:2506.11783

Summary

- **Machine learning and quantum computing are becoming important tools for high energy physics**
- We show some applications in jet reconstruction, which can boost different physics studies (Higgs, QCD, BSM…)
- And there will probably be much more than what we know today



Thank you！