Some applications of machine learning and quantum computing in jet reconstruction

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

Science Bulletin 70 (2025) 460

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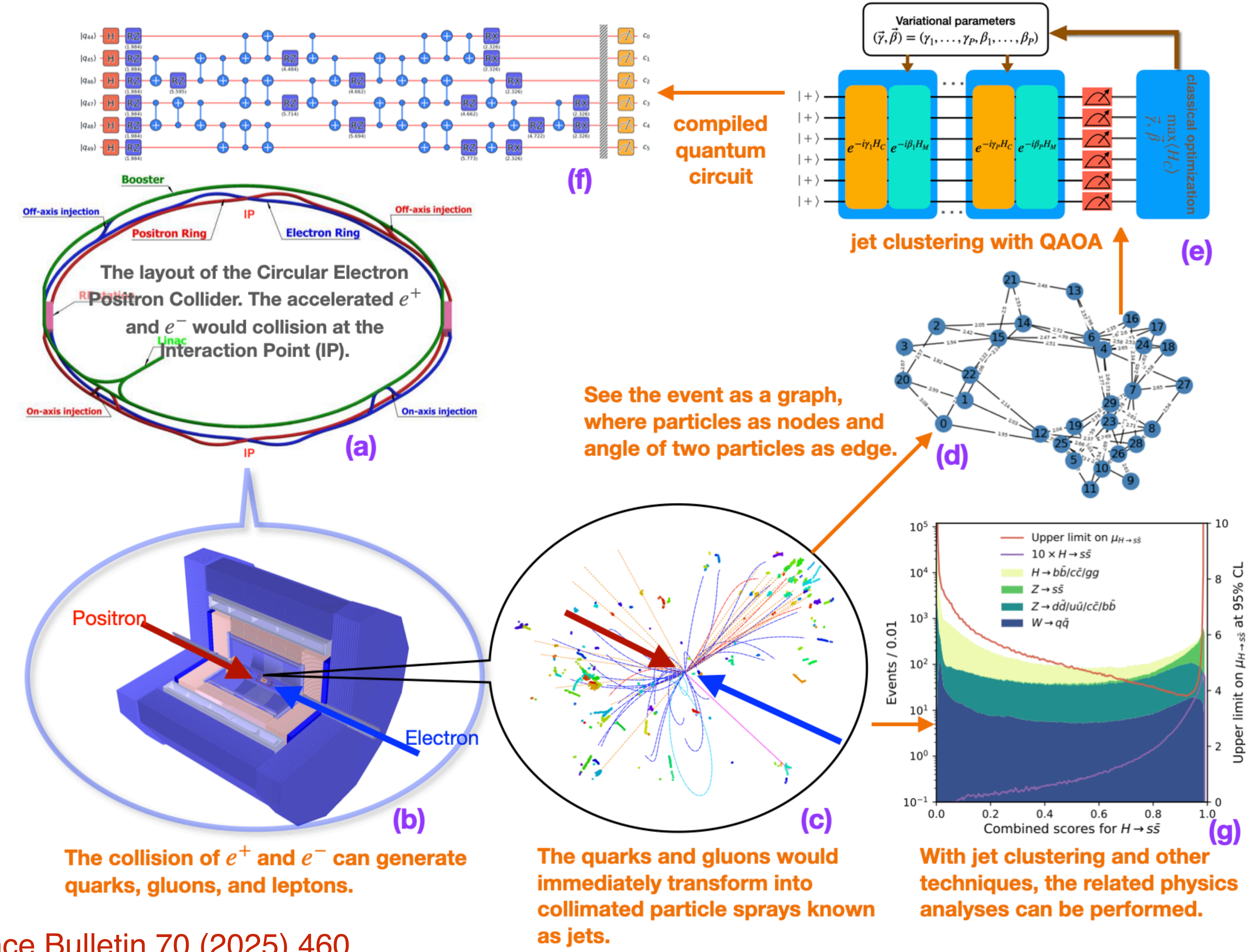

$$\widehat{H}_C = \frac{1}{2} \sum_{(i,j) \in E} W_{ij} \left(I - \sigma_i^z \sigma_j^z \right)$$

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

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

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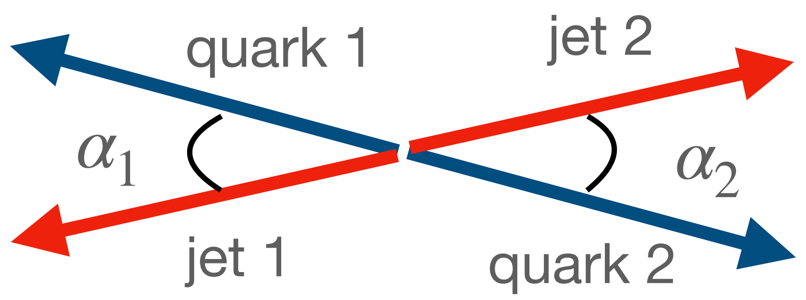
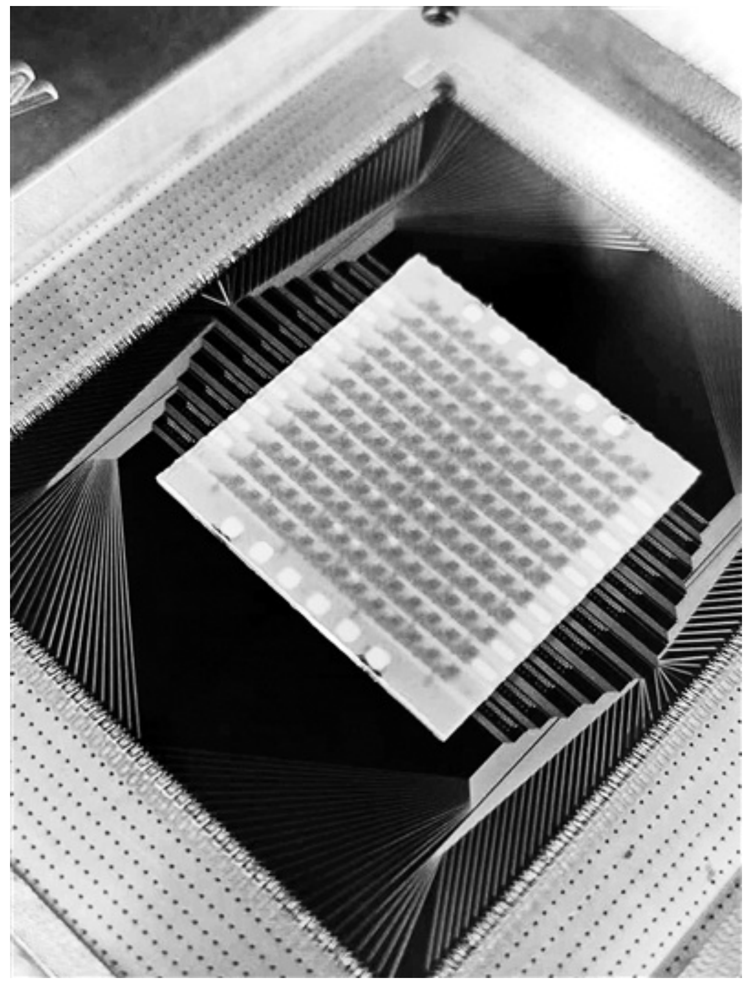
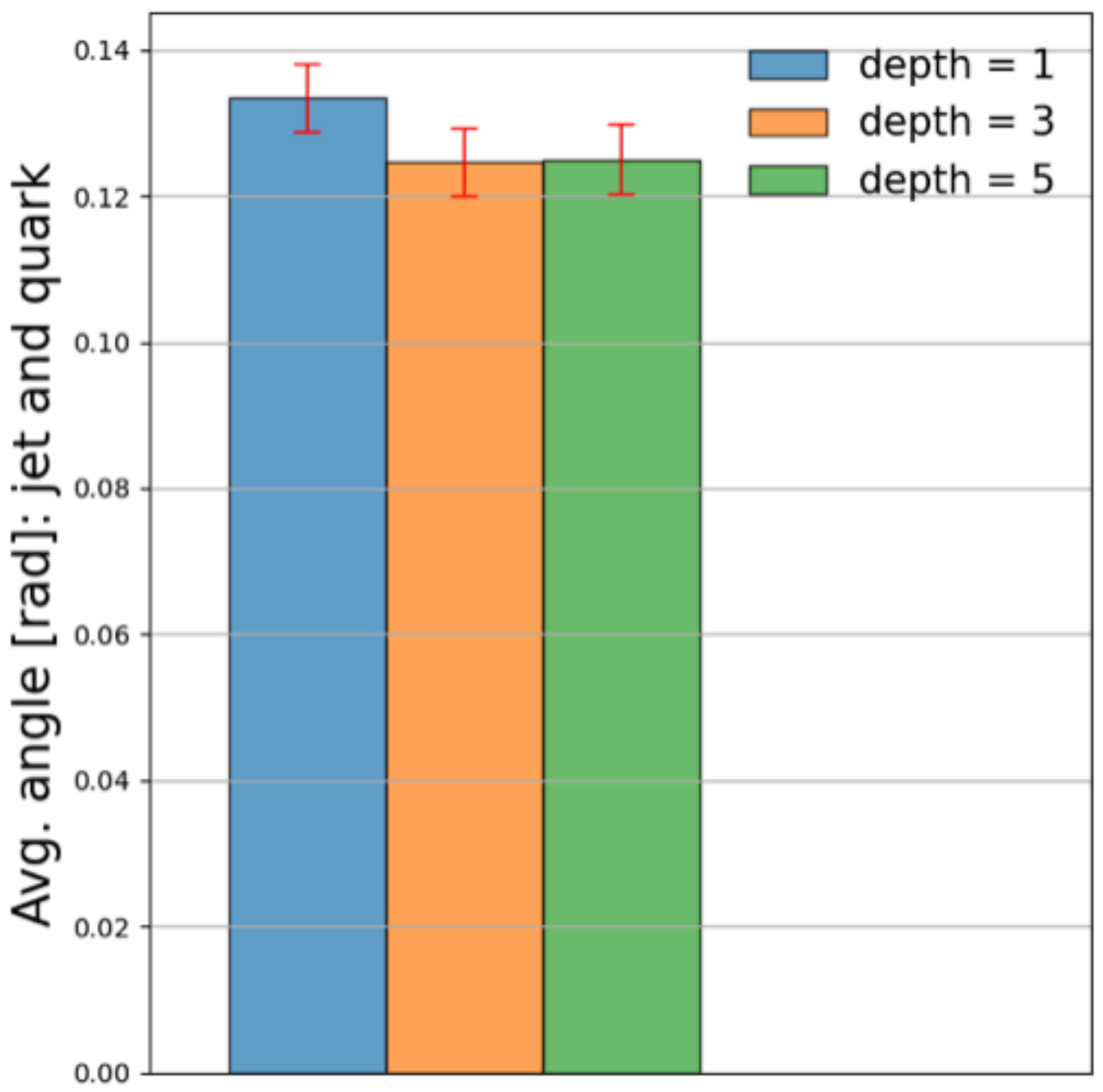
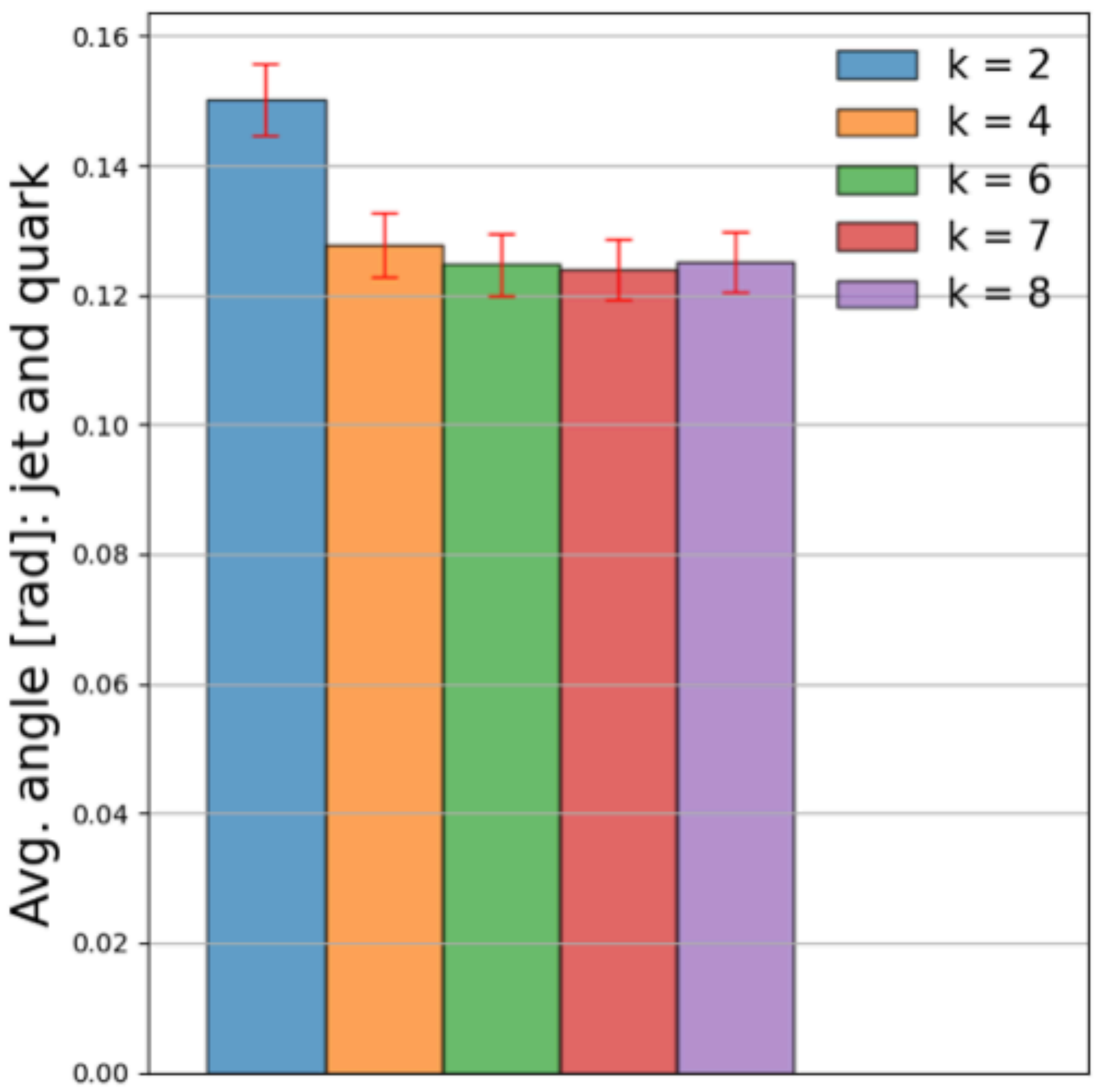






(a)



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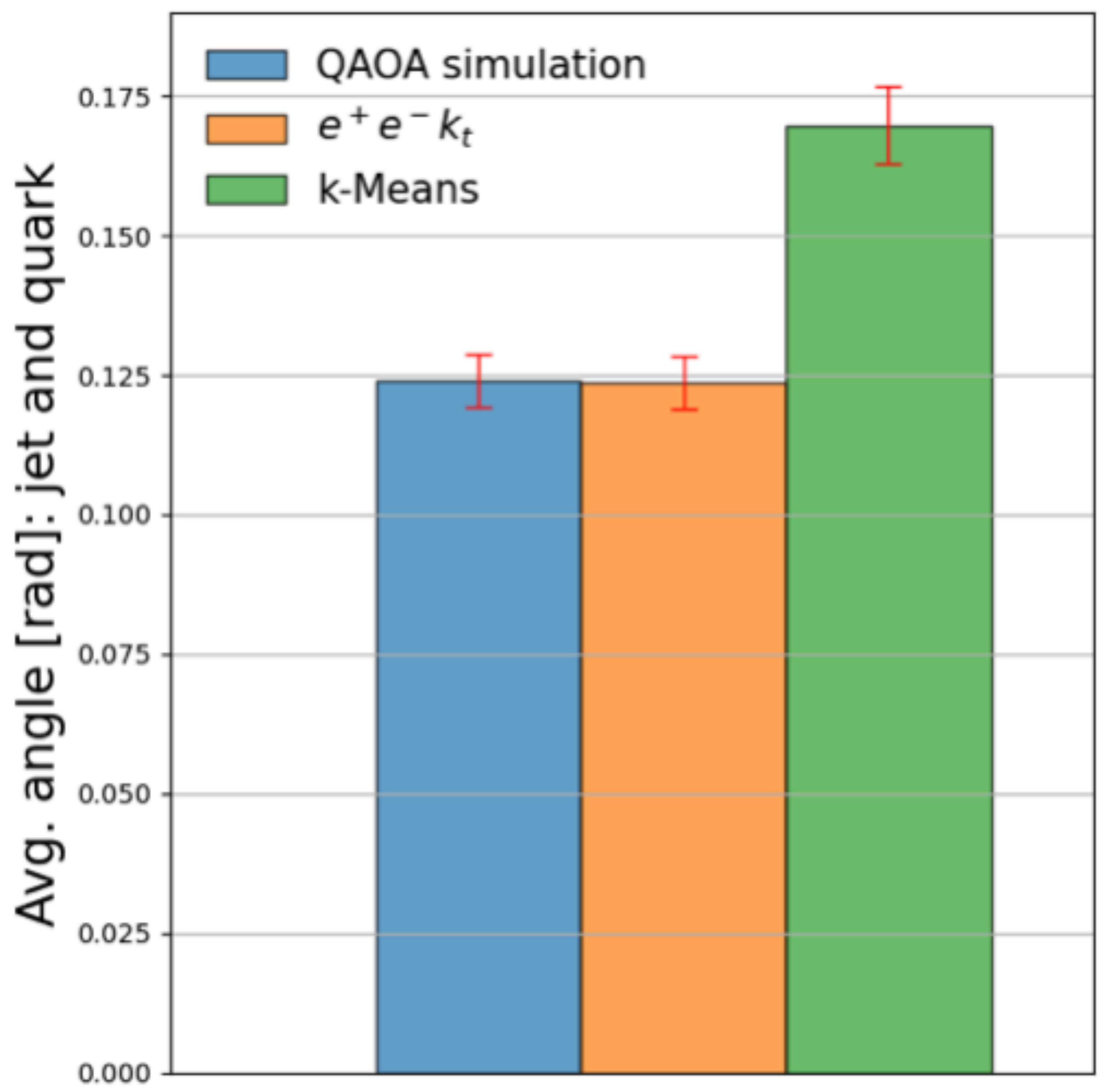

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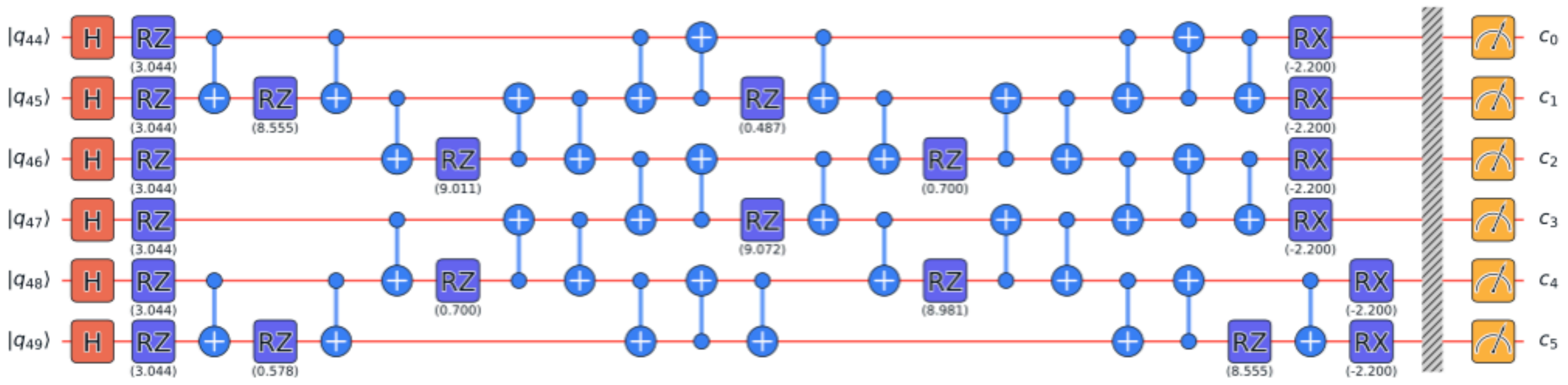

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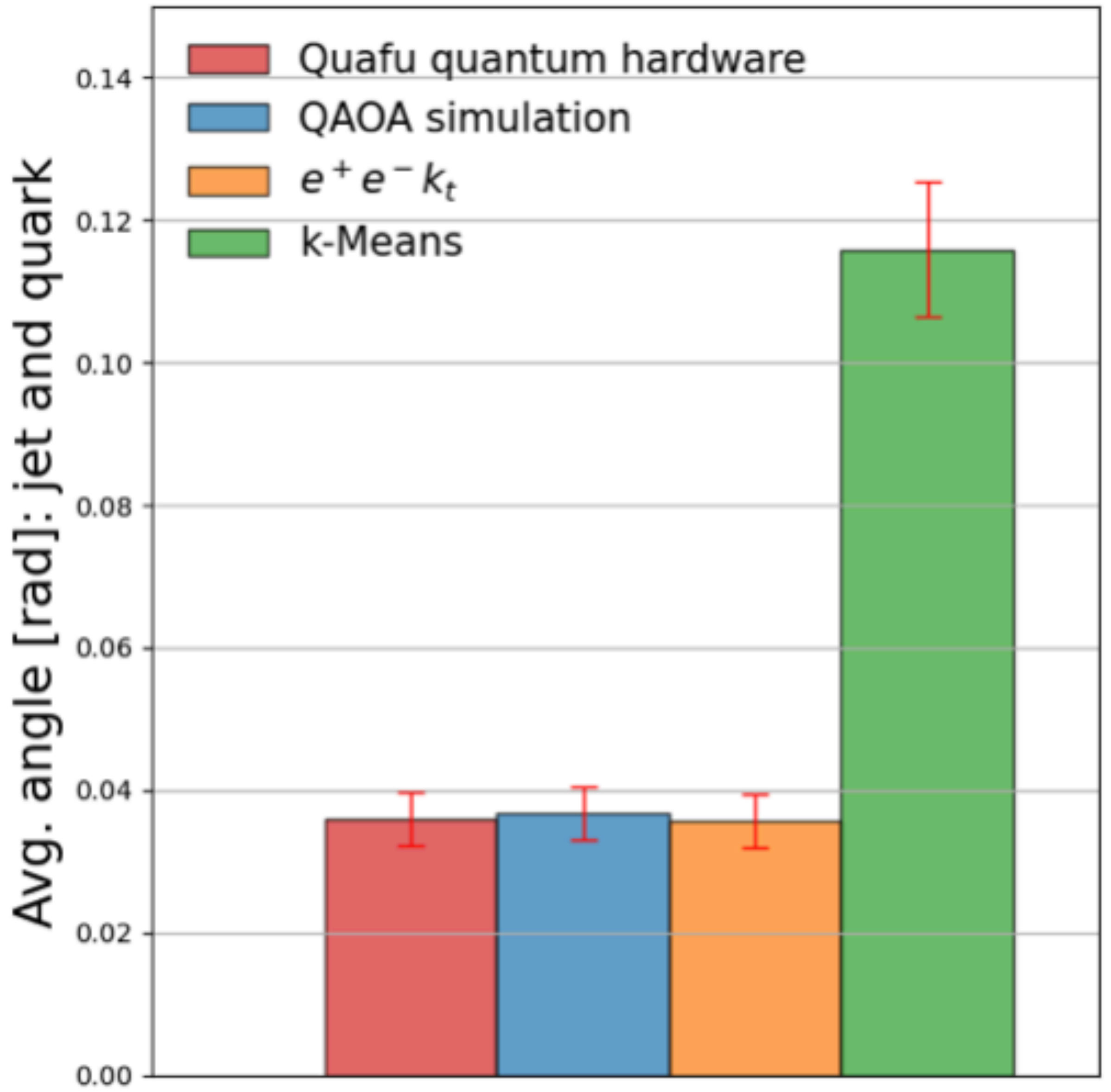

(e)

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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

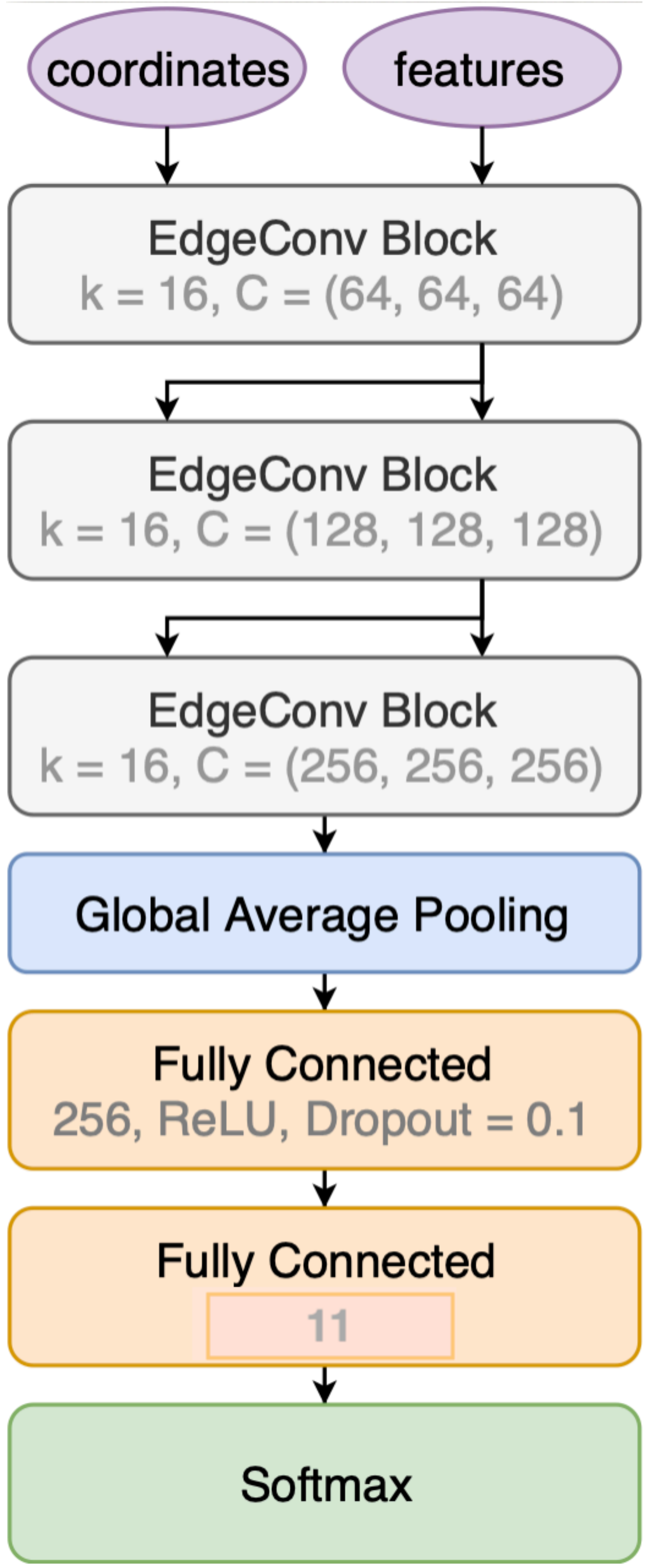
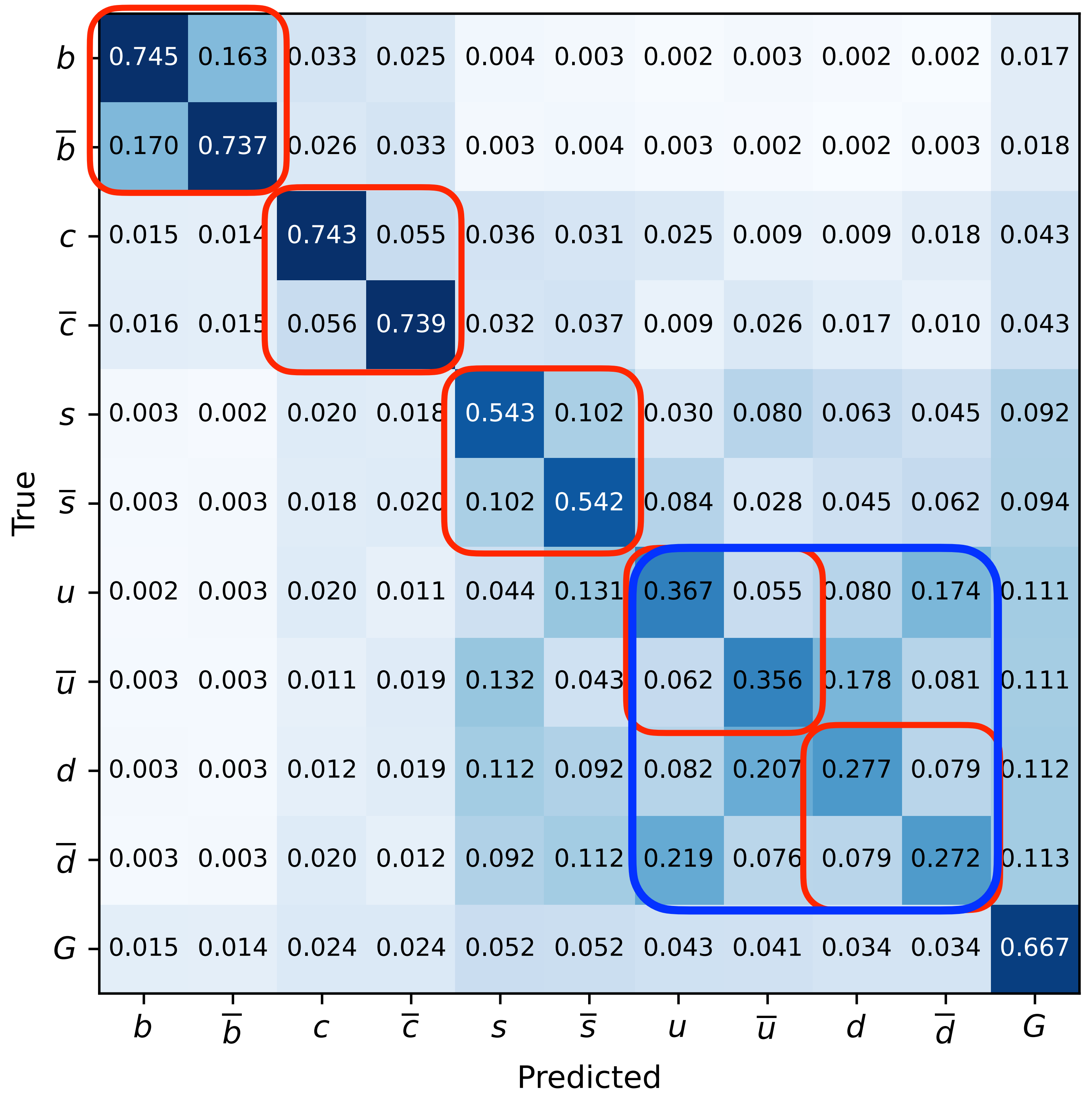
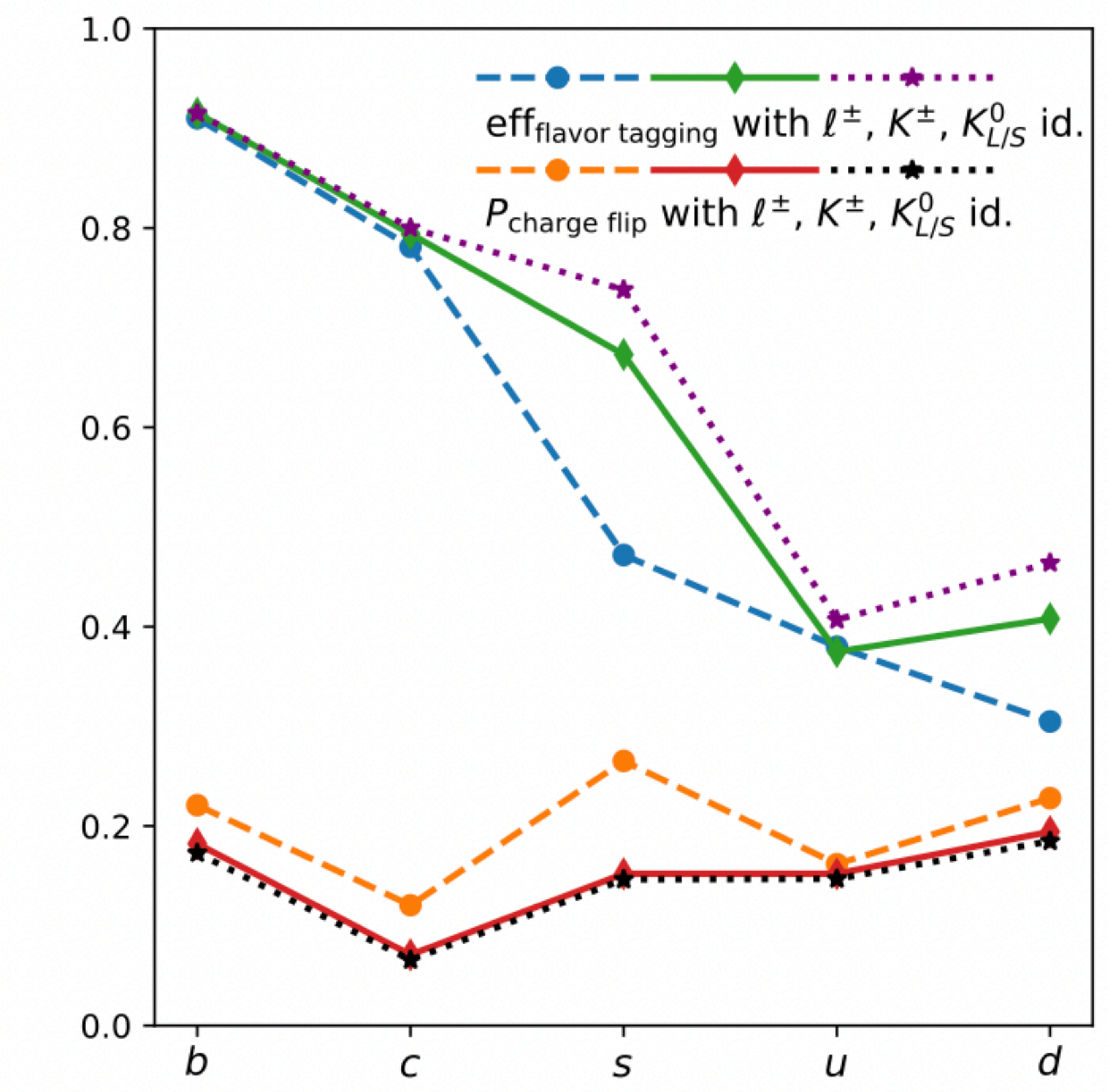


Table 3 The input variables used in ParticleNet for jet flavor tagging at the CEPC

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



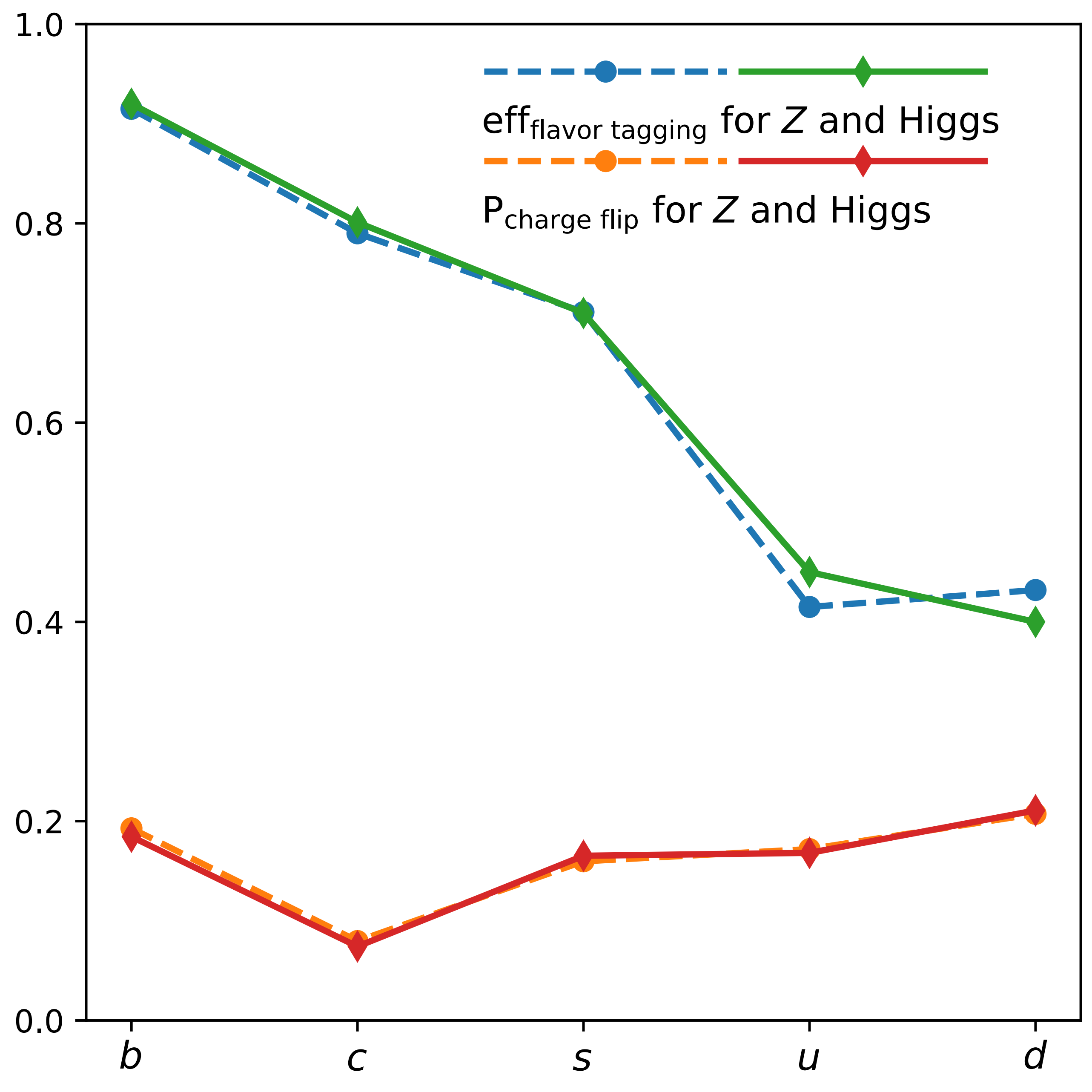


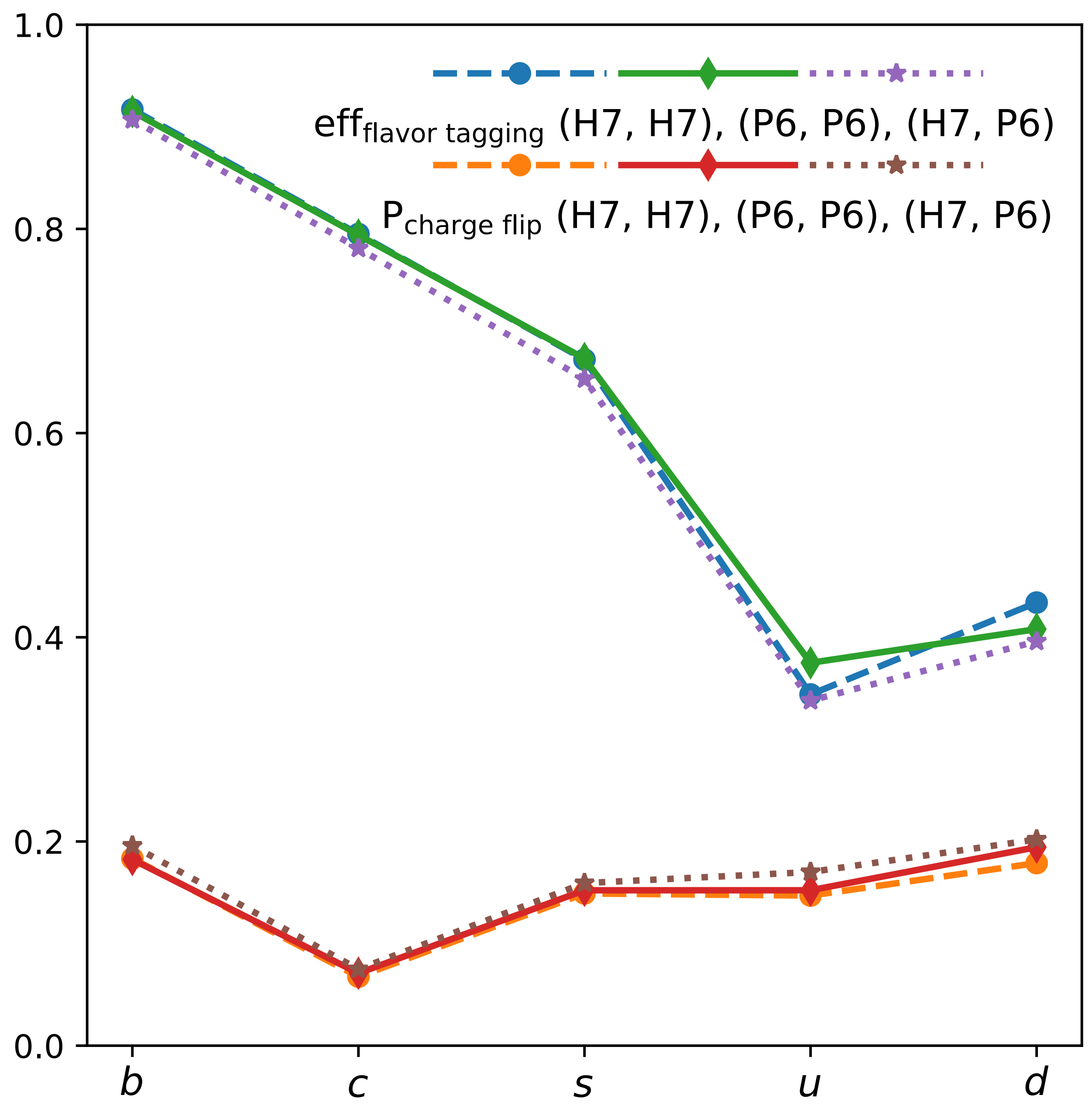
- Our jet-origin identification categorizes jets into five quark species (b, c, s, u, d), five antiquarks, and the gluon
- It reaches jet flavor tagging efficiencies ranging from 67% to 92% for b, c, and s quarks and jet charge flip rates of 7%–24% for all quark species

Phys. Rev. Lett. 132 (2024) 221802

Machine learning-based jet-origin identification

- We perform a series of companion 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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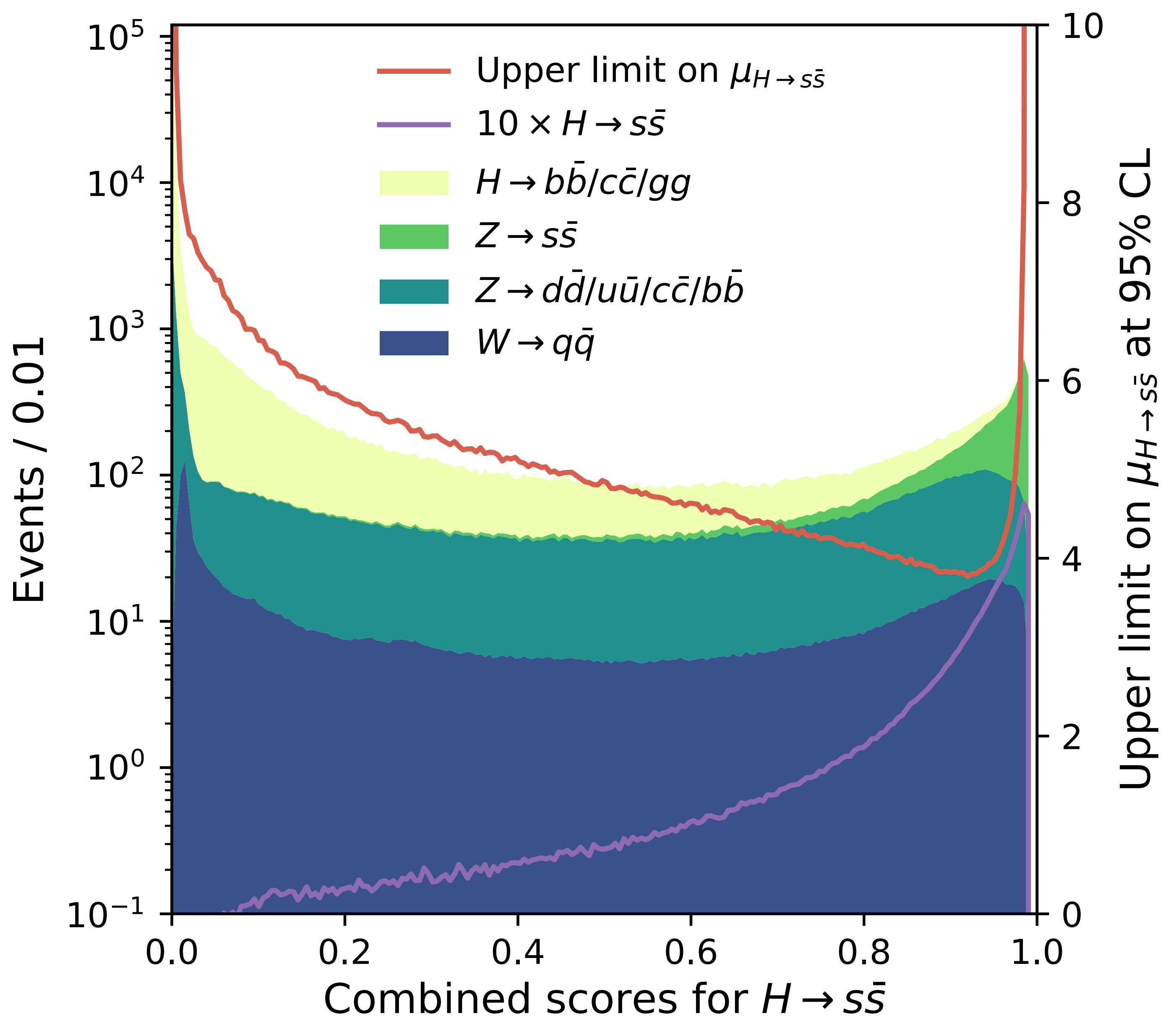
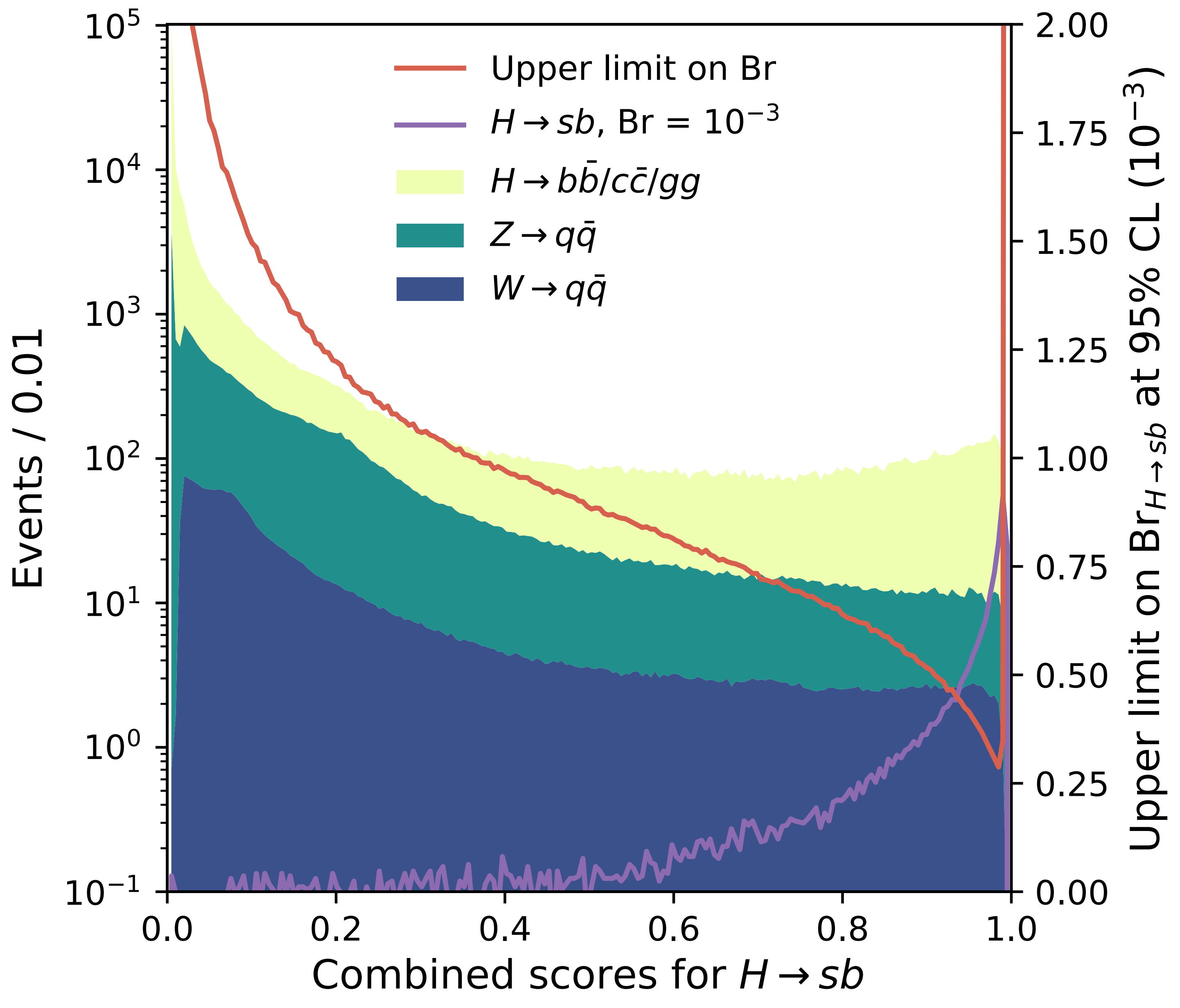
JOI's application at an electron-positron Higgs factory

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





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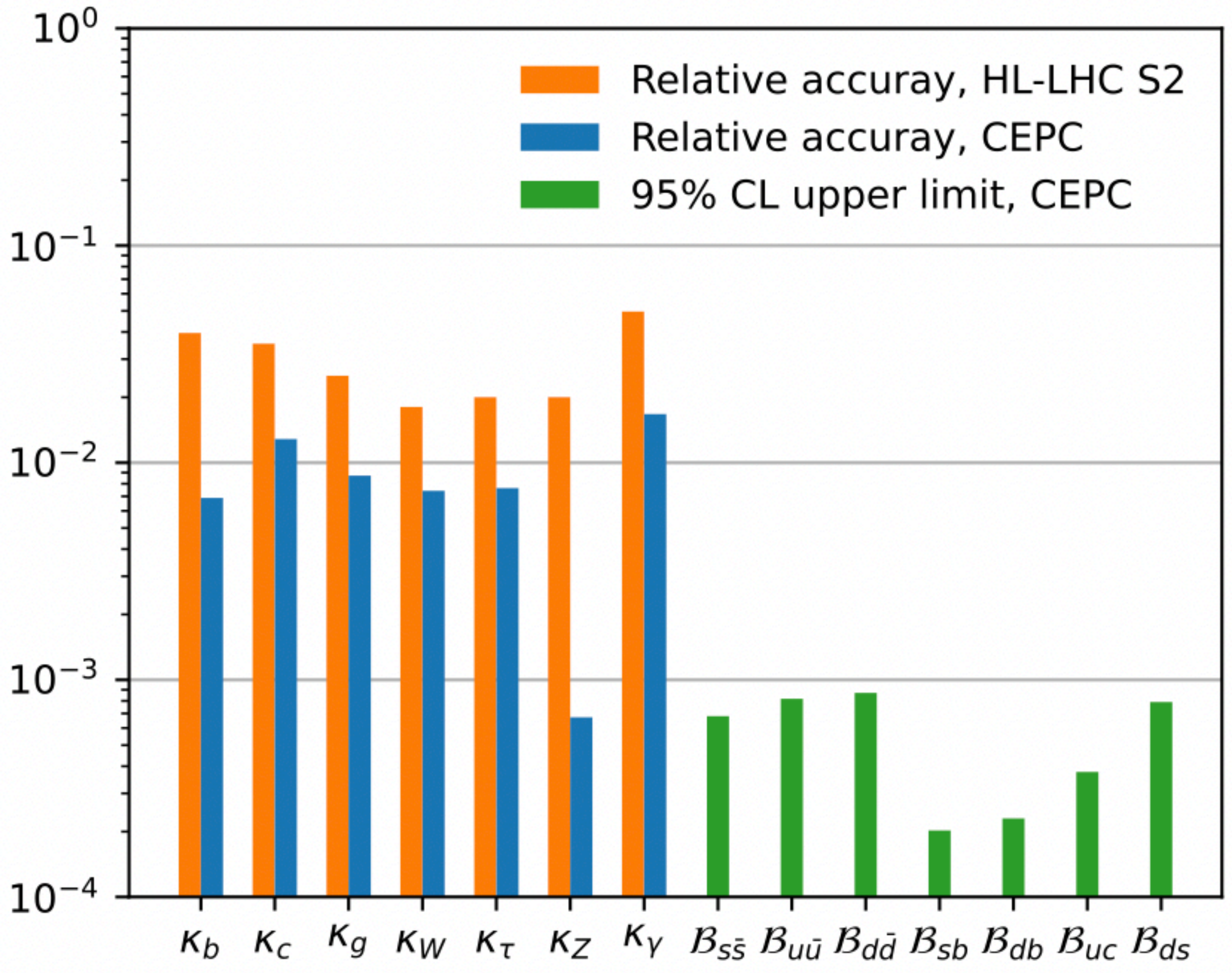
JOI’s application at an electron-positron Higgs factory

- 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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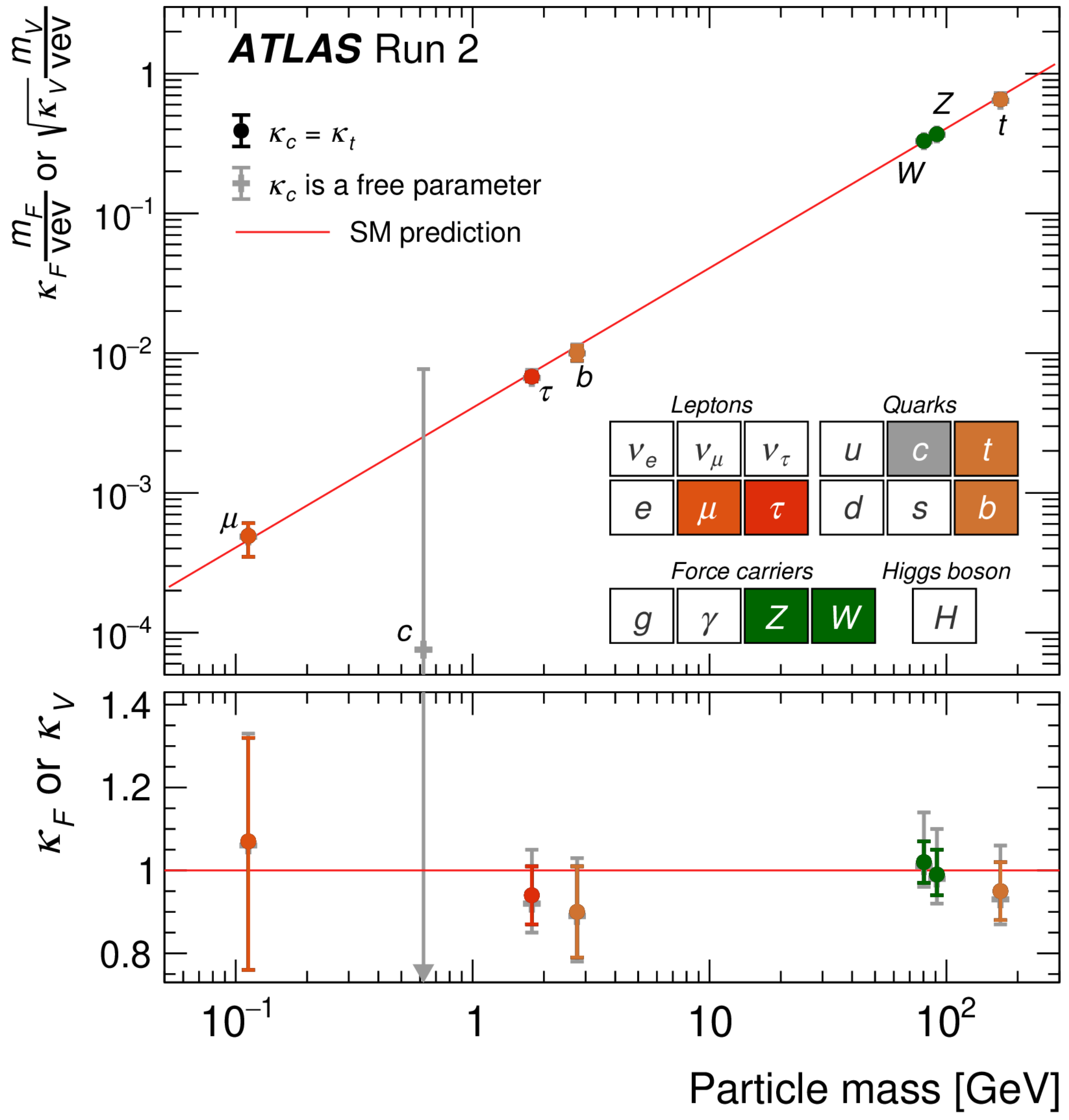
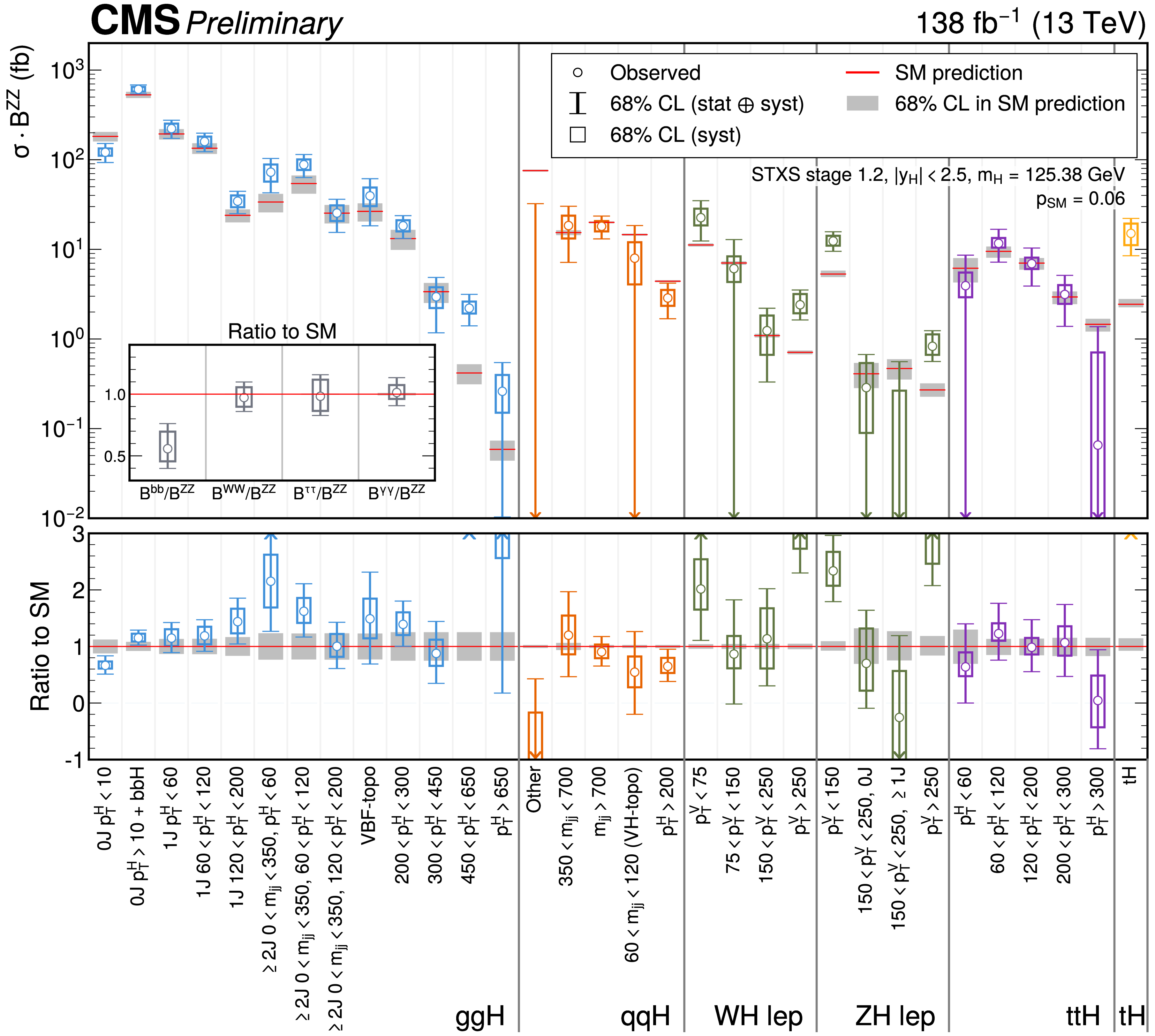
3. Some Higgs and new physics results

that benefit from better jet reconstruction

In this part, I will only discuss LHC results that I contributed to

Higgs couplings with other fundamental particles



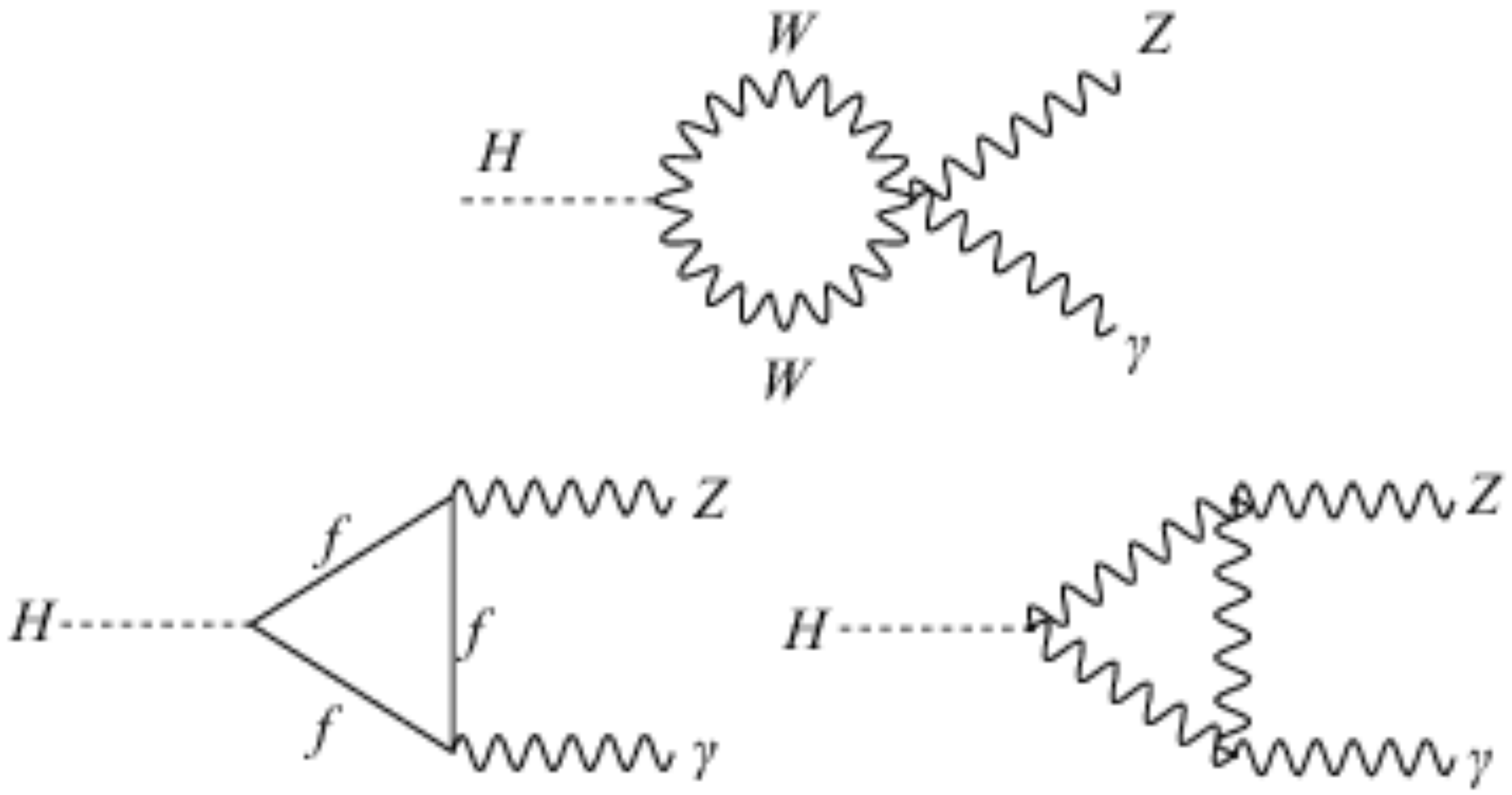


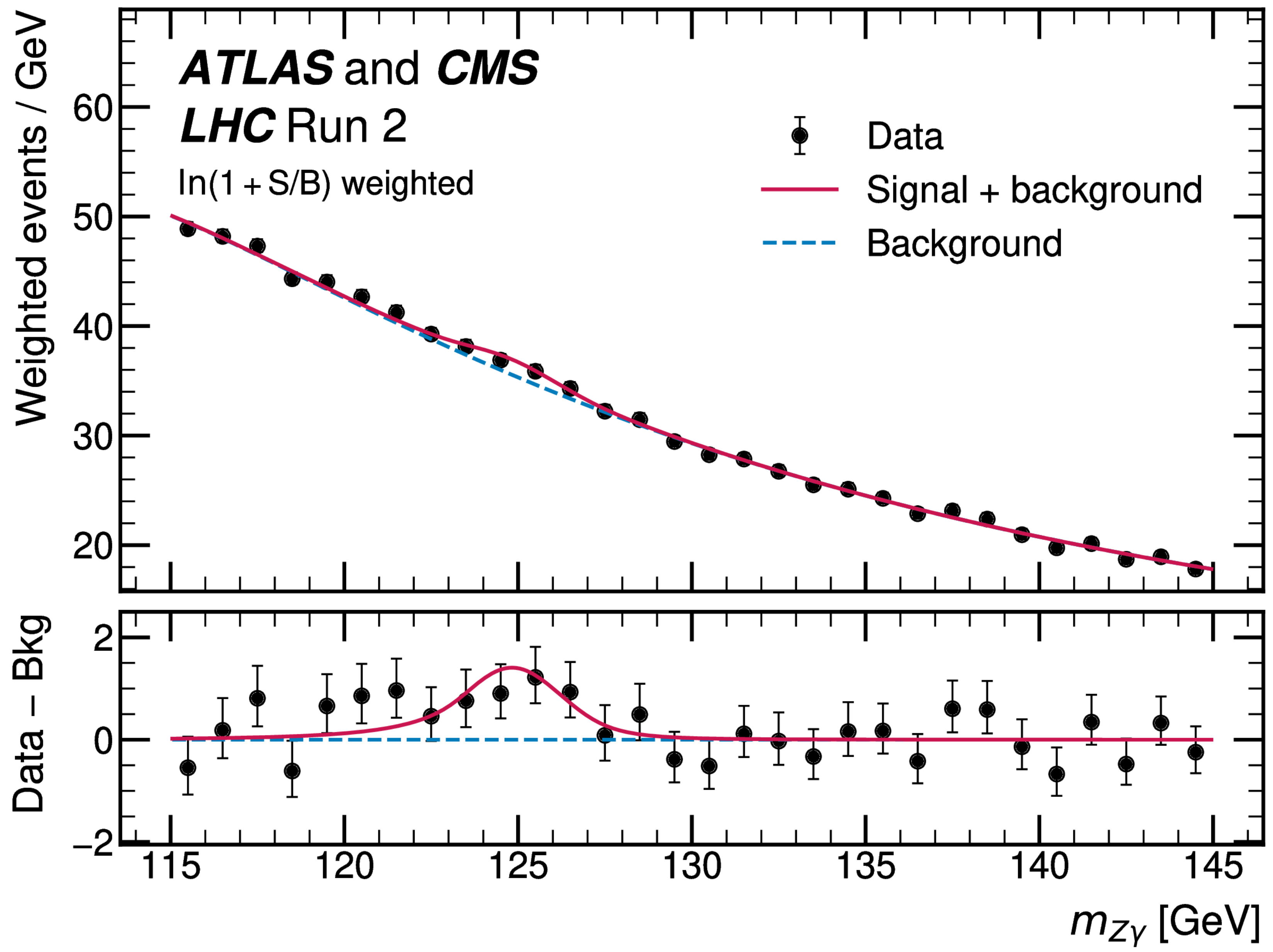
Nature 607 (2022) 52-59

Moriond 2025

- “Kappa” framework: assign coupling modifier to each interaction vertex (e.g. κ_t, …)
- “STXS” framework: split production cross sections into various phase space regions
- LHC Run 2: good agreement with the SM

H→Zγ decay

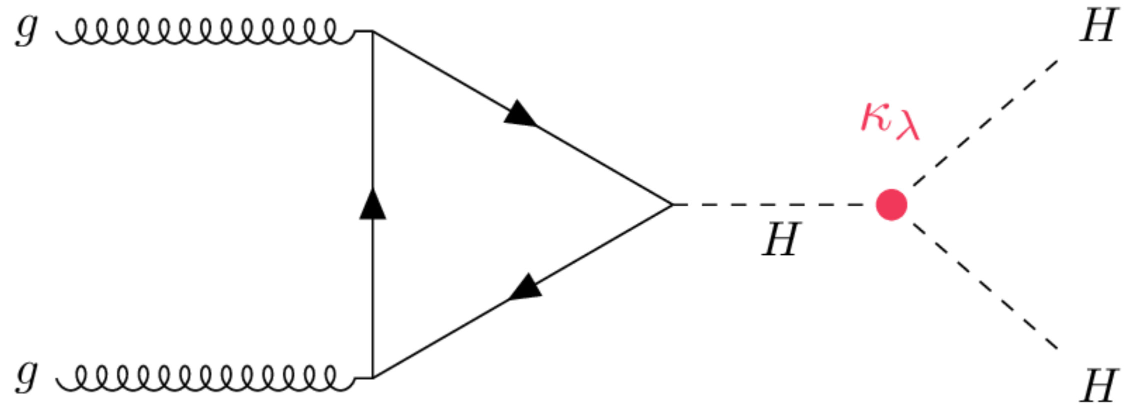


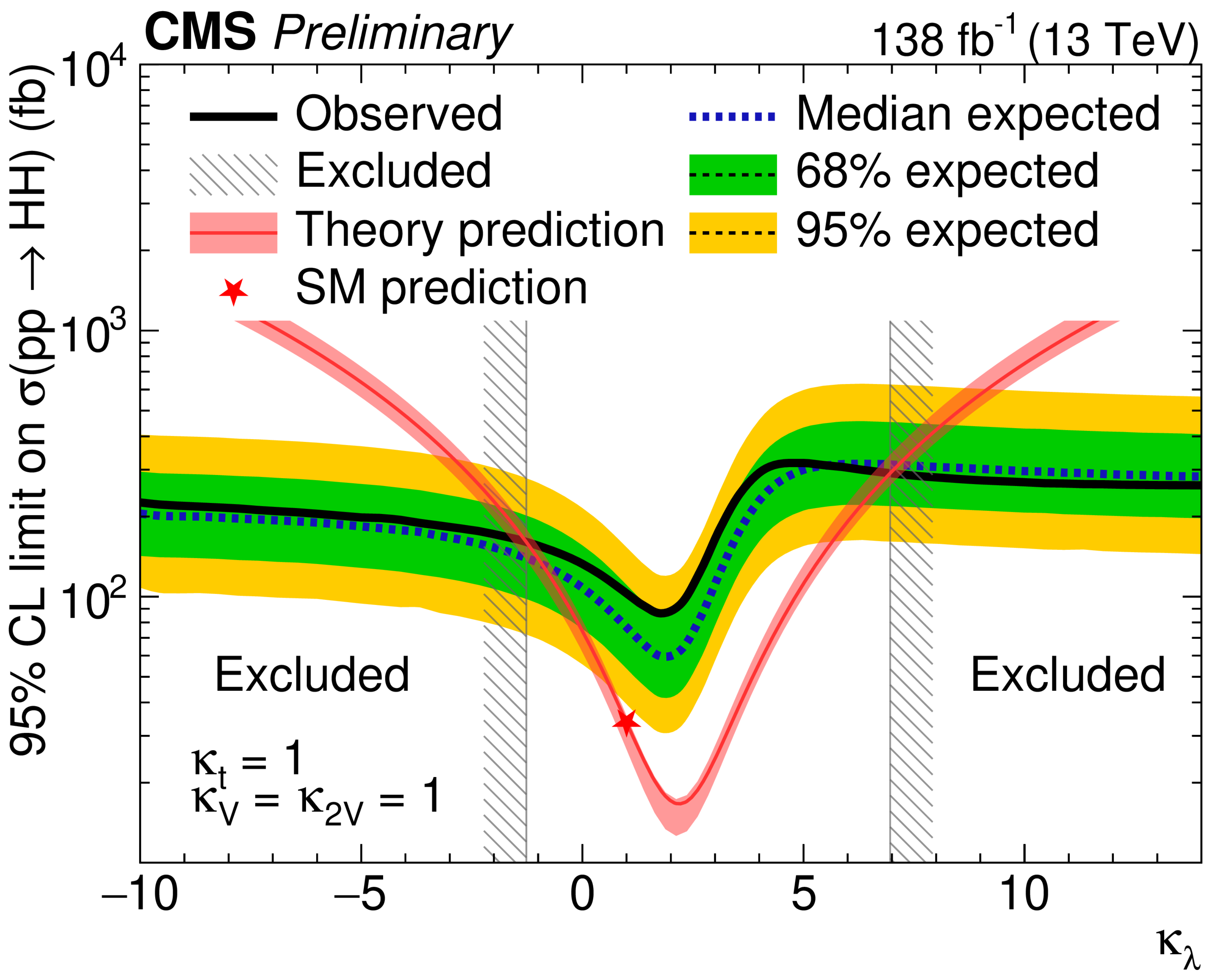


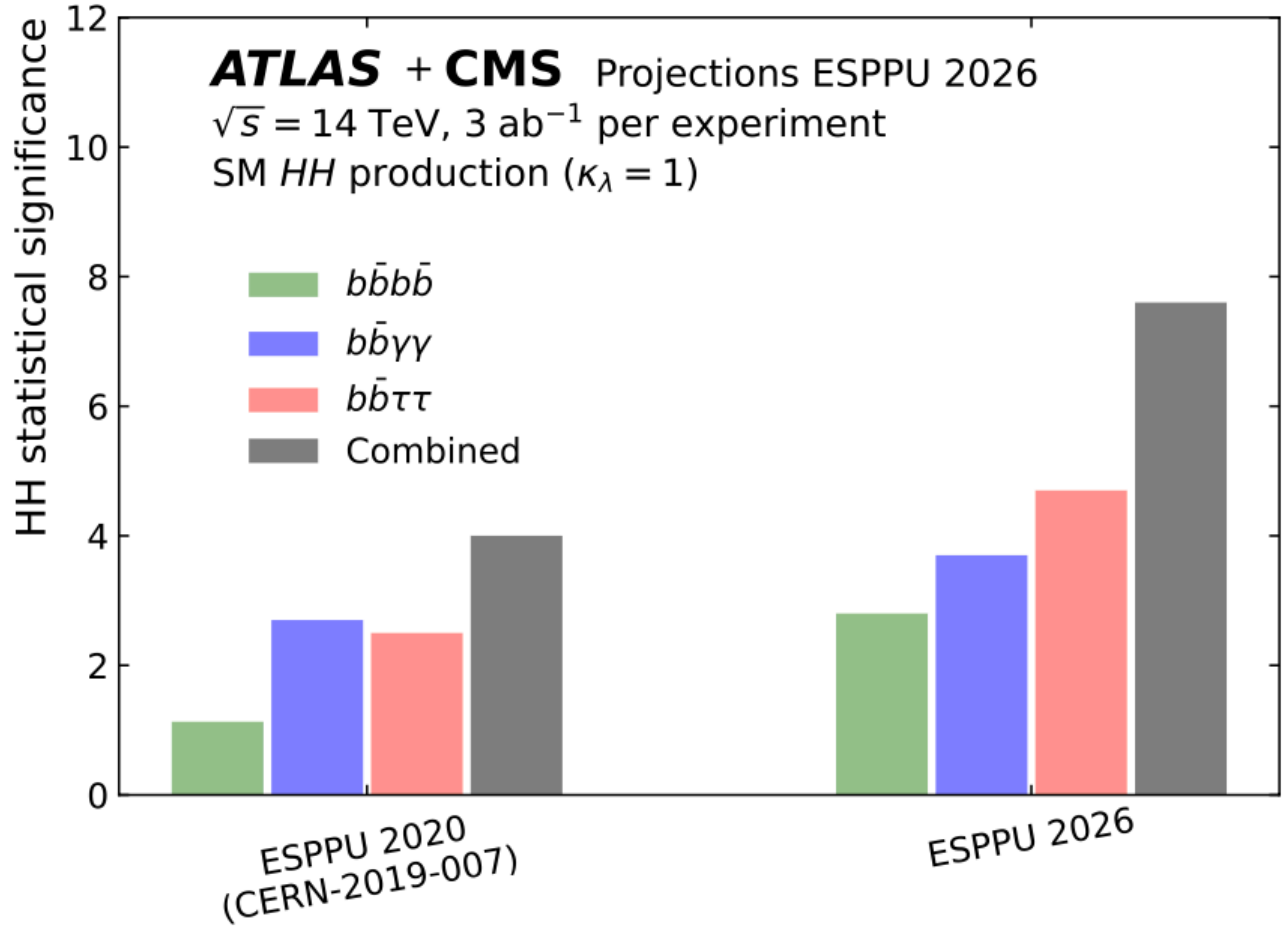
Phys. Rev. Lett. 132 (2024) 021803, Editor's Suggestion, Featured in Physics, Collection of the Year

- The observed H→Zγ significance in ATLAS+CMS combined result is **3.4σ** (expected 1.6σ)
  - **First evidence** of the H→Zγ decay
  - VBF channel (with 2 forward quark jets) is crucial

Higgs self-couplings







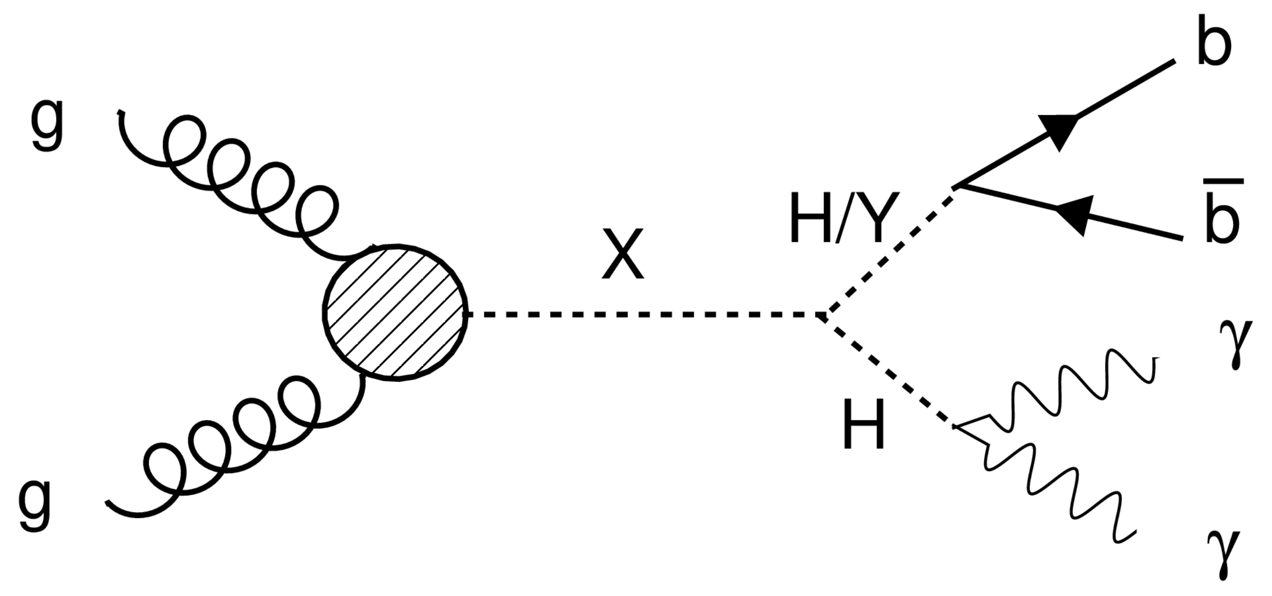
CERN Seminar 2024

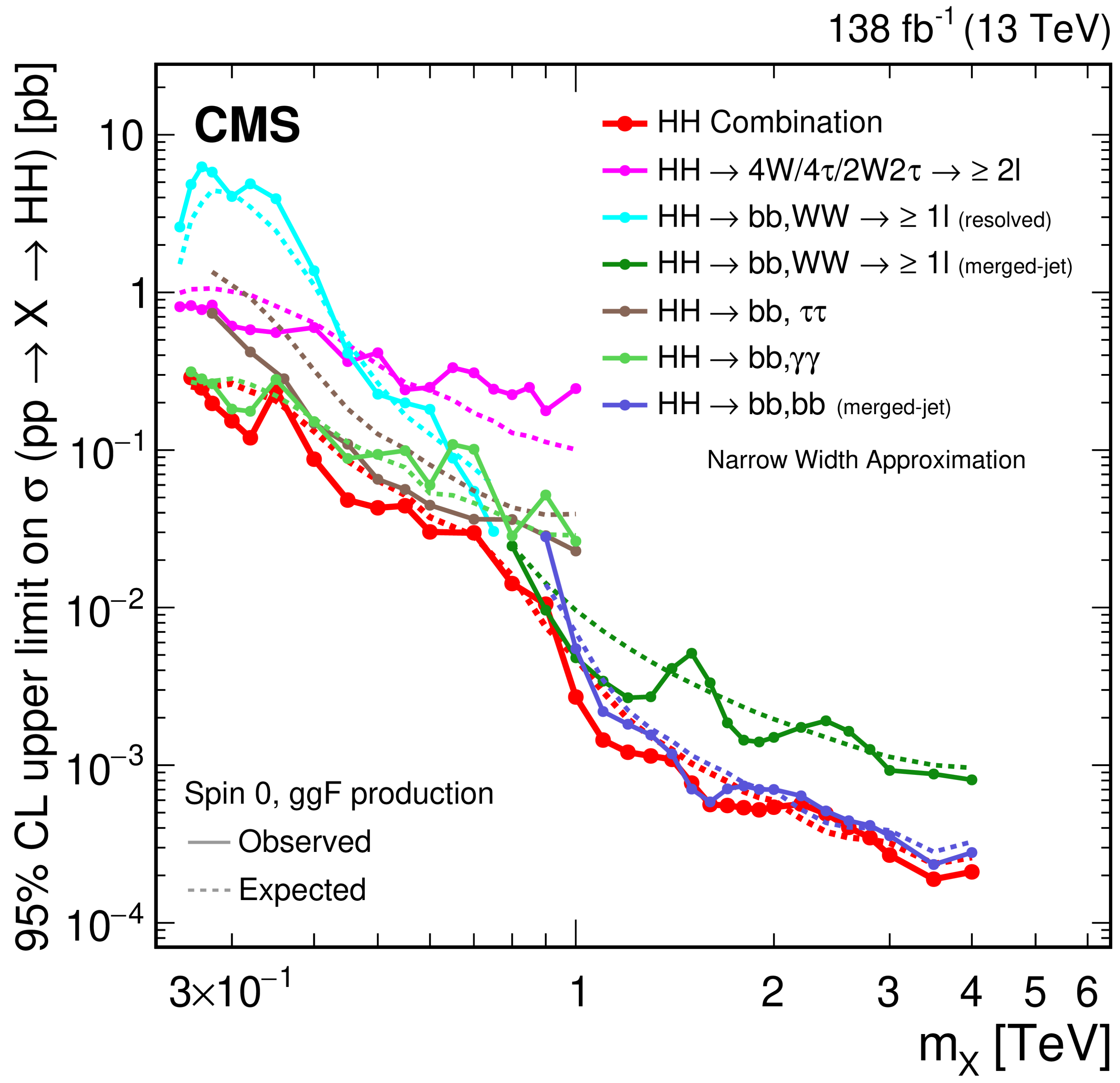
arxiv:2504.00672

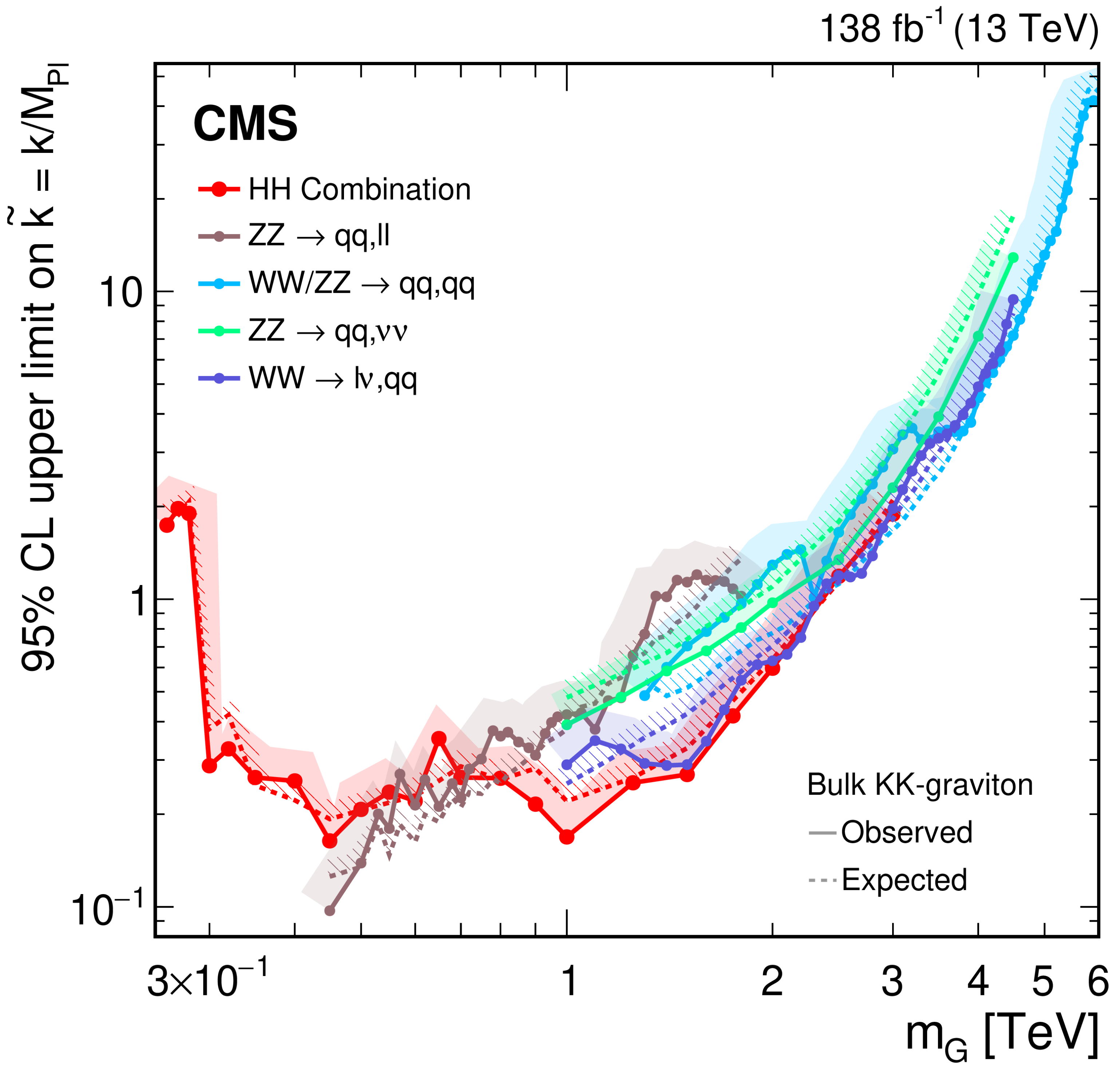
- **Higgs self-coupling may provide a portal to new physics beyond it**
  - Vacuum stability, early universe evolvement, …
- **Double Higgs production is the way to directly probe Higgs self-couplings at the LHC**
  - B-jet tagging is a key
- LHC Run 2: $-1.4<\kappa_\lambda<7.0$ (CMS); $-1.2<\kappa_\lambda<7.2$ (ATLAS)
- HL-LHC: $0.5<\kappa_\lambda<1.6$ (ATLAS+CMS)

Resonant production of Higgs boson

- **Heavy resonance search channels including at least one Higgs boson plus another particle have formed an important part of the new physics search program at the LHC**
- Combining searches channels at CMS, we obtain cross section limits on resonant production of Higgs boson and constraints on relevant new physics models







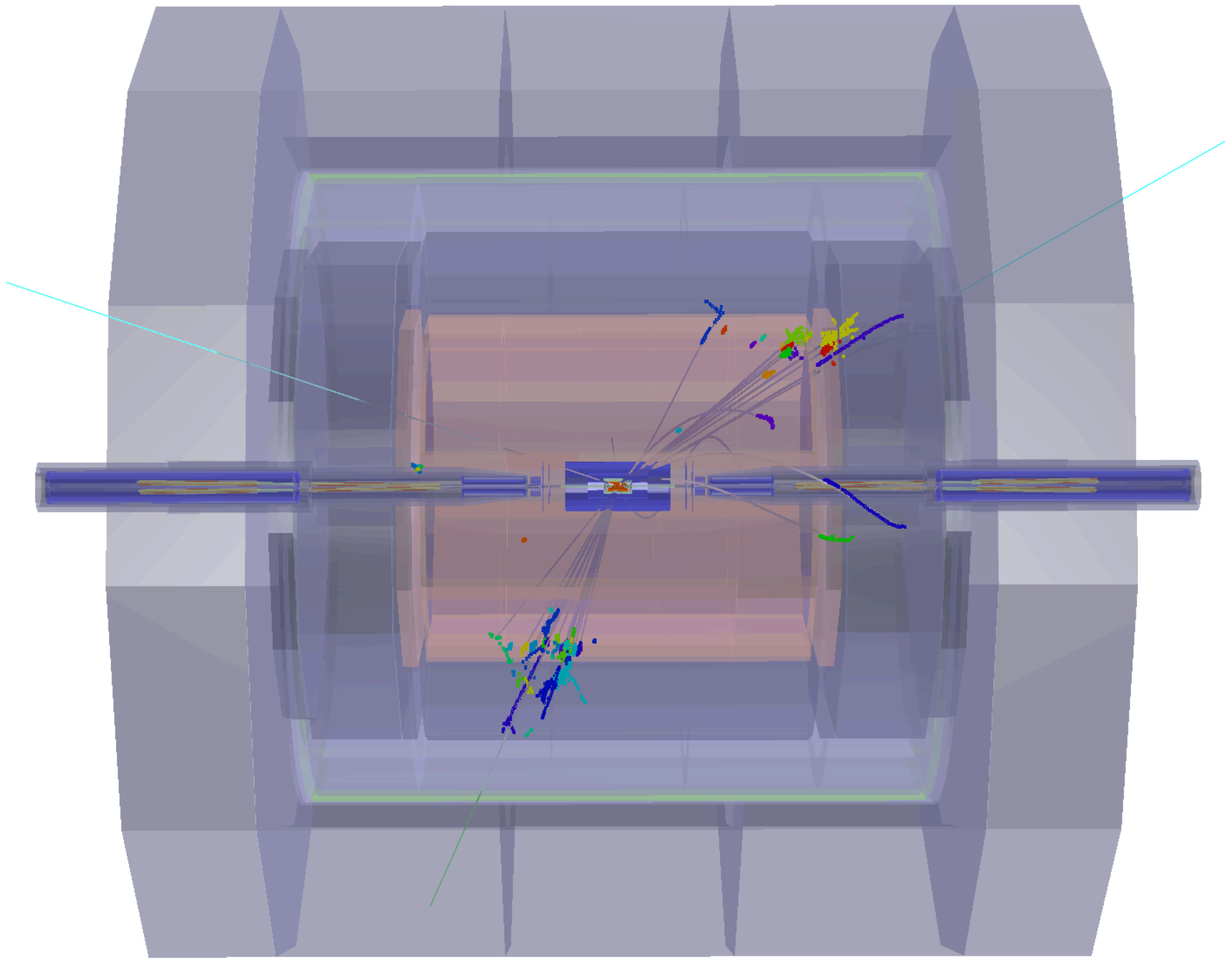
Physics Reports 1115 (2025) 368

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！