If the preview is not legible, please download the PDF file. Appendices A-C are included at the end of the main paper.

APPENDIX (ONLINE)

D. Datasets (Table II of the main paper)

We describe the representation, sources, and preprocessing steps of the datasets used in this work. As a default preprocessing step, we remove all duplicate hyperarcs and self-loops.

- **Metabolic datasets:** We use two metabolic datasets, `metabolic-iAF1260b`, and `metabolic-iJO1366`. Each node represents a gene, and each hyperarc represents a metabolic reaction, where each head and tail set indicates a set of genes. When the genes in the tail set participate in a metabolic reaction, they become the genes in the head set of the corresponding hyperarc. They are provided in the complete form of directed hypergraphs which do not require any preprocessing step.
- **Email datasets:** We use two email datasets, `email-enron`, and `email-eu`. Each node represents an account, and each hyperarc represents an email from a sender to one or more recipients, where the tail set consists of a node representing the sender, and the head set consists of nodes representing the recipients. We transformed the original pairwise graph into a directed hypergraph by considering all edges occurring at the same timestamp from the same sender as a single email (hyperarc). Note that the size of tail sets is always 1 in these datasets. (i.e., $|T_i| = 1, \forall i = \{1, \dots, |E|\}$.)
- **Citation datasets:** We use two citation datasets from DBLP: `citation-data-science`, and `citation-software`. We extracted papers in the fields of data science or software from the dataset. Nodes represent authors and the (head and tail) sets indicate co-authors of each publication. Hyperarcs indicate citation relationships, with the tail set representing the paper that cites the head set paper.
- **Question & Answering datasets:** We use two question & answering datasets, `qna-math` and `qna-server`. Following [2], we created a directed hypergraph from the log data of the two question-answering sites: Math Exchange and Server Fault. Each node represents a user, and each hyperarc represents a post, with the tail set consisting of the answerers and the head set consisting of the questioner. Note that the size of head sets is always 1 in these datasets. (i.e., $|H_i| = 1, \forall i = \{1, \dots, |E|\}$.)
- **Bitcoin transaction datasets:** We use three bitcoin transaction datasets, `bitcoin-2014`, `bitcoin-2015`, and `bitcoin-2016`, created from the original datasets, as suggested in [2]. They contain the first 1.5 million transactions in Nov 2014, Jun 2015, and Jan 2016, respectively. Each node represents an individual account, and each hyperarc represents a cryptocurrency transaction. The tail set of a hyperarc corresponds to the accounts selling the cryptocurrency, while the head set corresponds to the accounts buying the corresponding cryptocurrency.

E. Count Distributions (Section V-B of the main paper)

We analyze the occurrence distributions of DHGs in real-world and randomized directed hypergraphs (DHs). To ensure statistical significance, we generate ten randomized DHs and report the average counts. As shown in Figure 12, the counts of DHGs in real-world directed hypergraphs are distinct from those in randomized directed hypergraphs.

F. Temporal Analysis (Section V-E of the main paper)

We analyze time-evolving DHs (all considered DHs except for the `metabolic` datasets, which do not contain timestamps). A time-evolving DH $G = (V, E)$ has timestamp τ_e for each $e \in E$, i.e., $e = \langle H, T, \tau_e \rangle$. With regard to the `citation` datasets, `citation-data-science` consists of 41 timestamps, while `citation-software` includes 49 timestamps, with each publication year assigned as a timestamp. For the `email`, `qna`, and `bitcoin` datasets, we consider 10 timestamps $\{t_1, t_2, \cdots, t_{10}\}$ of the same interval, where $t_1 < \cdots < t_{10} = \max_{e \in E} \tau_e$ and $t_2 - t_1 = t_1 - \min_{e \in E} \tau_e$. For each timestamp t_i above, we create a snapshot (i.e., sub-DH) where the edge set is $E_i = \{e : \tau_e \leq t_i\}$ and the node set $V_i = \bigcup_{e \in E_i} \bar{e}$. Then, we compute the occurrence ratio of each DHG in each sub-DH.

G. Experimental Settings for Hyperarc Prediction (Section V-C of the main paper)

In this section, we list the hyperparameter settings of the feature vectors and classifiers used for the hyperarc prediction and report the detailed experimental setups.

Hyperparameter settings of feature vectors: The embedding dimensions of node2vec, hyper2vec, and deep hyperedges are all fixed to 91. Other hyperparameters of these methods are fixed to their default settings at the following links:

- **node2vec (n2v)**: https://github.com/aditya-grover/node2vec
- **hyper2vec (h2v)**: https://github.com/jeffhj/NHNE
- **deep hyperedges (deep-h)**: https://github.com/0xpayne/deep-hyperedges

Note that h-motif and triad do not have any hyperparameters.

Details of classifiers: The hyperparameters of the tree-based classifiers (Decision Tree, Random Forest, XGBoost, and LightGBM), Logistic Regressor, KNN, and MLP are fixed to their default settings at the following links:

- **Decision Tree (DT)**: https://scikit-learn.org/stable/modules/generated/sklearn.tree.DecisionTreeClassifier
- **Random Forest (RF)**: https://scikit-learn.org/stable/modules/generated/sklearn.ensemble.RandomForestClassifier
- **XGBoost (XGB)**: https://xgboost.readthedocs.io/en/stable/
- **LightGBM (LGBM)**: https://lightgbm.readthedocs.io/en/latest/pythonapi/lightgbm.LGBMClassifier
- **Logistic Regressor (LR)**: https://scikit-learn.org/stable/modules/generated/sklearn.linear_model.LogisticRegression
- **KNN**: https://scikit-learn.org/stable/modules/generated/sklearn.neighbors.KNeighborsClassifier
- **MLP**: https://scikit-learn.org/stable/modules/generated/sklearn.neural_network.MLPClassifier

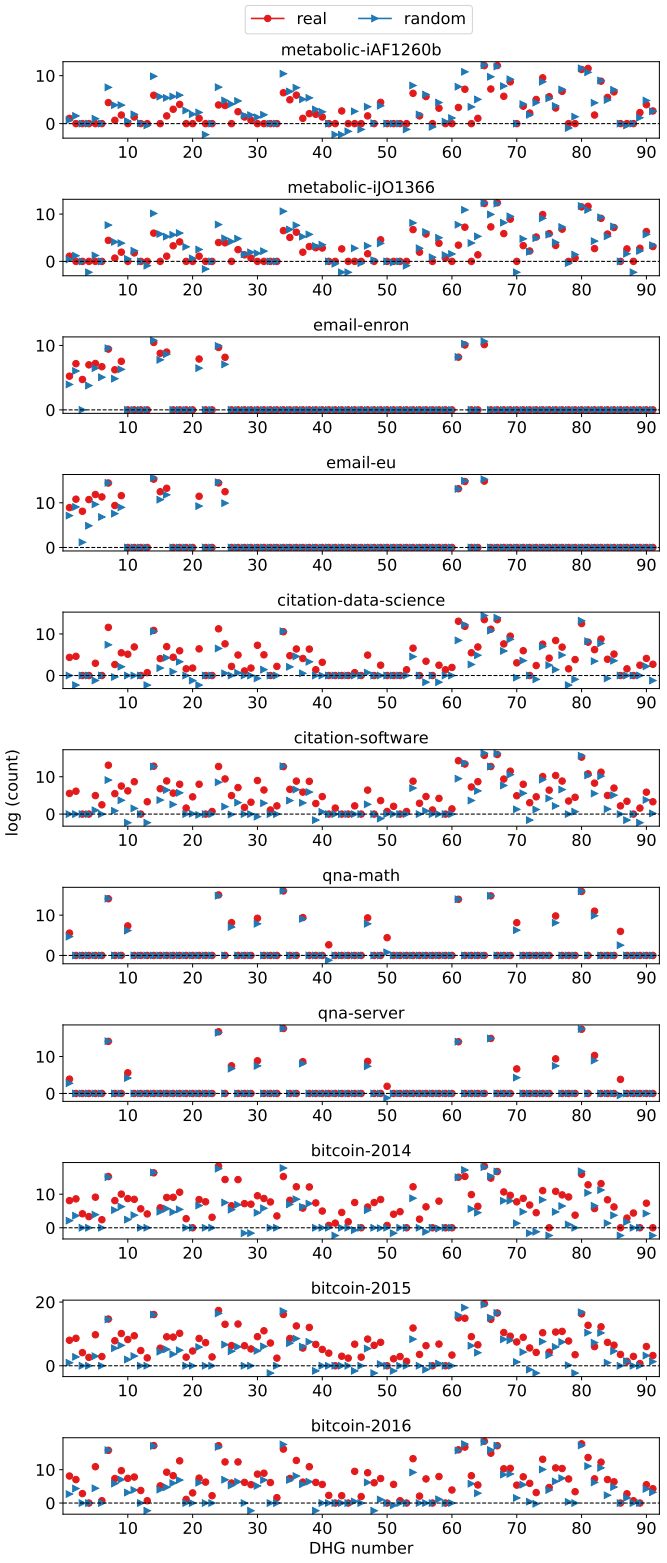

Fig. 12. Log counts of DHGs in real-world and randomized directed hypergraphs (DHs). The counts of DHGs are clearly distinguished in real-world and randomized DHs.

To utilize the hyperarc-level feature vectors for hypergraph-neural-network-based (HNN-based) classifiers (HGNN, FastHyperGCN, and UniGCNII), which assume that the input is an undirected hypergraph with node features, we use the "dual" hypergraph of a given directed hypergraph (DH) as the input of the classifiers. In the dual hypergraph $G^* = (V^*, E^*)$ of a DH $G = (V, E)$, each node is a hyperarc in G (i.e., $V^* = E$) and each hyperedge is the set of hyperarcs containing a node in G (i.e., $E^* = \{E_v : v \in V\}$).

The hyperparameters of these HNN-based classifiers are set as follows: the number of layers and hidden dimension are all fixed to 2 and 128, respectively. We train HGNN and UniGCNII for 500 epochs using Adam with a learning rate of 0.001 and a weight decay of 10^{-6}, and FastHyperGCN for 200 epochs using Adam with a learning rate of 0.01, a weight decay of 5×10^{-4}, and a dropout rate of 0.5.

For these HNN-based classifiers, we employ early stopping, and to this end, we divide the fake hyperarcs into the train, validation, and test sets using a 6:2:2 ratio. In each set, we uniformly sample the same number of real hyperarcs as the number of fake hyperarcs. For every 50 epochs, we measure the validation accuracy and save the model parameters. Then, we use the checkpoint (i.e., saved model parameters) with the highest validation accuracy to measure test performance.

H. Application Results (Section V-C of the main paper)

In this section, we report the full results of the hyperarc prediction problem. Table IV reports the accuracy and AUROC and results (average over 100 trials). The best performances are highlighted in bold, and the second-best performances are underlined. Notably, in terms of average ranking, using DHG vectors, including the dimension reduced versions, performs best in most settings, achieving up to 33% higher AUROC on the `bitcoin-2016` dataset and a 47% higher accuracy on the `bitcoin-2014` dataset than the second best features.

TABLE IV

HYPERARC PREDICTION PERFORMANCE. WE COMPARE NINE HYPERARC FEATURE VECTORS USING TEN CLASSIFIERS. THE BEST PERFORMANCES ARE HIGHLIGHTED IN BOLD, AND THE SECOND-BEST PERFORMANCES ARE UNDERLINED. NOTABLY, USING DHG VECTORS LEADS TO THE BEST PERFORMANCE (UP TO 47% AND 33% BETTER IN TERMS OF ACCURACY AND AUROC, RESPECTIVELY) IN MOST SETTINGS, INDICATING THAT DHGS EXTRACT HIGHLY INFORMATIVE HYPERARC FEATURES.

(a) `metabolic-iAF1260b`

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.664±0.050	0.549±0.061	0.664±0.047	0.649±0.049	0.656±0.057	0.504±0.050	0.511±0.044	0.701±0.055	**0.705±0.044**
	RF	**0.734±0.046**	0.650±0.067	0.733±0.048	0.681±0.059	0.690±0.063	0.531±0.054	0.518±0.047	0.714±0.050	0.717±0.060
	DT	**0.695±0.055**	0.597±0.063	0.683±0.051	0.632±0.065	0.651±0.053	0.512±0.057	0.506±0.056	0.583±0.055	0.615±0.065
	KNN	0.702±0.047	0.625±0.067	0.703±0.044	0.696±0.058	0.696±0.049	0.537±0.050	0.534±0.056	0.704±0.046	**0.720±0.050**
	MLP	0.709±0.049	0.603±0.062	**0.716±0.053**	0.646±0.054	0.654±0.063	0.533±0.051	0.537±0.047	0.705±0.054	0.667±0.054
	XGB	0.729±0.048	0.625±0.066	**0.741±0.050**	0.666±0.059	0.708±0.062	0.514±0.048	0.519±0.045	0.695±0.054	0.717±0.055
	LGBM	0.728±0.047	0.626±0.063	**0.740±0.047**	0.658±0.053	0.697±0.062	0.527±0.054	0.516±0.052	0.698±0.053	0.713±0.060
	HGNN	0.538±0.047	0.538±0.063	0.546±0.053	0.543±0.040	**0.549±0.055**	0.483±0.045	0.498±0.067	0.526±0.057	0.540±0.055
	FHGCN	0.562±0.067	0.555±0.055	0.588±0.064	0.535±0.051	**0.666±0.067**	0.507±0.045	0.491±0.059	0.538±0.050	0.619±0.070
	UGCNII	**0.643±0.051**	0.596±0.069	0.623±0.057	0.625±0.038	0.618±0.061	0.491±0.050	0.494±0.054	0.597±0.070	0.619±0.066
Max		0.734±0.046	0.650±0.067	**0.741±0.050**	0.696±0.058	0.708±0.062	0.537±0.050	0.537±0.047	0.714±0.050	0.720±0.050
Avg.		0.670±0.066	0.596±0.036	**0.674±0.064**	0.633±0.051	0.659±0.045	0.514±0.017	0.512±0.015	0.646±0.072	0.663±0.059
Rank Avg.		2.500±1.360	6.600±0.663	**2.200±0.980**	5.200±1.536	3.900±1.578	8.500±0.500	8.500±0.500	4.600±1.800	3.000±1.265

Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.735±0.059	0.580±0.067	0.727±0.052	0.724±0.049	0.728±0.056	0.506±0.067	0.509±0.052	0.785±0.051	**0.791±0.046**
	RF	0.815±0.045	0.703±0.087	0.817±0.046	0.784±0.058	0.826±0.046	0.539±0.066	0.533±0.068	0.793±0.051	**0.835±0.048**
	DT	**0.695±0.056**	0.599±0.062	0.683±0.051	0.632±0.065	0.651±0.053	0.512±0.057	0.506±0.056	0.583±0.055	0.615±0.065
	KNN	0.770±0.045	0.673±0.076	0.774±0.048	0.755±0.056	0.762±0.051	0.550±0.058	0.552±0.070	0.760±0.047	**0.788±0.051**
	MLP	0.759±0.053	0.622±0.071	0.778±0.053	0.694±0.074	0.696±0.068	0.543±0.065	0.559±0.059	**0.800±0.048**	0.710±0.063
	XGB	0.805±0.045	0.684±0.076	0.816±0.046	0.752±0.068	0.812±0.049	0.518±0.063	0.526±0.068	0.775±0.047	**0.824±0.047**
	LGBM	0.807±0.046	0.680±0.072	0.817±0.046	0.736±0.062	0.799±0.057	0.540±0.059	0.529±0.062	0.785±0.045	**0.823±0.049**
	HGNN	0.559±0.057	0.541±0.067	0.576±0.048	0.554±0.059	**0.594±0.060**	0.479±0.058	0.506±0.086	0.522±0.060	0.580±0.055
	FHGCN	0.603±0.080	0.612±0.056	0.637±0.077	0.567±0.072	**0.729±0.065**	0.506±0.059	0.490±0.067	0.561±0.060	0.693±0.069
	UGCNII	**0.702±0.045**	0.641±0.097	0.681±0.055	0.674±0.048	0.680±0.060	0.488±0.049	0.489±0.068	0.607±0.092	0.679±0.085
Max		0.815±0.045	0.703±0.087	0.817±0.046	0.784±0.058	0.826±0.046	0.550±0.058	0.559±0.059	0.800±0.048	**0.835±0.048**
Avg.		0.725±0.083	0.634±0.050	0.731±0.080	0.687±0.076	0.728±0.071	0.518±0.023	0.520±0.023	0.697±0.108	**0.734±0.087**
Rank Avg.		3.100±1.221	6.400±0.917	2.600±0.917	5.600±0.663	3.000±1.265	8.600±0.490	8.400±0.490	5.100±2.022	**2.200±1.470**

(b) `metabolic-iJO1366`

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.662±0.051	0.584±0.055	0.658±0.050	0.648±0.051	0.656±0.048	0.506±0.052	0.505±0.042	**0.713±0.057**	0.699±0.051
	RF	**0.742±0.050**	0.666±0.065	0.730±0.045	0.704±0.059	0.698±0.068	0.532±0.045	0.527±0.045	0.723±0.048	0.710±0.066
	DT	**0.694±0.051**	0.612±0.064	0.680±0.053	0.641±0.057	0.656±0.071	0.509±0.053	0.517±0.049	0.582±0.061	0.612±0.055
	KNN	0.705±0.049	0.628±0.063	0.689±0.045	0.691±0.055	0.682±0.051	0.520±0.053	0.539±0.049	**0.725±0.054**	0.715±0.061
	MLP	**0.718±0.049**	0.618±0.064	0.705±0.042	0.653±0.055	0.656±0.059	0.537±0.048	0.539±0.052	0.710±0.055	0.644±0.051
	XGB	**0.741±0.050**	0.657±0.062	0.732±0.045	0.681±0.054	0.709±0.053	0.519±0.051	0.523±0.048	0.703±0.050	0.719±0.059
	LGBM	**0.740±0.052**	0.632±0.058	0.734±0.051	0.663±0.056	0.720±0.057	0.509±0.050	0.530±0.047	0.702±0.050	0.713±0.063
	HGNN	0.542±0.052	0.550±0.043	0.564±0.046	0.553±0.036	**0.569±0.055**	0.499±0.056	0.522±0.037	0.545±0.036	0.558±0.050
	FHGCN	0.591±0.052	0.566±0.059	0.599±0.054	0.532±0.053	**0.653±0.071**	0.504±0.045	0.498±0.048	0.548±0.060	0.619±0.067
	UGCNII	**0.660±0.059**	0.610±0.050	0.646±0.055	0.616±0.048	0.621±0.051	0.518±0.047	0.514±0.034	0.633±0.035	0.647±0.052
Max		**0.742±0.050**	0.666±0.065	0.734±0.051	0.704±0.059	0.720±0.057	0.537±0.048	0.539±0.049	0.725±0.054	0.719±0.059
Avg.		**0.680±0.064**	0.612±0.035	0.674±0.055	0.638±0.054	0.662±0.042	0.515±0.011	0.521±0.013	0.658±0.070	0.664±0.053
Rank Avg.		**2.300±1.900**	6.400±0.917	2.800±0.980	5.300±1.005	3.800±1.720	8.600±0.490	8.400±0.490	4.000±2.049	3.400±1.497

Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.725±0.064	0.622±0.057	0.724±0.053	0.727±0.058	0.721±0.053	0.501±0.063	0.504±0.058	**0.795±0.048**	0.782±0.053
	RF	0.824±0.048	0.730±0.076	0.817±0.045	0.794±0.057	**0.834±0.048**	0.541±0.055	0.546±0.066	0.803±0.043	0.820±0.054
	DT	**0.694±0.051**	0.611±0.064	0.680±0.053	0.641±0.057	0.656±0.071	0.509±0.053	0.517±0.049	0.582±0.061	0.612±0.055
	KNN	0.774±0.051	0.673±0.077	0.762±0.046	0.752±0.055	0.746±0.054	0.535±0.065	0.560±0.059	0.778±0.051	**0.779±0.055**
	MLP	0.782±0.050	0.646±0.072	0.761±0.049	0.705±0.075	0.687±0.061	0.548±0.063	0.559±0.069	**0.804±0.048**	0.682±0.059
	XGB	0.814±0.049	0.710±0.070	0.813±0.047	0.765±0.054	**0.819±0.045**	0.530±0.063	0.537±0.061	0.792±0.047	0.818±0.049
	LGBM	0.818±0.049	0.687±0.063	0.813±0.049	0.747±0.055	**0.822±0.047**	0.515±0.057	0.541±0.064	0.794±0.046	0.812±0.047
	HGNN	0.571±0.060	0.552±0.052	0.587±0.048	0.551±0.049	**0.601±0.062**	0.509±0.051	0.526±0.027	0.534±0.043	0.596±0.053
	FHGCN	0.640±0.062	0.615±0.065	0.647±0.062	0.553±0.070	**0.720±0.072**	0.506±0.059	0.484±0.059	0.566±0.065	0.692±0.070
	UGCNII	**0.713±0.070**	0.647±0.056	0.692±0.059	0.663±0.044	0.663±0.058	0.502±0.045	0.503±0.035	0.642±0.043	0.704±0.069
Max		0.824±0.048	0.730±0.076	0.817±0.045	0.794±0.057	**0.834±0.048**	0.548±0.063	0.560±0.059	0.804±0.048	0.820±0.054
Avg.		**0.736±0.079**	0.649±0.050	0.730±0.074	0.690±0.082	0.727±0.075	0.520±0.016	0.528±0.024	0.709±0.108	0.730±0.080
Rank Avg.		**2.600±1.114**	6.400±0.800	3.400±0.800	5.200±1.166	2.900±2.071	8.900±0.300	8.100±0.300	4.600±2.289	2.900±1.513

(c) email-enron

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.772±0.058	0.732±0.058	0.795±0.065	0.752±0.053	**0.804±0.054**	0.578±0.069	0.492±0.058	0.590±0.062	0.749±0.068
	RF	0.775±0.056	0.712±0.058	0.780±0.071	0.773±0.056	**0.796±0.053**	0.626±0.069	0.562±0.073	0.592±0.063	0.754±0.066
	DT	0.696±0.064	0.654±0.057	**0.705±0.054**	0.689±0.071	0.705±0.069	0.551±0.069	0.528±0.073	0.542±0.068	0.650±0.076
	KNN	0.761±0.068	0.694±0.058	0.769±0.064	0.737±0.056	**0.777±0.055**	0.636±0.058	0.571±0.070	0.567±0.061	0.720±0.066
	MLP	**0.810±0.050**	0.731±0.054	0.808±0.062	0.751±0.053	0.805±0.055	0.639±0.073	0.551±0.080	0.588±0.064	0.721±0.070
	XGB	0.763±0.059	0.709±0.060	**0.780±0.064**	0.763±0.064	0.775±0.060	0.614±0.072	0.579±0.074	0.577±0.066	0.750±0.074
	LGBM	0.765±0.057	0.709±0.060	**0.775±0.060**	0.763±0.056	0.756±0.059	0.609±0.064	0.580±0.077	0.581±0.074	0.750±0.076
	HGNN	0.505±0.047	0.538±0.074	0.512±0.044	**0.543±0.063**	0.499±0.049	0.513±0.055	0.526±0.048	0.512±0.058	0.510±0.049
	FHGCN	0.587±0.077	**0.703±0.101**	0.598±0.079	0.651±0.090	0.693±0.117	0.536±0.061	0.566±0.076	0.550±0.069	0.680±0.096
	UGCNII	0.668±0.063	**0.727±0.046**	0.675±0.063	0.708±0.065	0.710±0.050	0.673±0.045	0.689±0.055	0.582±0.051	0.719±0.058
Max		**0.810±0.050**	0.732±0.058	0.808±0.062	0.773±0.056	0.805±0.055	0.673±0.045	0.689±0.055	0.592±0.063	0.754±0.066
Avg.		0.710±0.092	0.691±0.055	0.720±0.093	0.713±0.068	**0.732±0.087**	0.597±0.049	0.564±0.049	0.568±0.025	0.700±0.071
Rank Avg.		4.100±2.300	4.400±2.059	**2.800±1.939**	3.500±0.922	2.800±2.272	7.000±1.183	7.600±1.960	7.900±1.136	4.900±1.375

Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.855±0.052	0.783±0.062	0.870±0.059	0.826±0.058	**0.883±0.049**	0.627±0.071	0.480±0.076	0.634±0.074	0.820±0.066
	RF	0.839±0.055	0.773±0.059	0.850±0.068	0.856±0.054	**0.880±0.047**	0.684±0.071	0.624±0.098	0.623±0.074	0.841±0.069
	DT	0.699±0.064	0.652±0.057	**0.708±0.056**	0.690±0.071	0.707±0.069	0.551±0.069	0.529±0.073	0.542±0.068	0.651±0.075
	KNN	0.827±0.059	0.745±0.060	0.829±0.067	0.810±0.048	**0.846±0.051**	0.685±0.073	0.597±0.089	0.591±0.073	0.788±0.065
	MLP	0.881±0.039	0.780±0.062	0.881±0.059	0.825±0.061	**0.883±0.047**	0.697±0.067	0.618±0.096	0.636±0.069	0.786±0.073
	XGB	0.833±0.049	0.765±0.067	0.851±0.065	0.847±0.057	**0.863±0.052**	0.666±0.082	0.632±0.097	0.610±0.077	0.831±0.074
	LGBM	0.840±0.051	0.769±0.063	**0.849±0.063**	0.847±0.060	0.842±0.056	0.655±0.081	0.635±0.094	0.612±0.085	0.837±0.070
	HGNN	0.507±0.064	**0.554±0.070**	0.521±0.053	0.543±0.070	0.505±0.052	0.532±0.070	0.543±0.062	0.532±0.080	0.505±0.060
	FHGCN	0.642±0.078	0.773±0.073	0.663±0.085	0.738±0.099	**0.804±0.102**	0.548±0.075	0.619±0.084	0.570±0.073	0.763±0.103
	UGCNII	0.722±0.066	**0.788±0.052**	0.724±0.066	0.767±0.065	0.787±0.048	0.706±0.045	0.739±0.056	0.606±0.059	0.784±0.070
Max		0.881±0.039	0.788±0.052	0.881±0.059	0.856±0.054	**0.883±0.049**	0.706±0.045	0.739±0.056	0.636±0.069	0.841±0.069
Avg.		0.764±0.114	0.738±0.072	0.775±0.112	0.775±0.093	**0.800±0.111**	0.635±0.063	0.601±0.067	0.596±0.035	0.761±0.100
Rank Avg.		4.400±1.685	4.500±2.110	3.100±1.814	3.400±0.800	**2.100±2.071**	7.200±0.980	7.300±2.100	8.000±1.483	5.000±1.612

(d) email-eu

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.854±0.009	0.837±0.013	0.855±0.009	0.776±0.019	**0.869±0.010**	0.618±0.028	0.496±0.012	0.659±0.019	0.799±0.017
	RF	0.883±0.009	0.839±0.011	0.890±0.008	0.838±0.011	**0.907±0.010**	0.652±0.017	0.515±0.021	0.668±0.020	0.840±0.011
	DT	0.825±0.010	0.787±0.016	0.828±0.010	0.761±0.016	**0.849±0.012**	0.546±0.015	0.504±0.019	0.564±0.015	0.753±0.018
	KNN	0.867±0.009	0.838±0.011	0.868±0.008	0.780±0.014	**0.875±0.010**	0.573±0.009	0.556±0.040	0.677±0.013	0.795±0.013
	MLP	0.904±0.008	0.857±0.012	**0.911±0.007**	0.821±0.023	0.906±0.011	0.660±0.047	0.507±0.018	0.675±0.048	0.808±0.027
	XGB	0.885±0.008	0.854±0.011	0.891±0.008	0.831±0.012	**0.903±0.009**	0.654±0.018	0.522±0.017	0.656±0.022	0.840±0.011
	LGBM	0.889±0.009	0.856±0.011	0.895±0.008	0.839±0.010	**0.906±0.010**	0.645±0.027	0.512±0.010	0.645±0.026	0.846±0.011
	HGNN	0.521±0.015	0.520±0.015	0.523±0.016	0.523±0.020	**0.529±0.020**	0.512±0.018	0.505±0.014	0.513±0.017	0.526±0.021
	FHGCN	0.607±0.087	**0.790±0.136**	0.622±0.095	0.638±0.060	0.742±0.072	0.512±0.020	0.519±0.038	0.547±0.054	0.678±0.072
	UGCNII	0.772±0.014	**0.859±0.008**	0.788±0.013	0.726±0.009	0.783±0.013	0.724±0.014	0.740±0.020	0.706±0.013	0.762±0.011
Max		0.904±0.008	0.859±0.008	**0.911±0.007**	0.839±0.010	0.907±0.010	0.724±0.014	0.740±0.020	0.706±0.013	0.846±0.011
Avg.		0.801±0.125	0.804±0.098	0.807±0.124	0.753±0.097	**0.827±0.113**	0.610±0.067	0.538±0.069	0.631±0.062	0.765±0.093
Rank Avg.		3.600±1.020	3.700±1.487	2.400±1.114	5.400±1.114	**1.400±0.663**	8.100±0.300	8.600±0.917	7.200±0.600	4.600±1.200

Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.922±0.009	0.876±0.009	0.926±0.008	0.838±0.015	**0.933±0.008**	0.691±0.013	0.494±0.018	0.722±0.014	0.868±0.013
	RF	0.941±0.007	0.901±0.009	0.946±0.005	0.921±0.007	**0.960±0.005**	0.737±0.016	0.529±0.032	0.770±0.015	0.925±0.007
	DT	0.827±0.010	0.785±0.017	0.830±0.010	0.762±0.016	**0.852±0.012**	0.546±0.015	0.504±0.019	0.564±0.015	0.754±0.018
	KNN	0.915±0.008	0.881±0.010	0.915±0.007	0.854±0.013	**0.920±0.008**	0.701±0.013	0.586±0.059	0.749±0.014	0.870±0.010
	MLP	0.960±0.005	0.911±0.010	**0.963±0.004**	0.909±0.013	0.962±0.006	0.790±0.014	0.539±0.052	0.802±0.017	0.887±0.021
	XGB	0.945±0.006	0.905±0.009	0.949±0.005	0.917±0.007	**0.961±0.005**	0.747±0.014	0.557±0.033	0.777±0.014	0.925±0.008
	LGBM	0.948±0.006	0.908±0.008	0.952±0.005	0.923±0.006	**0.963±0.005**	0.761±0.014	0.555±0.032	0.796±0.013	0.930±0.007
	HGNN	0.524±0.020	0.516±0.017	0.524±0.020	0.520±0.020	**0.529±0.028**	0.504±0.018	0.502±0.014	0.500±0.017	0.524±0.024
	FHGCN	0.724±0.082	**0.888±0.041**	0.745±0.080	0.724±0.051	0.849±0.054	0.520±0.029	0.550±0.057	0.614±0.070	0.768±0.062
	UGCNII	0.864±0.011	**0.912±0.007**	0.881±0.010	0.805±0.010	0.874±0.010	0.793±0.014	0.812±0.020	0.784±0.012	0.849±0.008
Max		0.960±0.005	0.912±0.007	**0.963±0.004**	0.923±0.006	0.963±0.005	0.793±0.014	0.812±0.020	0.802±0.017	0.930±0.007
Avg.		0.857±0.131	0.848±0.116	0.863±0.130	0.817±0.119	**0.880±0.125**	0.679±0.107	0.563±0.087	0.708±0.103	0.830±0.118
Rank Avg.		3.300±0.640	4.200±1.833	2.300±0.900	5.500±0.671	**1.400±0.663**	8.000±0.447	8.500±0.922	7.400±0.800	4.400±1.200

(e) citation-data-science

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.907±0.008	0.602±0.018	0.918±0.007	0.751±0.039	**0.921±0.011**	0.527±0.017	0.504±0.008	0.593±0.022	0.837±0.027
	RF	0.952±0.006	0.644±0.022	0.952±0.008	0.855±0.017	**0.977±0.004**	0.548±0.015	0.500±0.012	0.599±0.023	0.923±0.007
	DT	0.914±0.011	0.583±0.018	0.906±0.015	0.777±0.026	**0.963±0.005**	0.511±0.016	0.497±0.015	0.539±0.015	0.848±0.015
	KNN	0.922±0.007	0.594±0.016	**0.925±0.007**	0.787±0.025	0.917±0.010	0.558±0.013	0.514±0.021	0.592±0.014	0.844±0.012
	MLP	0.967±0.005	0.637±0.026	**0.971±0.005**	0.822±0.035	0.969±0.005	0.545±0.024	0.502±0.010	0.633±0.037	0.888±0.018
	XGB	0.958±0.005	0.639±0.025	0.961±0.006	0.843±0.024	**0.975±0.004**	0.547±0.018	0.505±0.011	0.618±0.024	0.927±0.011
	LGBM	0.957±0.006	0.652±0.022	0.960±0.006	0.849±0.020	**0.977±0.004**	0.546±0.020	0.504±0.010	0.601±0.026	0.930±0.009
	HGNN	0.572±0.010	0.534±0.013	0.585±0.012	0.543±0.015	**0.595±0.009**	0.542±0.012	0.535±0.017	0.519±0.013	0.554±0.017
	FHGCN	0.593±0.093	0.556±0.067	0.621±0.095	0.597±0.087	**0.754±0.091**	0.505±0.015	0.504±0.013	0.502±0.008	0.622±0.099
	UGCNII	0.923±0.009	0.657±0.012	0.927±0.009	0.798±0.013	**0.932±0.005**	0.769±0.016	0.630±0.028	0.541±0.011	0.823±0.010
Max		0.967±0.005	0.657±0.012	0.971±0.005	0.855±0.017	**0.977±0.004**	0.769±0.016	0.630±0.028	0.633±0.037	0.930±0.009
Avg.		0.866±0.143	0.610±0.041	0.873±0.136	0.762±0.102	**0.898±0.119**	0.560±0.072	0.519±0.038	0.574±0.042	0.820±0.123
Rank Avg.		3.000±0.775	6.300±0.640	2.000±0.632	4.900±0.300	**1.300±0.640**	7.500±0.806	8.600±0.663	7.600±0.917	3.800±0.600

Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.963±0.005	0.644±0.016	0.969±0.006	0.857±0.019	**0.969±0.005**	0.564±0.015	0.512±0.016	0.653±0.013	0.927±0.012
	RF	0.987±0.003	0.703±0.023	0.987±0.003	0.939±0.008	**0.997±0.001**	0.573±0.019	0.498±0.017	0.707±0.020	0.975±0.004
	DT	0.914±0.011	0.583±0.018	0.906±0.015	0.777±0.026	**0.963±0.005**	0.511±0.016	0.497±0.015	0.539±0.015	0.848±0.015
	KNN	0.963±0.005	0.629±0.020	**0.965±0.005**	0.857±0.023	0.962±0.006	0.595±0.015	0.520±0.030	0.633±0.016	0.908±0.010
	MLP	0.993±0.002	0.693±0.028	**0.994±0.002**	0.914±0.021	0.990±0.004	0.597±0.021	0.510±0.016	0.776±0.013	0.938±0.012
	XGB	0.991±0.002	0.703±0.025	0.992±0.002	0.937±0.009	**0.997±0.001**	0.579±0.016	0.507±0.022	0.747±0.012	0.983±0.003
	LGBM	0.990±0.002	0.719±0.021	0.992±0.002	0.941±0.008	**0.998±0.001**	0.587±0.014	0.511±0.023	0.782±0.011	0.984±0.003
	HGNN	0.595±0.016	0.523±0.013	0.616±0.016	0.528±0.017	**0.629±0.008**	0.537±0.014	0.540±0.022	0.510±0.013	0.555±0.019
	FHGCN	0.703±0.069	0.637±0.060	0.728±0.069	0.700±0.053	**0.861±0.059**	0.516±0.028	0.513±0.021	0.505±0.011	0.753±0.059
	UGCNII	0.972±0.005	0.714±0.013	0.974±0.005	0.874±0.010	**0.975±0.005**	0.851±0.016	0.672±0.042	0.547±0.012	0.899±0.008
Max		0.993±0.002	0.719±0.021	0.994±0.002	0.941±0.008	**0.998±0.001**	0.851±0.016	0.672±0.042	0.782±0.011	0.984±0.003
Avg.		0.907±0.133	0.655±0.061	0.912±0.125	0.832±0.125	**0.934±0.108**	0.591±0.092	0.528±0.049	0.640±0.104	0.877±0.126
Rank Avg.		2.800±0.600	6.900±0.539	2.000±0.632	5.200±0.600	**1.400±0.800**	7.500±0.806	8.400±1.200	7.000±1.342	3.800±0.600

(f) citation-software

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.908±0.005	0.662±0.015	0.912±0.004	0.767±0.007	**0.919±0.007**	0.541±0.018	0.508±0.013	0.625±0.019	0.829±0.010
	RF	0.966±0.003	0.702±0.019	0.968±0.003	0.866±0.022	**0.984±0.002**	0.568±0.018	0.501±0.012	0.621±0.022	0.941±0.004
	DT	0.945±0.004	0.623±0.012	0.944±0.004	0.783±0.045	**0.974±0.002**	0.519±0.010	0.498±0.016	0.548±0.009	0.875±0.012
	KNN	**0.947±0.004**	0.652±0.013	0.945±0.003	0.834±0.013	0.941±0.005	0.578±0.010	0.521±0.026	0.606±0.006	0.884±0.008
	MLP	0.978±0.002	0.699±0.018	0.979±0.002	0.844±0.029	**0.980±0.002**	0.575±0.032	0.512±0.022	0.652±0.041	0.919±0.011
	XGB	0.971±0.002	0.704±0.018	0.973±0.002	0.850±0.037	**0.984±0.002**	0.562±0.023	0.506±0.008	0.636±0.024	0.943±0.007
	LGBM	0.969±0.003	0.713±0.016	0.971±0.002	0.860±0.032	**0.984±0.002**	0.560±0.028	0.502±0.006	0.622±0.025	0.946±0.006
	HGNN	0.560±0.009	0.529±0.008	0.562±0.009	0.534±0.011	0.555±0.007	0.553±0.009	**0.568±0.009**	0.521±0.006	0.543±0.007
	FHGCN	0.561±0.074	0.594±0.089	0.572±0.074	0.609±0.086	**0.738±0.098**	0.503±0.013	0.502±0.009	0.503±0.009	0.630±0.084
	UGCNII	0.917±0.005	0.718±0.010	**0.921±0.005**	0.739±0.010	0.917±0.006	0.827±0.016	0.823±0.009	0.578±0.012	0.792±0.006
Max		0.978±0.002	0.718±0.010	0.979±0.002	0.866±0.022	**0.984±0.002**	0.827±0.016	0.823±0.009	0.652±0.041	0.946±0.006
Avg.		0.872±0.157	0.660±0.058	0.875±0.155	0.769±0.108	**0.898±0.134**	0.579±0.086	0.544±0.095	0.591±0.049	0.830±0.132
Rank Avg.		2.900±1.221	6.200±1.077	2.300±1.005	5.200±1.077	**1.700±1.100**	7.200±1.400	7.800±2.561	7.500±0.806	4.200±1.077

Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.977±0.003	0.722±0.015	0.979±0.002	0.890±0.008	**0.980±0.003**	0.584±0.010	0.516±0.008	0.688±0.008	0.943±0.005
	RF	0.993±0.001	0.777±0.012	0.994±0.001	0.945±0.012	**0.999±0.000**	0.611±0.015	0.502±0.017	0.739±0.013	0.986±0.001
	DT	0.945±0.004	0.623±0.012	0.944±0.004	0.783±0.045	**0.974±0.002**	0.519±0.010	0.498±0.016	0.548±0.009	0.875±0.012
	KNN	**0.976±0.002**	0.702±0.015	**0.976±0.002**	0.899±0.010	0.974±0.003	0.632±0.011	0.531±0.034	0.659±0.007	0.940±0.006
	MLP	**0.997±0.001**	0.775±0.016	**0.997±0.001**	0.930±0.018	0.996±0.002	0.671±0.019	0.544±0.048	0.806±0.009	0.964±0.008
	XGB	0.995±0.001	0.781±0.014	0.996±0.001	0.939±0.019	**0.999±0.000**	0.620±0.017	0.522±0.020	0.786±0.009	0.991±0.001
	LGBM	0.995±0.001	0.792±0.012	0.996±0.001	0.946±0.017	**0.999±0.000**	0.626±0.019	0.525±0.020	0.807±0.008	0.991±0.001
	HGNN	0.584±0.012	0.510±0.012	0.589±0.011	0.509±0.023	0.587±0.006	0.562±0.009	**0.590±0.012**	0.508±0.007	0.551±0.014
	FHGCN	0.651±0.094	0.714±0.054	0.659±0.085	0.718±0.050	**0.852±0.044**	0.513±0.025	0.511±0.024	0.505±0.013	0.732±0.045
	UGCNII	0.972±0.002	0.792±0.011	**0.973±0.003**	0.812±0.010	0.971±0.003	0.899±0.016	0.895±0.007	0.609±0.015	0.868±0.005
Max		0.997±0.001	0.792±0.012	0.997±0.001	0.946±0.017	**0.999±0.000**	0.899±0.016	0.895±0.007	0.807±0.008	0.991±0.001
Avg.		0.909±0.147	0.719±0.086	0.910±0.145	0.837±0.132	**0.933±0.123**	0.624±0.103	0.564±0.113	0.666±0.113	0.884±0.134
Rank Avg.		2.900±1.300	6.400±1.020	2.200±1.077	5.300±1.269	**1.800±0.980**	7.200±1.400	7.700±2.532	7.300±1.187	4.200±1.077

(g) qna-math

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.606±0.010	0.553±0.013	0.607±0.010	0.579±0.011	0.604±0.009	0.500±0.005	0.504±0.006	0.566±0.009	**0.615±0.012**
	RF	0.640±0.008	0.620±0.012	0.641±0.008	0.613±0.017	**0.673±0.010**	0.503±0.010	0.502±0.010	0.581±0.024	0.656±0.015
	DT	0.598±0.009	0.572±0.010	0.595±0.009	0.547±0.016	**0.617±0.011**	0.502±0.008	0.502±0.011	0.547±0.013	0.574±0.017
	KNN	**0.607±0.008**	0.553±0.011	0.605±0.007	0.576±0.011	0.601±0.010	0.504±0.009	0.506±0.015	0.523±0.008	0.603±0.010
	MLP	0.639±0.017	0.590±0.014	0.640±0.016	0.598±0.015	**0.679±0.010**	0.505±0.009	0.503±0.005	0.611±0.043	0.626±0.020
	XGB	0.643±0.008	0.629±0.011	0.644±0.009	0.607±0.019	**0.681±0.010**	0.502±0.010	0.508±0.008	0.601±0.027	0.668±0.016
	LGBM	0.651±0.008	0.641±0.012	0.652±0.009	0.618±0.019	**0.690±0.009**	0.504±0.009	0.506±0.008	0.577±0.027	0.686±0.015
	HGNN	0.552±0.010	0.529±0.008	**0.552±0.009**	0.525±0.011	0.549±0.011	0.520±0.011	0.546±0.007	0.545±0.008	0.548±0.008
	FHGCN	0.501±0.006	**0.516±0.029**	0.501±0.004	0.503±0.007	0.512±0.022	0.500±0.003	0.502±0.008	0.507±0.016	0.508±0.017
	UGCNII	0.613±0.005	0.599±0.010	0.614±0.004	0.583±0.009	0.607±0.006	0.615±0.010	0.637±0.008	**0.743±0.013**	0.609±0.008
Max		0.651±0.008	0.641±0.012	0.652±0.009	0.618±0.019	0.690±0.009	0.615±0.010	0.637±0.008	**0.743±0.013**	0.686±0.015
Avg.		0.605±0.044	0.580±0.041	0.605±0.045	0.575±0.037	**0.621±0.057**	0.515±0.034	0.521±0.040	0.580±0.063	0.609±0.052
Rank Avg.		3.500±1.628	5.600±1.855	3.100±1.814	6.200±1.249	**2.500±1.910**	8.200±1.778	7.100±2.071	5.700±1.847	3.100±1.375

Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.653±0.008	0.580±0.014	0.655±0.010	0.620±0.011	0.652±0.011	0.499±0.009	0.514±0.010	0.600±0.009	**0.666±0.013**
	RF	0.692±0.009	0.663±0.015	0.695±0.009	0.657±0.020	0.734±0.011	0.505±0.012	0.504±0.014	**0.767±0.020**	0.716±0.019
	DT	0.602±0.009	0.569±0.010	0.599±0.009	0.547±0.016	**0.621±0.011**	0.502±0.008	0.502±0.011	0.547±0.013	0.574±0.017
	KNN	**0.647±0.009**	0.570±0.012	0.644±0.009	0.601±0.013	0.638±0.012	0.506±0.011	0.511±0.019	0.561±0.012	0.638±0.013
	MLP	0.696±0.015	0.634±0.015	0.700±0.016	0.649±0.015	0.737±0.013	0.514±0.013	0.509±0.010	**0.834±0.011**	0.679±0.022
	XGB	0.700±0.009	0.677±0.014	0.702±0.009	0.660±0.020	0.744±0.011	0.504±0.012	0.513±0.011	**0.823±0.010**	0.736±0.016
	LGBM	0.708±0.008	0.694±0.015	0.711±0.010	0.679±0.016	0.755±0.010	0.505±0.014	0.513±0.012	**0.844±0.009**	0.758±0.013
	HGNN	**0.576±0.010**	0.535±0.012	0.575±0.008	0.520±0.011	0.570±0.013	0.519±0.012	0.566±0.009	0.551±0.010	0.568±0.009
	FHGCN	0.504±0.011	**0.545±0.044**	0.502±0.008	0.507±0.010	0.538±0.031	0.501±0.005	0.507±0.020	0.521±0.028	0.525±0.028
	UGCNII	0.666±0.008	0.642±0.011	0.667±0.007	0.620±0.011	0.658±0.007	0.661±0.012	0.689±0.007	**0.817±0.014**	0.659±0.009
Max		0.708±0.008	0.694±0.015	0.711±0.010	0.679±0.016	0.755±0.010	0.661±0.012	0.689±0.007	**0.844±0.009**	0.758±0.013
Avg.		0.644±0.062	0.611±0.055	0.645±0.064	0.606±0.058	0.665±0.072	0.521±0.047	0.533±0.055	**0.687±0.133**	0.652±0.073
Rank Avg.		3.700±1.847	5.900±1.814	3.500±1.688	6.600±1.200	**2.900±1.578**	8.400±1.200	7.000±2.145	3.500±2.617	3.500±1.360

(h) qna-server

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.556±0.007	0.530±0.011	0.557±0.007	0.533±0.009	**0.561±0.007**	0.502±0.004	0.509±0.008	0.556±0.007	0.553±0.007
	RF	0.643±0.005	0.590±0.012	0.640±0.004	0.565±0.012	**0.661±0.004**	0.500±0.006	0.503±0.005	0.565±0.018	0.631±0.010
	DT	0.615±0.005	0.572±0.012	0.614±0.005	0.528±0.008	**0.626±0.006**	0.500±0.007	0.501±0.007	0.545±0.009	0.571±0.011
	KNN	**0.628±0.005**	0.566±0.010	0.626±0.005	0.538±0.007	0.619±0.006	0.504±0.007	0.502±0.009	0.576±0.005	0.562±0.008
	MLP	**0.670±0.005**	0.603±0.014	**0.670±0.005**	0.544±0.013	0.668±0.005	0.509±0.006	0.506±0.011	0.598±0.040	0.584±0.014
	XGB	0.658±0.005	0.612±0.016	0.656±0.005	0.575±0.013	**0.679±0.005**	0.503±0.005	0.503±0.007	0.585±0.019	0.647±0.010
	LGBM	0.666±0.004	0.624±0.013	0.665±0.005	0.585±0.011	**0.688±0.004**	0.504±0.006	0.503±0.007	0.567±0.018	0.657±0.009
	HGNN	0.588±0.005	0.546±0.005	0.588±0.005	0.539±0.005	0.579±0.006	0.535±0.007	0.572±0.006	0.571±0.005	**0.591±0.005**
	FHGCN	0.502±0.008	0.515±0.027	0.502±0.007	0.505±0.014	**0.530±0.041**	0.501±0.003	0.501±0.005	0.502±0.009	0.514±0.030
	UGCNII	0.657±0.006	0.605±0.005	0.656±0.006	0.595±0.007	0.713±0.005	0.563±0.005	0.653±0.006	**0.752±0.007**	0.652±0.005
Max		0.670±0.005	0.624±0.013	0.670±0.005	0.595±0.007	0.713±0.005	0.563±0.005	0.653±0.006	**0.752±0.007**	0.657±0.009
Avg.		0.619±0.052	0.576±0.035	0.617±0.051	0.551±0.027	**0.632±0.057**	0.512±0.020	0.525±0.047	0.582±0.062	0.596±0.046
Rank Avg.		2.500±1.432	5.100±1.513	3.200±1.400	6.700±1.100	**1.800±1.077**	8.600±0.490	7.800±1.470	4.900±1.700	4.400±1.497

Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.596±0.005	0.558±0.009	0.597±0.006	0.553±0.010	**0.598±0.006**	0.512±0.006	0.528±0.006	0.586±0.006	0.587±0.009
	RF	0.704±0.005	0.637±0.017	0.701±0.005	0.595±0.016	0.728±0.005	0.501±0.008	0.504±0.009	**0.748±0.017**	0.692±0.013
	DT	0.619±0.005	0.571±0.010	0.618±0.005	0.524±0.008	**0.630±0.006**	0.500±0.007	0.501±0.007	0.545±0.009	0.571±0.011
	KNN	**0.681±0.005**	0.599±0.013	0.678±0.005	0.552±0.009	0.669±0.006	0.505±0.008	0.503±0.013	0.610±0.008	0.586±0.010
	MLP	0.719±0.006	0.630±0.014	0.719±0.006	0.573±0.013	0.717±0.006	0.511±0.006	0.525±0.013	**0.815±0.010**	0.631±0.015
	XGB	0.713±0.006	0.653±0.021	0.711±0.005	0.612±0.016	0.745±0.005	0.504±0.007	0.507±0.011	**0.801±0.007**	0.712±0.013
	LGBM	0.719±0.005	0.669±0.018	0.719±0.005	0.628±0.014	0.753±0.005	0.506±0.009	0.513±0.010	**0.813±0.007**	0.729±0.010
	HGNN	0.629±0.006	0.563±0.006	0.629±0.005	0.543±0.006	0.619±0.008	0.534±0.008	0.599±0.007	0.585±0.009	**0.631±0.009**
	FHGCN	0.508±0.016	0.546±0.049	0.507±0.016	0.528±0.025	**0.593±0.041**	0.502±0.007	0.503±0.012	0.511±0.018	0.557±0.045
	UGCNII	0.731±0.007	0.649±0.007	0.728±0.006	0.636±0.008	0.645±0.005	0.594±0.010	0.713±0.006	**0.824±0.008**	0.719±0.007
Max		0.731±0.007	0.669±0.018	0.728±0.006	0.636±0.008	0.753±0.005	0.594±0.010	0.713±0.006	**0.824±0.008**	0.729±0.010
Avg.		0.662±0.069	0.607±0.043	0.661±0.068	0.575±0.039	0.670±0.058	0.517±0.027	0.540±0.064	**0.684±0.121**	0.641±0.063
Rank Avg.		3.000±1.265	5.600±1.020	3.500±1.628	6.900±1.044	**2.700±1.792**	8.900±0.300	7.500±1.285	3.100±2.166	3.800±1.400

(i) bitcoin-2014

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.552±0.003	0.524±0.002	0.581±0.006		**0.626±0.022**	0.527±0.027	0.527±0.014	0.580±0.027	
	RF	0.914±0.003	0.731±0.029	0.919±0.003		**0.927±0.010**	0.540±0.013	0.517±0.005	0.608±0.039	
	DT	0.886±0.003	0.703±0.027	0.891±0.003		**0.896±0.017**	0.507±0.010	0.503±0.005	0.549±0.011	
	KNN	**0.879±0.003**	0.699±0.014	0.878±0.003		0.838±0.016	0.577±0.011	0.537±0.010	0.639±0.004	
	MLP	0.763±0.011	0.612±0.049	0.838±0.015		**0.922±0.002**	0.555±0.031	0.538±0.023	0.629±0.039	
	XGB	0.902±0.004	0.760±0.036	0.912±0.003		**0.935±0.003**	0.554±0.014	0.520±0.012	0.615±0.032	
	LGBM	0.882±0.005	0.765±0.036	0.896±0.004	O.O.T.*	**0.935±0.002**	0.560±0.018	0.526±0.016	0.606±0.034	O.O.T.*
	HGNN	0.730±0.003	0.633±0.003	**0.731±0.003**		0.727±0.003	0.632±0.004	0.628±0.003	0.600±0.003	
	FHGCN	0.517±0.027	0.623±0.090	0.516±0.025		**0.705±0.103**	0.504±0.009	0.504±0.010	0.505±0.009	
	UGCNII	0.853±0.003	0.771±0.003	**0.855±0.002**		0.845±0.003	0.773±0.008	0.711±0.005	0.652±0.003	
Max		0.914±0.003	0.771±0.003	0.919±0.003		**0.935±0.003**	0.773±0.008	0.711±0.005	0.652±0.003	
Avg.		0.788±0.139	0.682±0.077	0.802±0.137		**0.836±0.106**	0.573±0.075	0.551±0.063	0.598±0.042	
Rank Avg.		2.700±0.781	4.300±1.187	2.000±0.775		**1.600±0.917**	5.700±0.640	6.600±0.663	5.100±1.136	

Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
Check AUROC	LR	0.559±0.013	0.616±0.007	0.674±0.021		**0.693±0.014**	0.569±0.003	0.559±0.002	0.640±0.003	
	RF	0.971±0.001	0.799±0.034	0.972±0.001		**0.976±0.004**	0.562±0.015	0.524±0.008	0.729±0.022	
	DT	0.885±0.004	0.704±0.031	0.890±0.003		**0.900±0.014**	0.507±0.010	0.503±0.005	0.549±0.011	
	KNN	**0.941±0.002**	0.744±0.016	0.941±0.003		0.905±0.015	0.606±0.013	0.556±0.012	0.694±0.005	
	MLP	0.854±0.013	0.679±0.053	0.917±0.010		**0.968±0.002**	0.622±0.029	0.577±0.031	0.771±0.009	
	XGB	0.966±0.002	0.841±0.033	0.971±0.002		**0.980±0.003**	0.575±0.015	0.549±0.009	0.784±0.005	
	LGBM	0.954±0.003	0.847±0.030	0.962±0.002	O.O.T.*	**0.980±0.002**	0.583±0.018	0.558±0.011	0.789±0.005	O.O.T.*
	HGNN	0.815±0.002	0.663±0.004	**0.816±0.003**		0.808±0.002	0.664±0.004	0.664±0.003	0.607±0.002	
	FHGCN	0.536±0.044	0.714±0.055	0.540±0.046		**0.822±0.028**	0.510±0.021	0.506±0.015	0.506±0.012	
	UGCNII	0.932±0.003	0.854±0.003	**0.933±0.002**		0.926±0.003	0.855±0.008	0.790±0.005	0.713±0.003	
Max		0.971±0.001	0.854±0.003	0.972±0.001		**0.980±0.003**	0.855±0.008	0.790±0.005	0.789±0.005	
Avg.		0.841±0.155	0.746±0.081	0.862±0.138		**0.896±0.090**	0.605±0.095	0.579±0.083	0.678±0.094	
Rank Avg.		3.100±1.513	4.200±0.980	1.900±0.539		**1.600±0.917**	5.500±0.671	6.400±0.917	5.300±1.269	

* O.O.T: out-of-time (> 1 day).

(j) bitcoin-2015

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.539±0.016	0.539±0.006	0.561±0.003		0.566±0.002	0.528±0.029	0.532±0.013	**0.569±0.027**	
	RF	0.928±0.003	0.686±0.034	**0.929±0.003**		0.926±0.012	0.552±0.012	0.520±0.006	0.598±0.037	
	DT	0.904±0.004	0.664±0.036	**0.905±0.003**		0.889±0.021	0.512±0.009	0.504±0.005	0.543±0.011	
	KNN	**0.906±0.002**	0.658±0.028	0.895±0.003		0.839±0.025	0.592±0.008	0.539±0.009	0.628±0.004	
	MLP	0.825±0.018	0.635±0.027	0.854±0.014		**0.920±0.015**	0.571±0.029	0.553±0.023	0.619±0.039	
	XGB	0.918±0.005	0.721±0.042	0.923±0.004		**0.939±0.005**	0.571±0.012	0.519±0.011	0.606±0.028	
	LGBM	0.901±0.007	0.725±0.038	0.908±0.006	O.O.T.*	**0.941±0.003**	0.574±0.019	0.526±0.015	0.596±0.030	O.O.T.*
	HGNN	0.748±0.003	0.636±0.003	**0.750±0.003**		**0.750±0.003**	0.641±0.006	0.630±0.004	0.603±0.002	
	FHGCN	0.545±0.063	0.599±0.098	0.574±0.067		**0.699±0.112**	0.506±0.013	0.503±0.008	0.503±0.006	
	UGCNII	0.866±0.003	0.773±0.005	**0.867±0.002**		0.858±0.002	0.782±0.005	0.717±0.003	0.651±0.003	
Max		0.928±0.003	0.773±0.005	0.929±0.003		**0.941±0.003**	0.782±0.005	0.717±0.003	0.651±0.003	
Avg.		0.808±0.142	0.664±0.064	0.817±0.134		**0.833±0.118**	0.583±0.076	0.554±0.064	0.592±0.041	
Rank Avg.		2.800±1.077	4.000±0.775	**1.800±0.748**		2.000±0.894	5.600±0.917	6.700±0.458	5.100±1.578	

Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.552±0.008	0.612±0.010	0.692±0.005		**0.696±0.012**	0.592±0.003	0.563±0.003	0.627±0.003	
	RF	0.977±0.001	0.755±0.040	**0.978±0.001**		0.977±0.004	0.578±0.014	0.528±0.008	0.715±0.023	
	DT	0.903±0.004	0.672±0.035	**0.904±0.004**		0.893±0.019	0.512±0.009	0.504±0.005	0.543±0.011	
	KNN	**0.957±0.002**	0.705±0.032	0.952±0.002		0.906±0.021	0.627±0.012	0.558±0.011	0.681±0.006	
	MLP	0.917±0.014	0.690±0.020	0.938±0.008		**0.967±0.005**	0.639±0.032	0.596±0.030	0.761±0.013	
	XGB	0.974±0.002	0.797±0.046	0.977±0.002		**0.981±0.004**	0.596±0.012	0.553±0.009	0.776±0.007	
	LGBM	0.965±0.003	0.806±0.040	0.969±0.003	O.O.T.*	**0.983±0.002**	0.597±0.012	0.561±0.009	0.782±0.007	O.O.T.*
	HGNN	0.832±0.003	0.663±0.003	**0.834±0.003**		0.828±0.002	0.681±0.006	0.666±0.005	0.605±0.002	
	FHGCN	0.592±0.079	0.712±0.070	0.623±0.077		**0.823±0.040**	0.510±0.018	0.504±0.011	0.503±0.008	
	UGCNII	0.940±0.002	0.857±0.006	**0.941±0.002**		0.935±0.002	0.863±0.005	0.795±0.004	0.713±0.004	
Max		0.977±0.001	0.857±0.006	0.978±0.001		**0.983±0.002**	0.863±0.005	0.795±0.004	0.782±0.007	
Avg.		0.861±0.150	0.727±0.072	0.881±0.120		**0.899±0.088**	0.619±0.095	0.583±0.084	0.671±0.093	
Rank Avg.		2.900±1.578	4.200±0.980	**1.700±0.640**		2.000±1.000	5.400±0.800	6.500±0.671	5.300±1.269	

* O.O.T: out-of-time (> 1 day).

(k) `bitcoin-2016`

Dimension		13		26		91				431
Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
ACC	LR	0.545±0.002	0.549±0.022	0.551±0.002		0.556±0.003	0.527±0.022	0.530±0.015	**0.569±0.028**	
	RF	0.915±0.002	0.694±0.030	0.921±0.001		**0.934±0.007**	0.529±0.010	0.521±0.007	0.609±0.039	
	DT	0.888±0.002	0.671±0.029	0.894±0.002		**0.907±0.016**	0.509±0.008	0.504±0.005	0.547±0.011	
	KNN	0.888±0.001	0.668±0.028	**0.890±0.001**		0.866±0.020	0.567±0.010	0.536±0.009	0.626±0.003	
	MLP	0.825±0.010	0.591±0.030	0.830±0.011		**0.923±0.003**	0.549±0.027	0.545±0.026	0.630±0.040	
	XGB	0.897±0.002	0.722±0.038	0.913±0.002		**0.938±0.005**	0.544±0.012	0.522±0.013	0.621±0.030	
	LGBM	0.875±0.002	0.733±0.041	0.897±0.002	O.O.T.*	**0.937±0.003**	0.551±0.016	0.529±0.016	0.610±0.032	O.O.T.*
	HGNN	0.750±0.002	0.633±0.003	**0.751±0.002**		0.749±0.003	0.627±0.005	0.629±0.003	0.597±0.004	
	FHGCN	0.551±0.064	0.608±0.100	0.553±0.067		**0.712±0.110**	0.504±0.011	0.504±0.010	0.504±0.011	
	UGCNII	0.862±0.004	0.762±0.005	**0.862±0.003**		0.854±0.003	0.771±0.010	0.720±0.004	0.646±0.004	
Max		0.915±0.002	0.762±0.005	0.921±0.001		**0.938±0.005**	0.771±0.010	0.720±0.004	0.646±0.004	
Avg.		0.800±0.133	0.663±0.064	0.806±0.135		**0.838±0.121**	0.568±0.075	0.554±0.065	0.596±0.041	
Rank Avg.		3.000±0.894	4.000±0.775	1.900±0.700		**1.700±0.900**	6.000±0.775	6.400±0.800	5.000±1.612	

Measure	Model	DHG-13	triad	DHG-26	h-motif	DHG	n2v	h2v	deep-h	3h-motif
AUROC	LR	0.622±0.006	0.612±0.009	0.630±0.011		**0.654±0.012**	0.564±0.003	0.567±0.003	0.635±0.002	
	RF	0.971±0.001	0.766±0.035	0.974±0.001		**0.978±0.003**	0.550±0.012	0.529±0.009	0.725±0.021	
	DT	0.885±0.002	0.681±0.032	0.893±0.002		**0.909±0.016**	0.509±0.008	0.504±0.005	0.547±0.011	
	KNN	**0.948±0.001**	0.716±0.029	**0.948±0.001**		0.927±0.014	0.592±0.014	0.553±0.011	0.678±0.006	
	MLP	0.909±0.006	0.655±0.021	0.915±0.008		**0.968±0.002**	0.600±0.026	0.587±0.033	0.770±0.007	
	XGB	0.964±0.001	0.801±0.041	0.971±0.001		**0.982±0.003**	0.562±0.012	0.550±0.011	0.783±0.005	
	LGBM	0.951±0.001	0.814±0.044	0.963±0.001	O.O.T.*	**0.982±0.002**	0.563±0.011	0.558±0.010	0.788±0.006	O.O.T.*
	HGNN	0.833±0.002	0.659±0.003	**0.834±0.002**		0.827±0.002	0.659±0.006	0.663±0.004	0.596±0.003	
	FHGCN	0.598±0.074	0.712±0.062	0.597±0.078		**0.825±0.049**	0.508±0.020	0.507±0.017	0.505±0.015	
	UGCNII	0.937±0.003	0.847±0.006	**0.937±0.002**		0.931±0.002	0.856±0.010	0.801±0.004	0.704±0.005	
Max		0.971±0.001	0.847±0.006	0.974±0.001		**0.982±0.003**	0.856±0.010	0.801±0.004	0.788±0.006	
Avg.		0.862±0.132	0.726±0.074	0.866±0.133		**0.898±0.099**	0.596±0.096	0.582±0.085	0.673±0.095	
Rank Avg.		2.700±0.781	4.300±1.005	2.100±0.831		**1.600±0.917**	5.700±0.781	6.400±0.917	5.200±1.470	

* O.O.T: out-of-time ($>$ 1 day).