Higgs Hadronic Decays at CEPC

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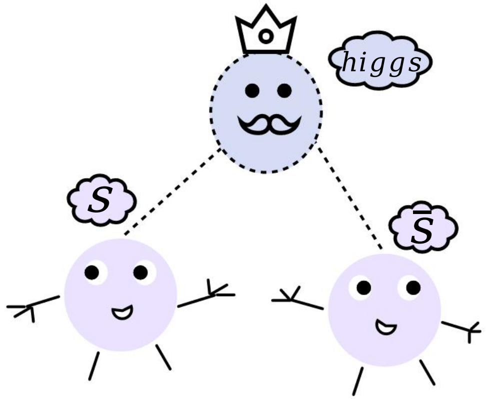
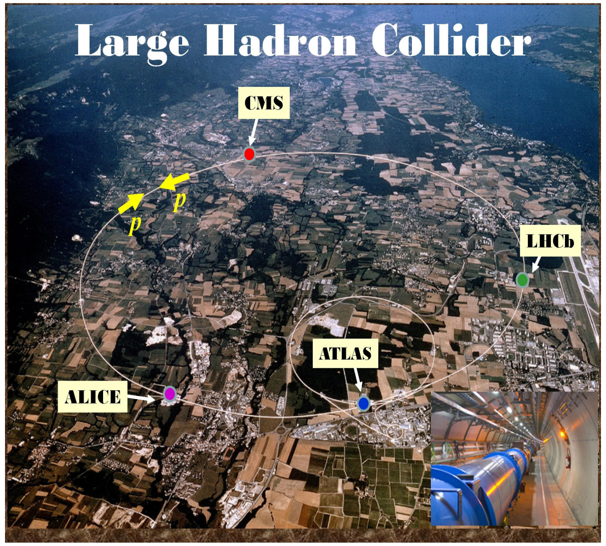
Outline

- Precision study of Higgs hadronic decays is crucial for testing Yukawa couplings
- Our study shows that **CEPC's advantages**, together with advanced **machine-learning** techniques, can significantly improve the precision in H→bb/cc/gg/ss
- H→ss: **first time a relative error is quantified** (with main backgrounds considered)



Precision measurements of the Higgs boson

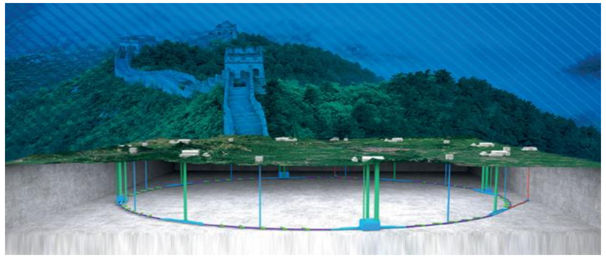
- Over ten years after Higgs discovery, it's still central to particle physics
- Studying Higgs decays is important at the LHC
- **Higgs Hadronic decays** is **Challenging** in LHC
- Proton-proton collisions produce overwhelming QCD backgrounds and pile-up

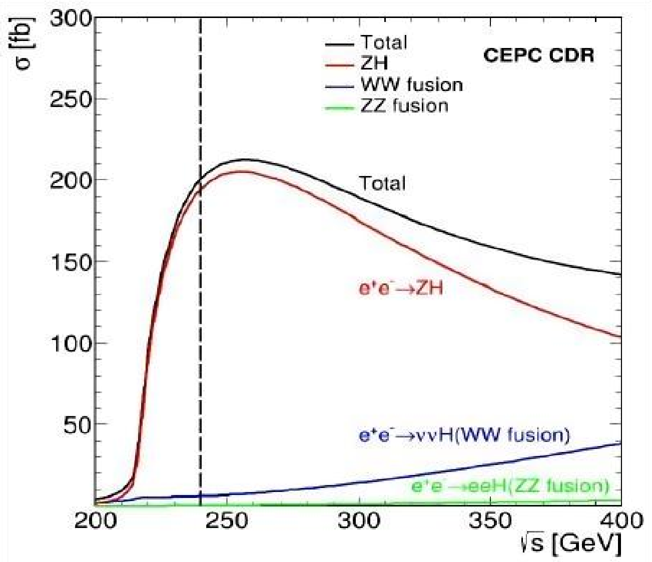


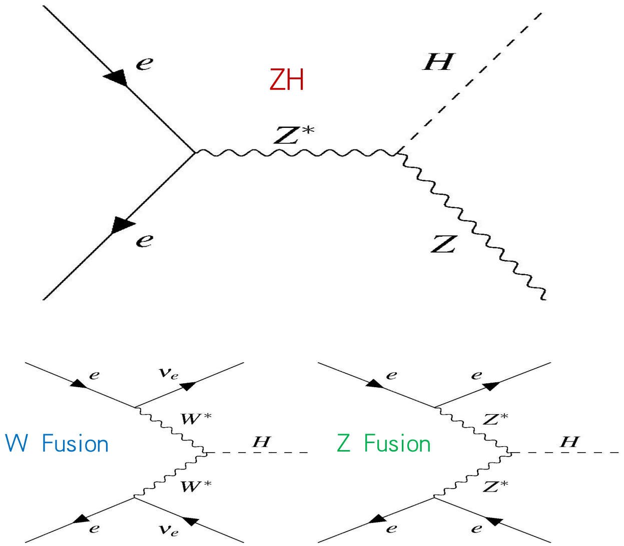
Decay channel	Reported quantity	Relative uncertainty	Reference
H → bb	$\mu_{bb} \approx 1.04 \pm 0.20$	**~19 %**	CMS-PAS-HIG-18-016
H → cc	$\kappa_c < 5.7 \times$ SM (95% CL upper limit)	—	Nature 607 (2022) 52
H → gg, ss	**Unobserved**	—	—
H → γγ	$\mu_{\gamma\gamma} = 1.18^{+0.17}_{-0.14}(stat) \pm 0.09(syst)$	~15–16 %	arXiv:1804.02716
H → μμ	$\mu_{\gamma\gamma} = 1.19^{+0.40}_{-0.39}(stat)^{+0.15}_{-0.14}(syst)$	~35–40 %	arXiv:2009.04363
H → Zγ	$\mu_{Z\gamma} = 2.2 \pm 0.7$ (relative to SM)	~32 %	HIG-23-002
H → ττ	$\mu_{\tau\tau} = 1.09^{+0.27}_{-0.26}$	~25 %	arXiv:1708.00373
H → WW/ZZ	$\mu = 1.002 \pm 0.057$ (combined fits)	~5.7 %	arXiv:2207.00043

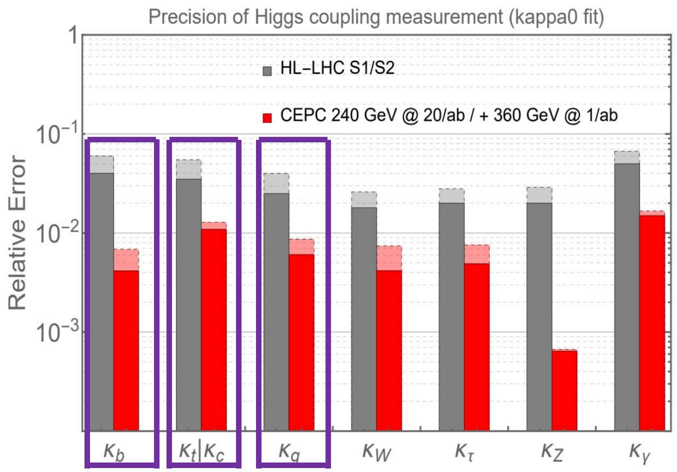
Higgs factory: CEPC

- CEPC is a next-gen e^+e^- collider purpose-built for Higgs boson physics
- Produce **4** million higgs bosons by $e^+e^- \rightarrow ZH$ mode @ 240 GeV
- **Low QCD background, no pile-up, well-defined initial state**
- Higgs coupling precision can be improved by an order of magnititude









CEPC snowmass 2021

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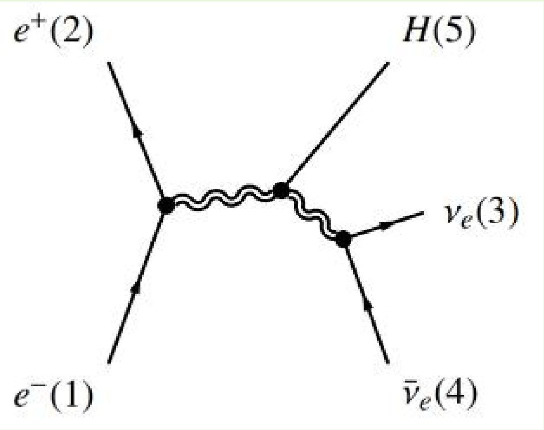
Simulation samples

- **Signal**: $e^+e^- \rightarrow$ ZH, Z $\rightarrow \nu\bar{\nu}$, $H \rightarrow b\bar{b}, c\bar{c}, s\bar{s}, u\bar{u}, d\bar{d}$ and gg @ 240GeV
  - **10** Million samples for each channel, 25% for jet taging training, 75% for event selection

- **Backgrounds**: Dominated by 2fermions and 4fermions processes
  - 2f process has large cross section → add Event filter to save computing resources

Signal: ZH, Z→vv, H→qq/gg



Category	channel	cross section [fb]	expected events [M]	simulated events [M]
Signal	ZH, Z→vv, H->bb	26.71	0.5342	10
	ZH, Z→vv, H->cc	1.35	0.027	10
	ZH, Z→vv, H->ss	0.01	0.0002	10
	ZH, Z→vv, H->gg	3.97	0.0794	10
Background	ZH, Z→vv, H->ZZ; Z->vv, Z->qq	0.34	0.0068	10
	4f	369.71	7.3942	44
	2f	54106.86 1213.25	1082.1372 24.2650	6

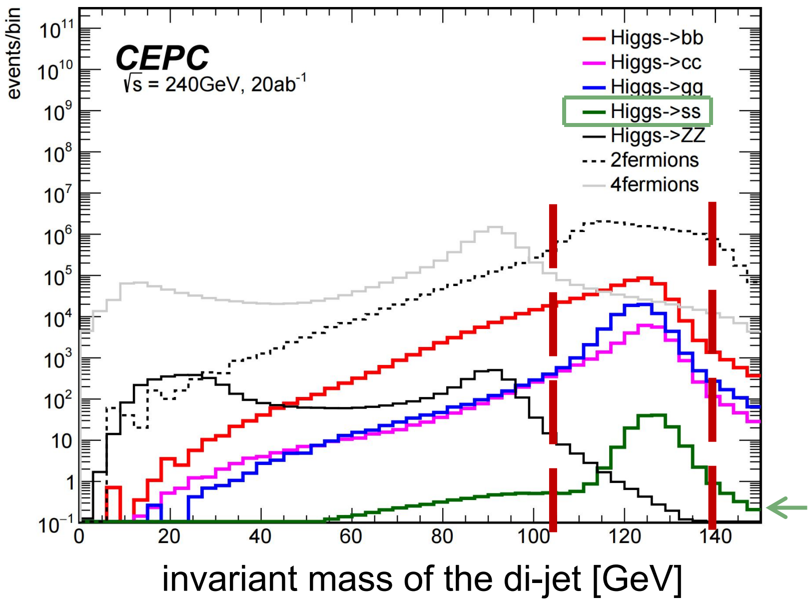
https://arxiv.org/pdf/2203.01469

Pre-cut

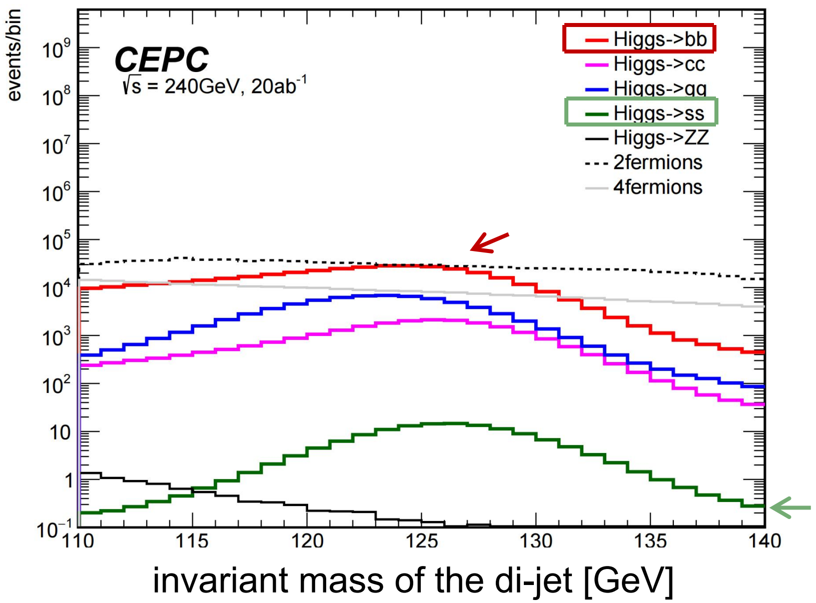
- **Take H->ss as signal**, before pre-cuts: Significance Z ≈ 0.03 (almost negligible)
- With simple pre-cut on observables: Significance Z ≈ 0.11 (improved but still low)
  - pre-cut on jet momentum, missing energy and invariant mass of the di-jet
- Jet flavor separation (e.g. h → ss vs h → bb/cc/gg) remains challenging

$$Z = \sqrt{2[(S+B)\ln(1+S/B) - S]}$$
$$\approx \frac{S}{\sqrt{B}} \; when \; S \ll B$$

before pre-cut



after pre-cut

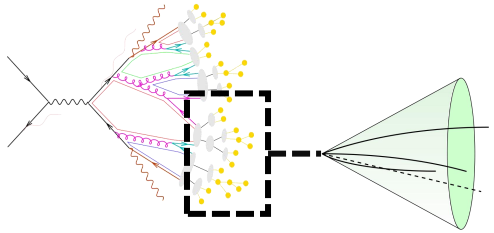


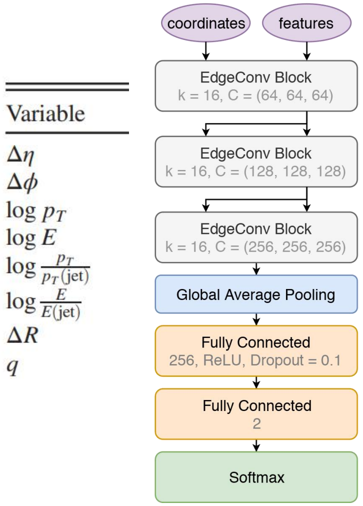
pre-cut

leading jet pz: (-95~95)GeV
leading jet pt: (15~100)GeV
missing energy Z: (-55,55)GeV
invariant mass: (110, 140)GeV

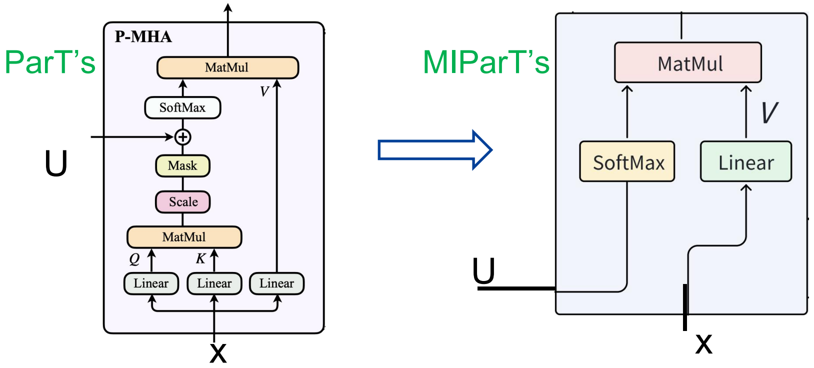
Jet Flavor Tagging

- **Jet**: A detectable particle shower from a single quark or gluon
- The internal structure of jets carries information about their parent particle -> basis of **jet tagging**
- 3 Advanced Jet Flavor Tagging Networks
  - ParticleNet (PN): Uses dynamic graph convolutions to learn both local and global jet substructure (1902.08570)
  - Particle Transformer (ParT): Based on Attention Mechanism, capturing long-range correlations among jet constituents (2202.03772)
  - More-Interaction Particle Transformer (MIParT) :reduces model complexity compared with ParT for more efficience (2407.08682)

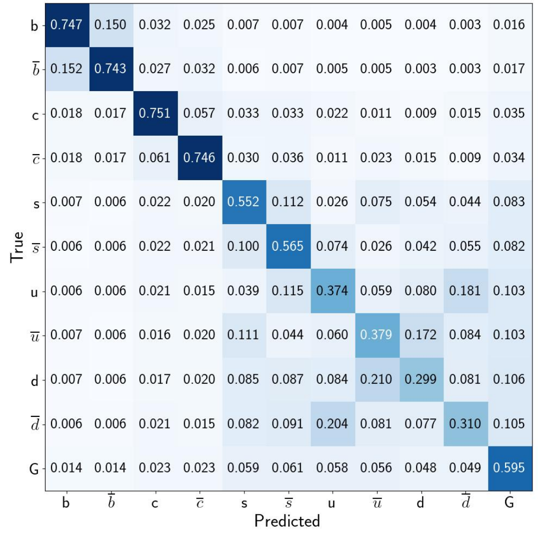




PN



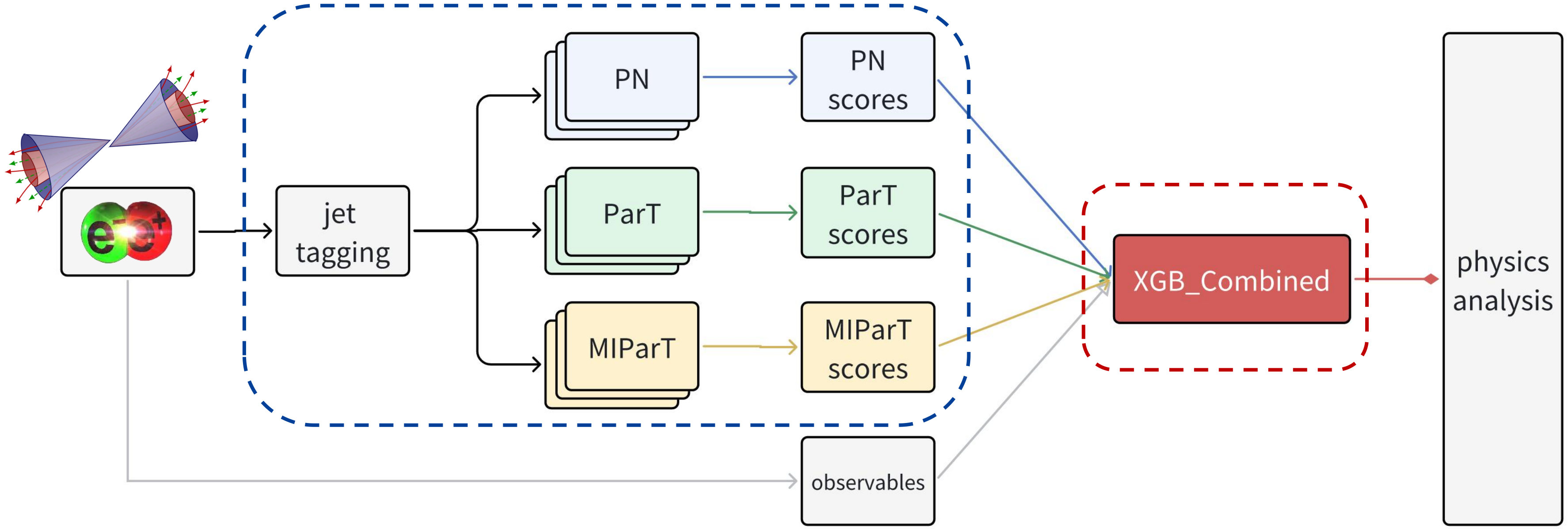
network	Params
ParticleNet	370k
ParT	2.14M
MIParT	720.9k



Capable of tagging light jets even charged jets

Analysis strategy

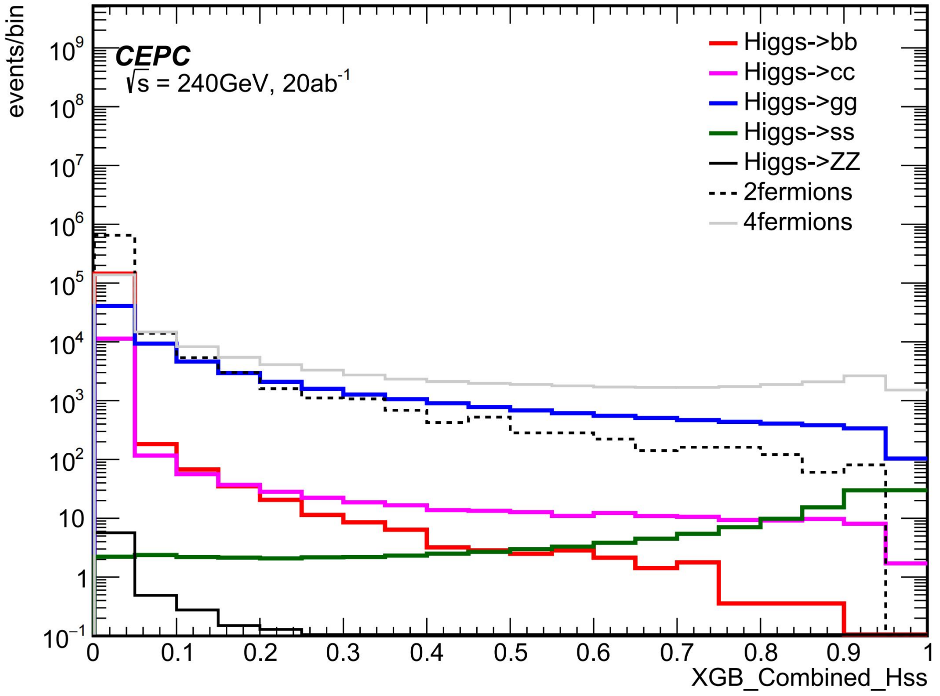
- Jet tagging train: Each network trained three times → improves tagging reliability
- Jet tagging prediction: Apply the trained networks to every jet in the event to obtain per-jet flavor scores
- XGB_Combined: At event level, Combine jet scores with physical observables to train an XGBoost classifier
  - six categories: h → bb, h → cc, h → gg, h → ss, 2fermions, 4fermions



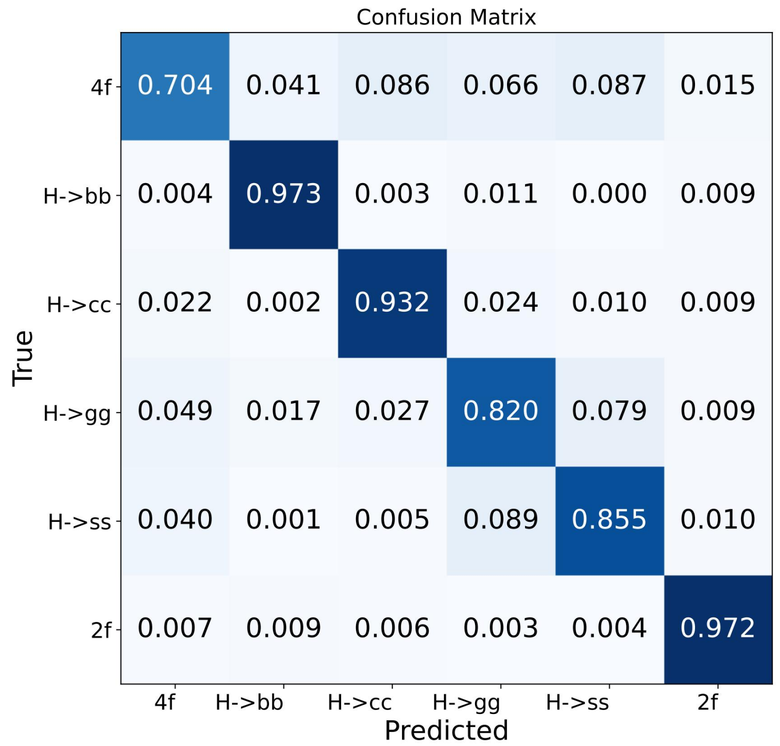
XGBoost Output

- Xgboost score distribution(take H→ss as signal)
- Xgboost six categories confusion matrix

Higgs→ss as Signal



XGB_Combined score



Higgs—>ss events selection

- H->ss as signal
- Total-cut means combining the pre-cut with the cut on the XGBoost score
  - chosen at the point of maximum signal significance Z
- Event yields in the final row are normalized to 20 ab^{-1}
- ML boosts the significance to Z = 1.29 （**0.03**[before pre-cut]→**0.1**[after pre-cut]→**1.29**[after total-cut] ）

eff & Selected	H->bb	H->cc	H->gg	**H->ss**	H->ZZ	4f	2f
Total-cut	6.67E-07	0.05%	0.75%	**44.68%**	1.65E-06	0.05%	4.16E-06
Selected events (20/ab)	0.36	13.63	593.77	**89.36**	0.01	4059.50	101.05

Higgs–> $b\bar{b}/c\bar{c}/gg$ events selection

- The selections for H→bb, H→cc, and H→gg follow the same procedure as H→ss.

signal	eff & Selected	H->bb	H->cc	H->gg	H->ss	H->ZZ	4f	2f
H->bb	total-cut	**53.89**	2.73E-05	0.43	1.47E-05	8.39E-06	0.09	2.23E-06
	Selected events (20/ab)	**287924.98**	0.73	347.03	0.003	0.06	7161.45	2414.79
H->cc	total-cut	0.01%	**43.51%**	0.36%	5.14E-05	5.77E-06	0.0007	8.11E-07
	Selected events (20/ab)	61.25	**11747.07**	283.73	0.01	0.04	5824.03	878.10
H->gg	total-cut	0.16%	0.39%	**50.17%**	1.76%	4.19E-06	0.04%	1.62E-06
	Selected events (20/ab)	853.22	107.21	**39836.00**	3.52	0.030	3099.98	1756.21

Relative error result

- Relative error = $\frac{\sqrt{S+B}}{S}$
- For H->bb/cc/gg, compare with "Precision Higgs Physics at CEPC(2018)" [α], show significant improvements
- For H → ss, we report a **78%** relative error — the first time this has been quantified with main backgrounds considered

20 ab^{-1}

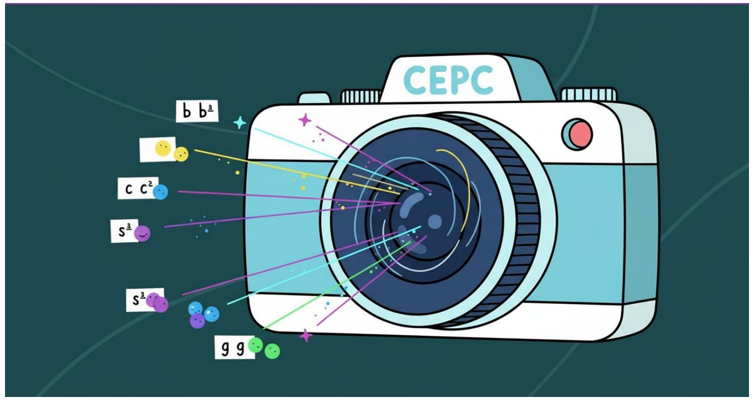
channel	published*	XGB_Combined (Ours)	precision improvement
Z →νν, H->bb	0.20%	**0.18%**	10%
Z →νν, H->cc	1.85%	**1.06%**	**43%**
Z →νν, H->gg	0.70%	**0.52%**	26%
Z →νν, H->ss	—	**78%**	∞

α arXiv: 1810.09037

* normalise to 20 ab-1

Summary

- Sample
  - Signal: $e^{+}e^{-} \rightarrow$ ZH, Z $\rightarrow \nu\bar{\nu}$, $H \rightarrow$ q$\bar{\text{q}}$ $and\ gg$ @ 240GeV
  - Main Background: 2fermions and 4fermions processes
- Combined advanced jet tagging (ParticleNet/PartT/MI-PartT) with XGBoost classifier to achieve encouraging results
- Relative error = $\frac{\sqrt{S+B}}{S}$, Event yields normalize to 20 ab^{-1}
  - H->bb: 0.18% (improvement 10%)
  - H->cc: 1.06% (improvement 43%)
  - H->gg: 0.52% (improvement 26%)
  - H->ss: 78% (first-time quantification, main backgrounds included)



Thanks for your listening !

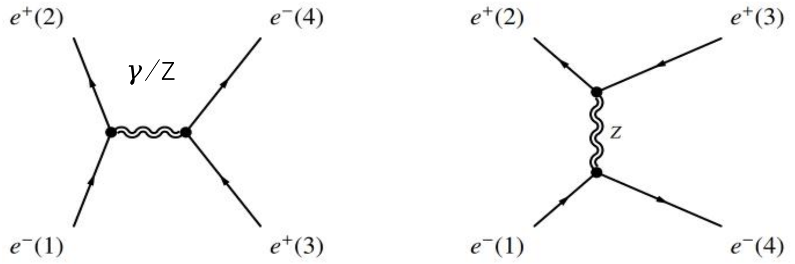
Backup

Background Simulation

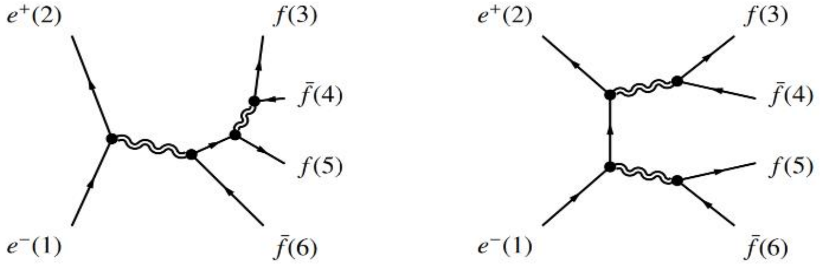
- Background: 4fermions, 2fermions, HZZ
- 2f process has big cross section → Event filter applied for efficiency

	channel	cross section [fb]	expected events [M]	simulated events [M]	**scale factor**
	ZH, Z→νν, H->ZZ; Z->νν, Z->qq	0.34	0.0068	2	0.003
4f	ZZ, Z→νν, Z→dd/ss/bb	139.71	2.7942	2.2	1.270
4f	ZZ, Z→νν, Z→uu/cc	84.38	1.6876	2.2	0.767
4f	Single Z, νν, Z→dd/ss/bb	90.03	1.8006	2.2	0.818
4f	Single Z, νν, Z→uu/cc	55.59	1.1118	2.2	0.505
	2f, qq	54106.86 1213.25	1082.1372 24.2650	1.2	20.22

2fermions process



4 fermions_nu process

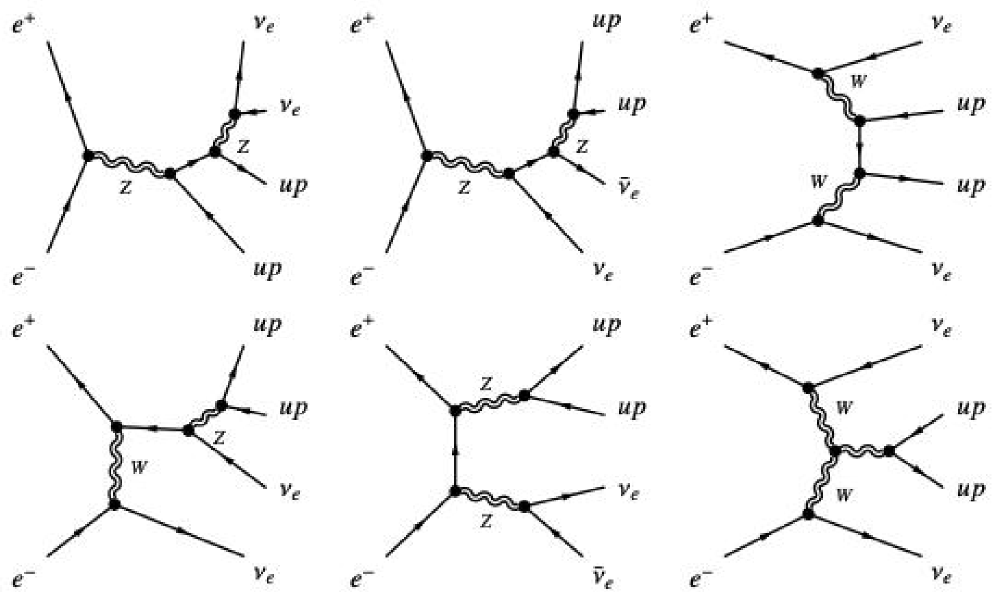


Feynman diagram from the CEPC note

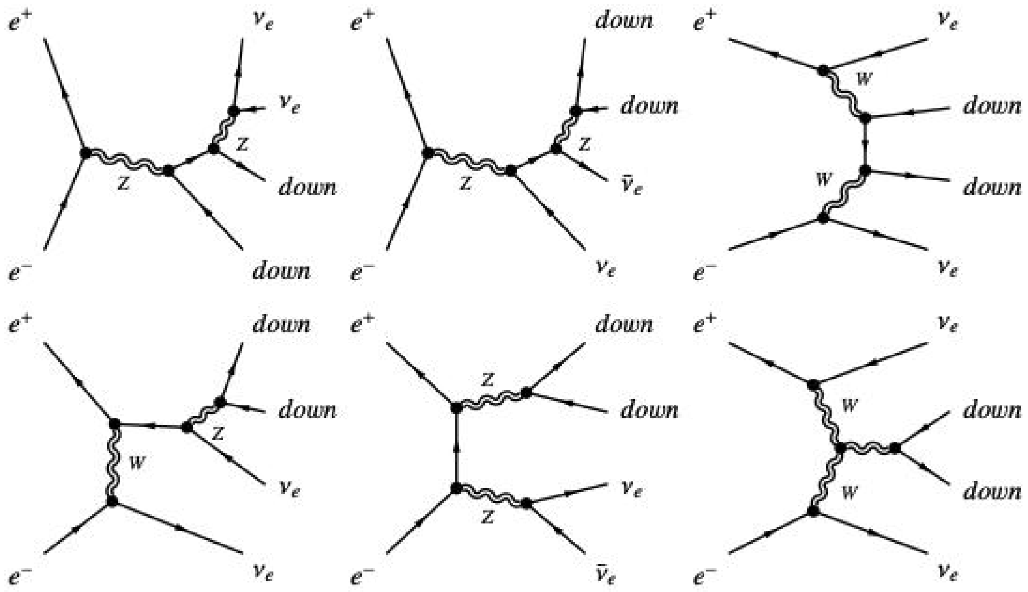
Input channels 4f

- single Z_nu

6.35 sznu_sl0nu_up



6.36 sznu_sl0nu_down

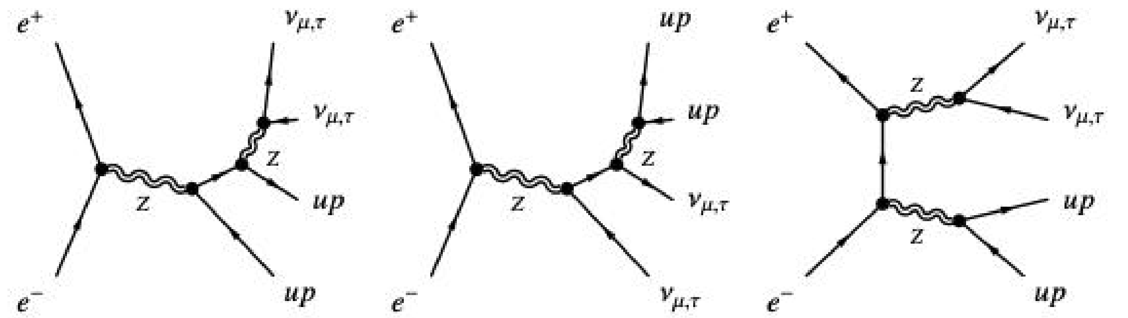


Feynman diagram from the CEPC note

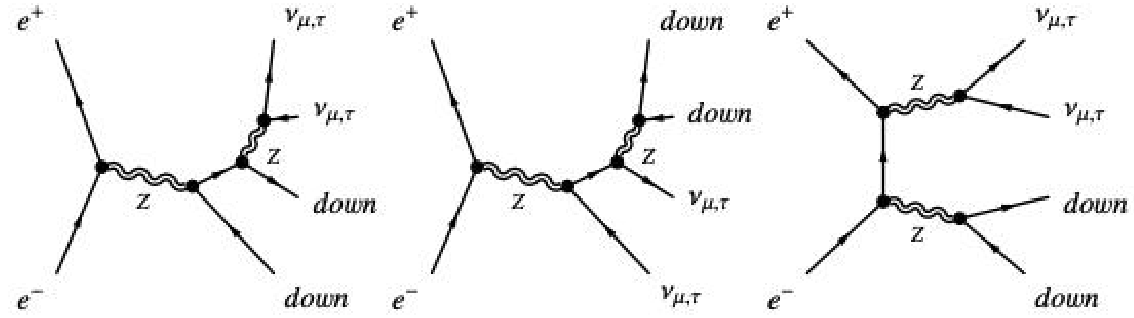
Input channels 4f

- ZZ_nu

185 **6.5 zz_sl0nu_up**



186 **6.6 zz_sl0nu_down**



Feynman diagram from the CEPC note

Input features

- Jet constructed by eekt algorithm, each event has 2 jets
  - each jet-level feature, both leading and subleading jet are contained
- For PN/ParT/MIParT, each trained three times
  - 3 scores per type of tagging model per jet

Single Jet Kinematics: jet_pt, jet_pz, jet_eta, jet_theta, jet_phi, jet_energy

Jet Shape & Composition: jet_nParticles, jet_dR, jet_dPT

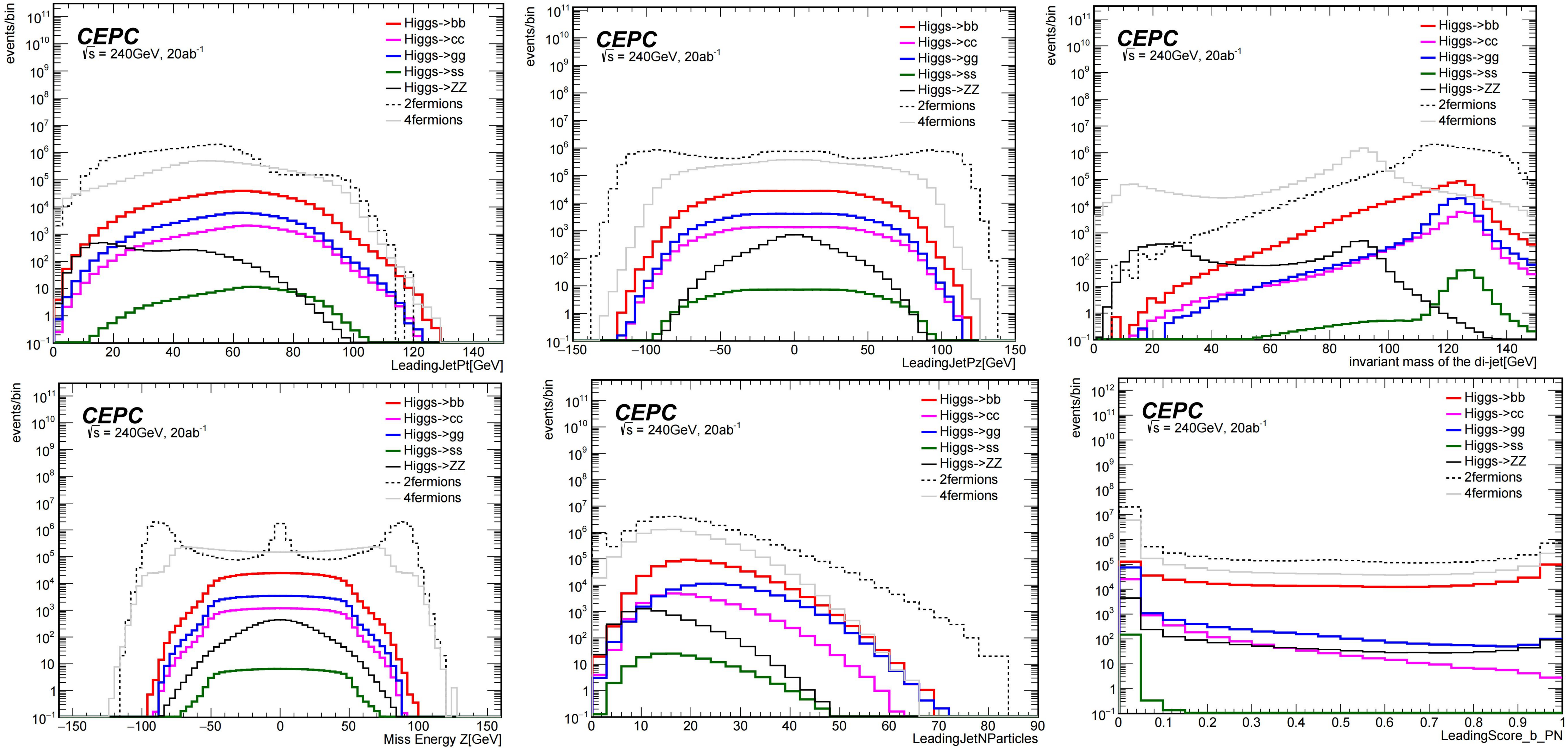
Jet Pair Observables: mjj, detajj, dthetajj, dphijj

Missing Energy: MET, ME_eta, ME_theta, ME_phi, MEZ, METOHT

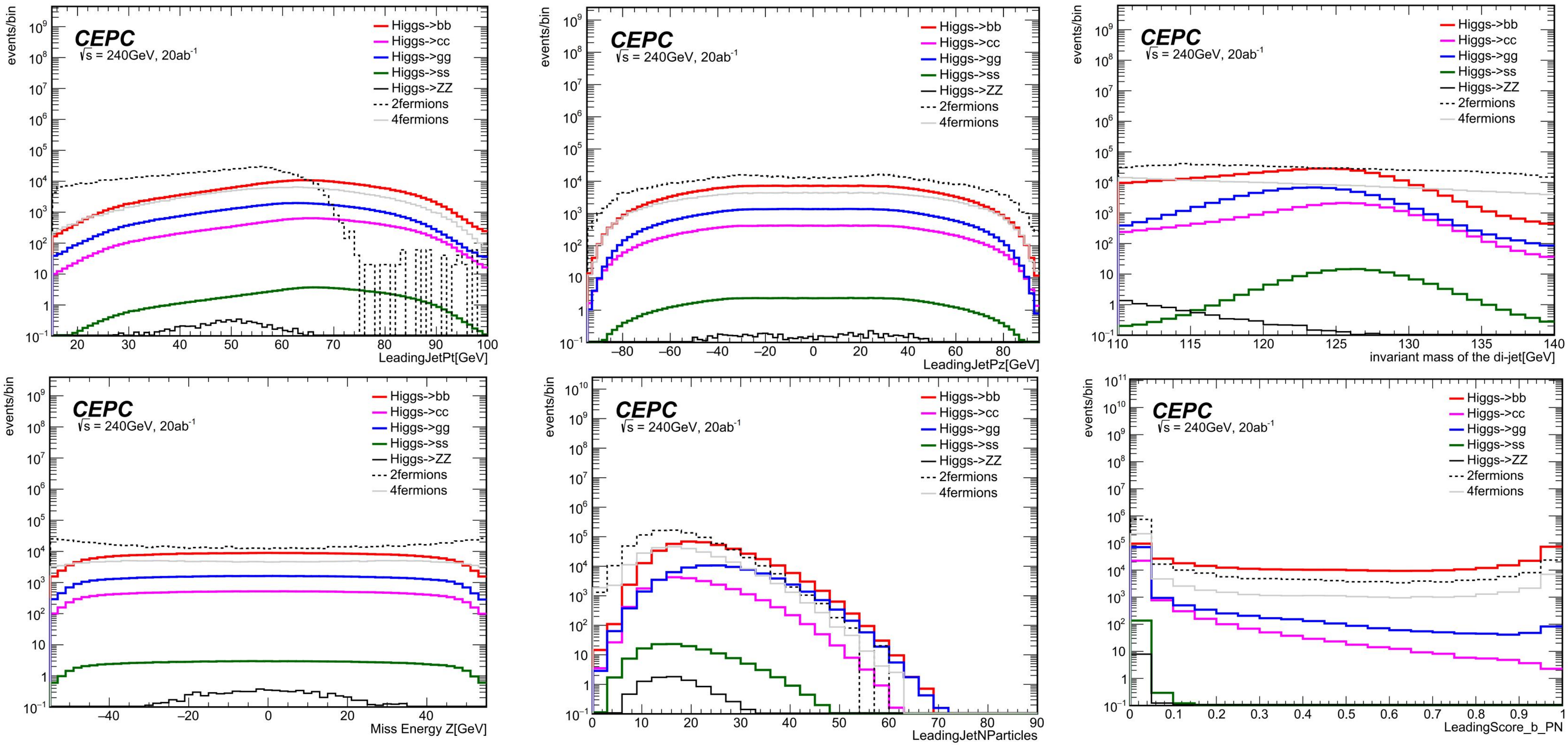
Jet–MET Angular Correlations: jet_ME_deta/dphi/dtheta

Jet Flavor Tagging Scores: jet_flavor_score(PN/ParT/MIParT)

Sample Distribution before pre-cut



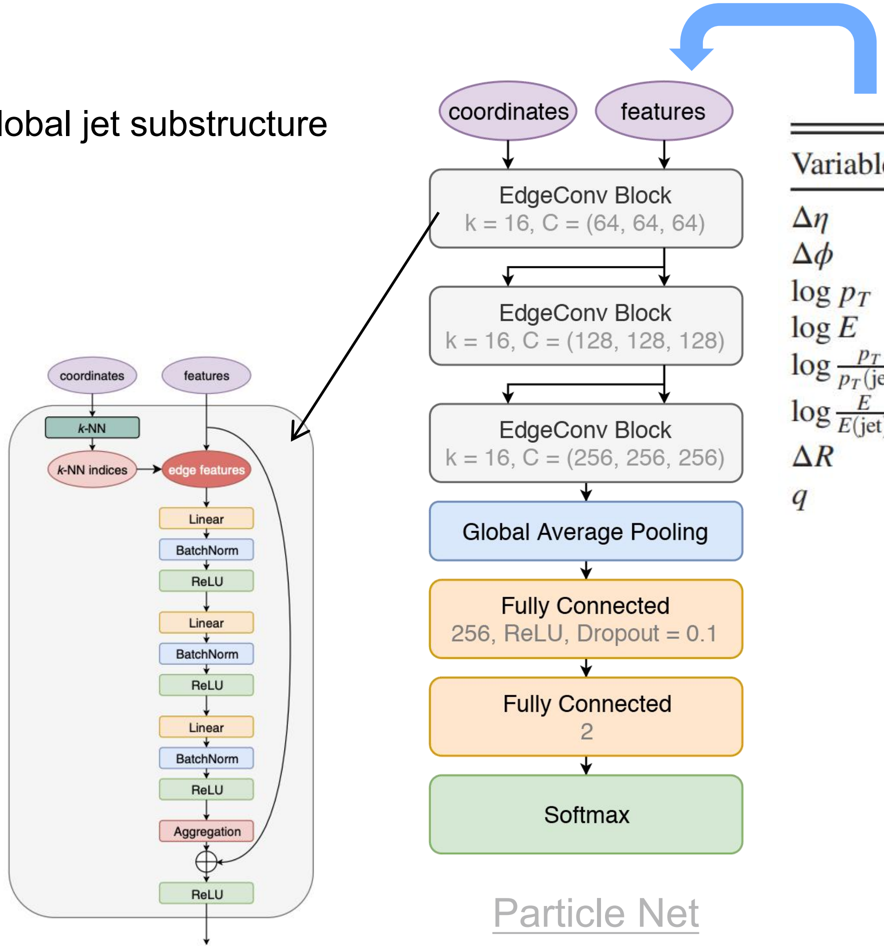
Sample Distribution after pre-cut



ParticleNet

- Treat a jet as a particle cloud
  - Uses dynamic graph convolutions to learn both local and global jet substructure
- Capable of tagging light jets even charged jets

True \ Predicted	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.747	0.150	0.032	0.025	0.007	0.007	0.004	0.005	0.004	0.003	0.016
$\bar{b}$	0.152	0.743	0.027	0.032	0.006	0.007	0.005	0.005	0.003	0.003	0.017
c	0.018	0.017	0.751	0.057	0.033	0.033	0.022	0.011	0.009	0.015	0.035
$\bar{c}$	0.018	0.017	0.061	0.746	0.030	0.036	0.011	0.023	0.015	0.009	0.034
s	0.007	0.006	0.022	0.020	0.552	0.112	0.026	0.075	0.054	0.044	0.083
$\bar{s}$	0.006	0.006	0.022	0.021	0.100	0.565	0.074	0.026	0.042	0.055	0.082
u	0.006	0.006	0.021	0.015	0.039	0.115	0.374	0.059	0.080	0.181	0.103
$\bar{u}$	0.007	0.006	0.016	0.020	0.111	0.044	0.060	0.379	0.172	0.084	0.103
d	0.007	0.006	0.017	0.020	0.085	0.087	0.084	0.210	0.299	0.081	0.106
$\bar{d}$	0.006	0.006	0.021	0.015	0.082	0.091	0.204	0.081	0.077	0.310	0.105
G	0.014	0.014	0.023	0.023	0.059	0.061	0.058	0.056	0.048	0.049	0.595



Particle Net

Variable
$\Delta\eta$
$\Delta\phi$
$\log p_T$
$\log E$
$\log \frac{p_T}{p_T(\text{jet})}$
$\log \frac{E}{E(\text{jet})}$
ΔR
q

ParT & MI-ParT

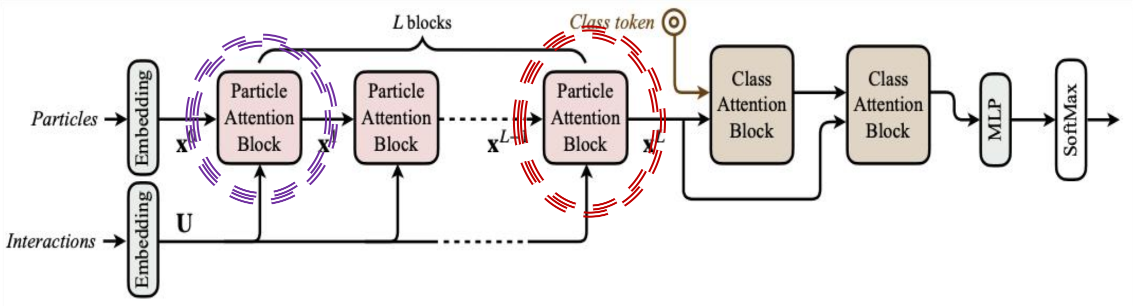
- attention on particle and their “interactions”
  - Particle attention: particle <-> particle
  - Class attention: particles <-> class/jet flavor
  - More-Interaction attention: reduces model complexity compared with particle transformer

$$
\begin{aligned}
\Delta &= \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2}, \\
k_{\mathrm{T}} &= \min(p_{\mathrm{T},a}, p_{\mathrm{T},b})\Delta, \\
z &= \min(p_{\mathrm{T},a}, p_{\mathrm{T},b})/(p_{\mathrm{T},a} + p_{\mathrm{T},b}), \\
m^2 &= (E_a + E_b)^2 - \|\mathbf{p}_a + \mathbf{p}_b\|^2,
\end{aligned}
$$

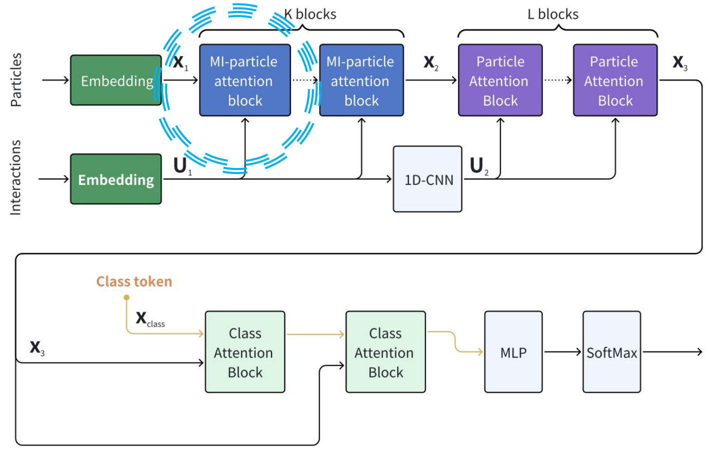
interactions

model	Params
ParticleNet	370k
ParT	2.14M
MIParT	720.9k

3x



Particle Transformer

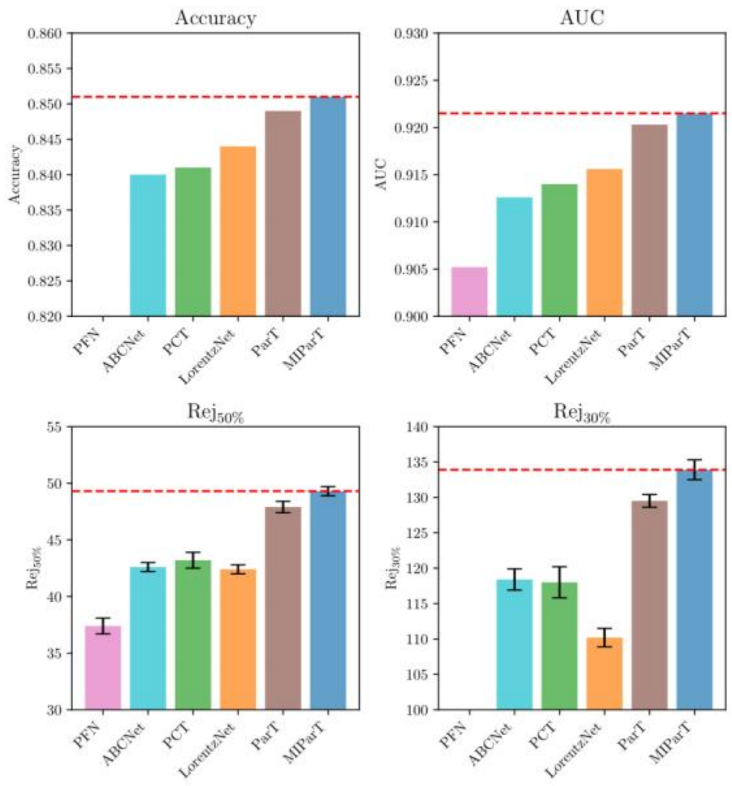


More-Interaction Particle Transformer

Performance

- Jet level kinematics + PID from Quark-gluon tagging dataset
- Representation suit with model structure

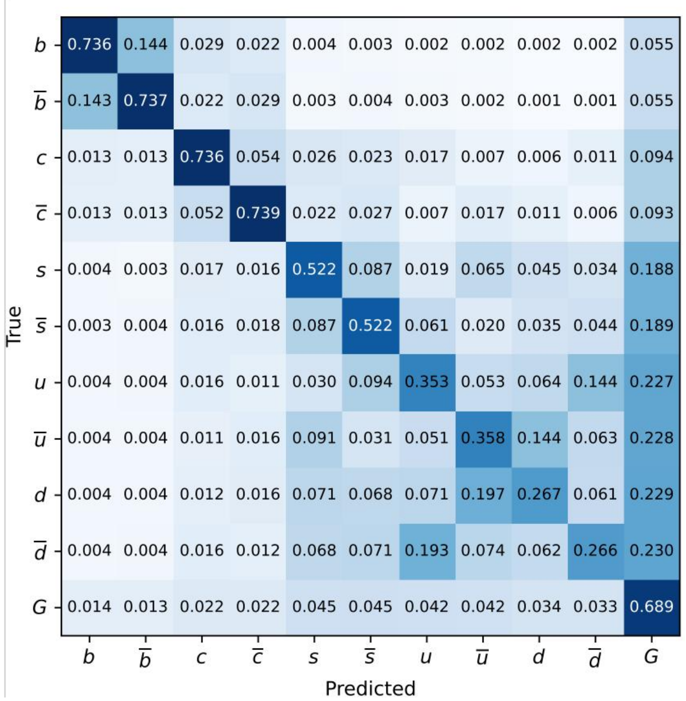
$$\mathrm{Rej}_{50\%} = \frac{1}{\text{bkg mis–id rate}}\Big|_{\text{signal efficiency [\%]}}$$



	Accuracy	AUC	$\mathrm{Rej}_{50\%}$
PFN	—	0.9052	37.4±0.7
ABCNet	0.840	0.9126	42.6±0.4
PCT	0.841	0.9140	43.2±0.7
LorentzNet	0.844	0.9156	42.4±0.4
ParT	0.849	0.9203	47.9±0.5
MIParT (ours)	**0.851**	**0.9215**	**49.3±0.4**
ParT f.t.	0.852	0.9230	50.6±0.2
MIParT-L f.t. (ours)	**0.853**	**0.9237**	**51.9±0.5**

Jet tagging output

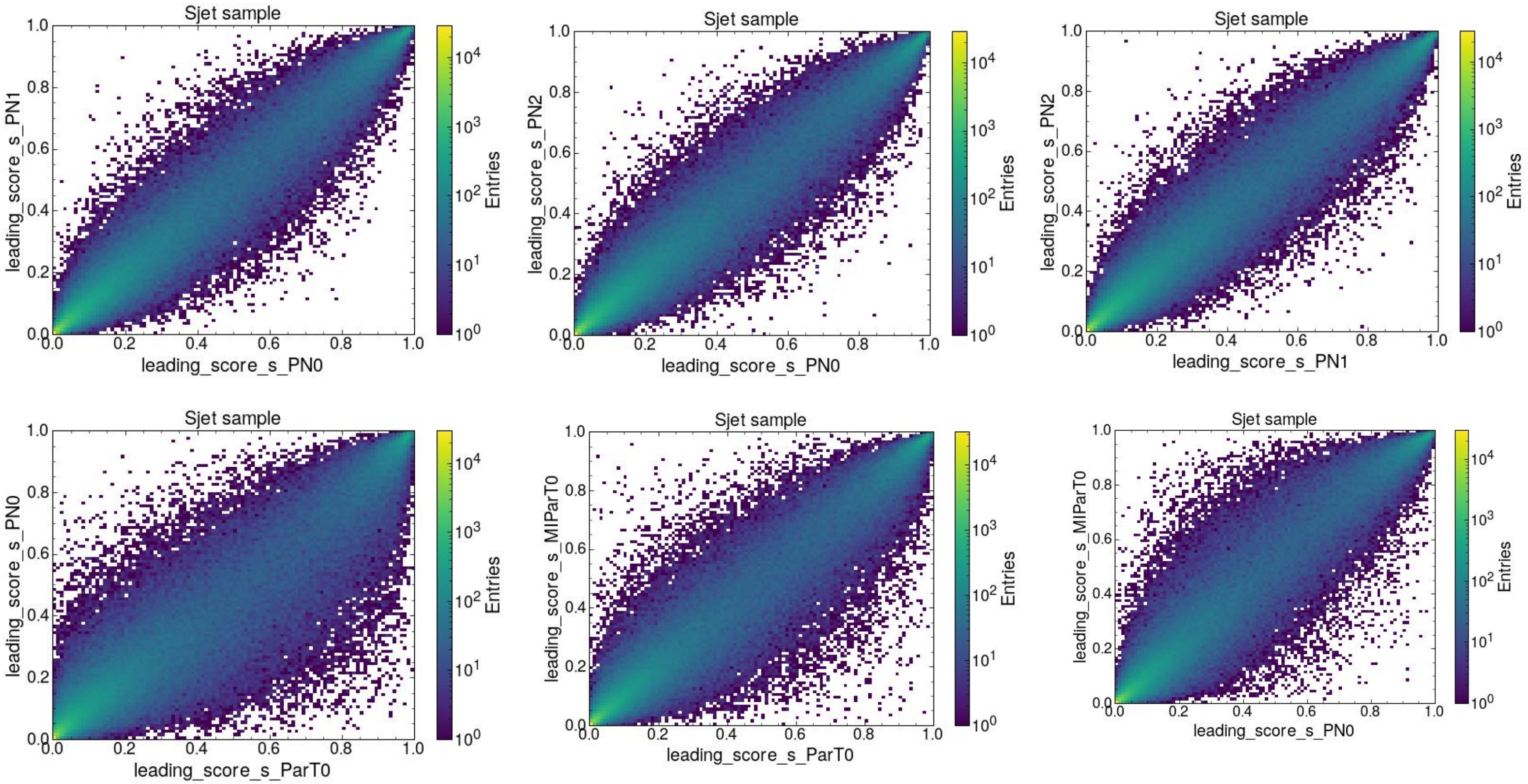
- Capable of tagging light jets even charged jets
- ParticleNet, Fast simulation, CDR
- diag = trace(matrix)
- Each model trained 3 times



	ParticleNet	ParT	MIParT
diag	**5.907 ± 0.018**	**6.050 ± 0.006**	**6.006 ± 0.017**
b tag as $b/\bar{b}$	0.878 ± 0.002	**0.891 ± 0.001**	0.885 ± 0.001
c tag as $c/\bar{c}$	0.79 ± 0.003	**0.8 ± 0.002**	0.797 ± 0.004
s tag as $s/\bar{s}$	0.608 ± 0.003	0.616 ± 0.002	**0.618 ± 0.005**
g tag as g	**0.686 ± 0.003**	0.67 ± 0.003	0.664 ± 0.007

Background Simulation

- Distribution for different models' score
- The same network trained multiple times can give different tagging scores for the same jet

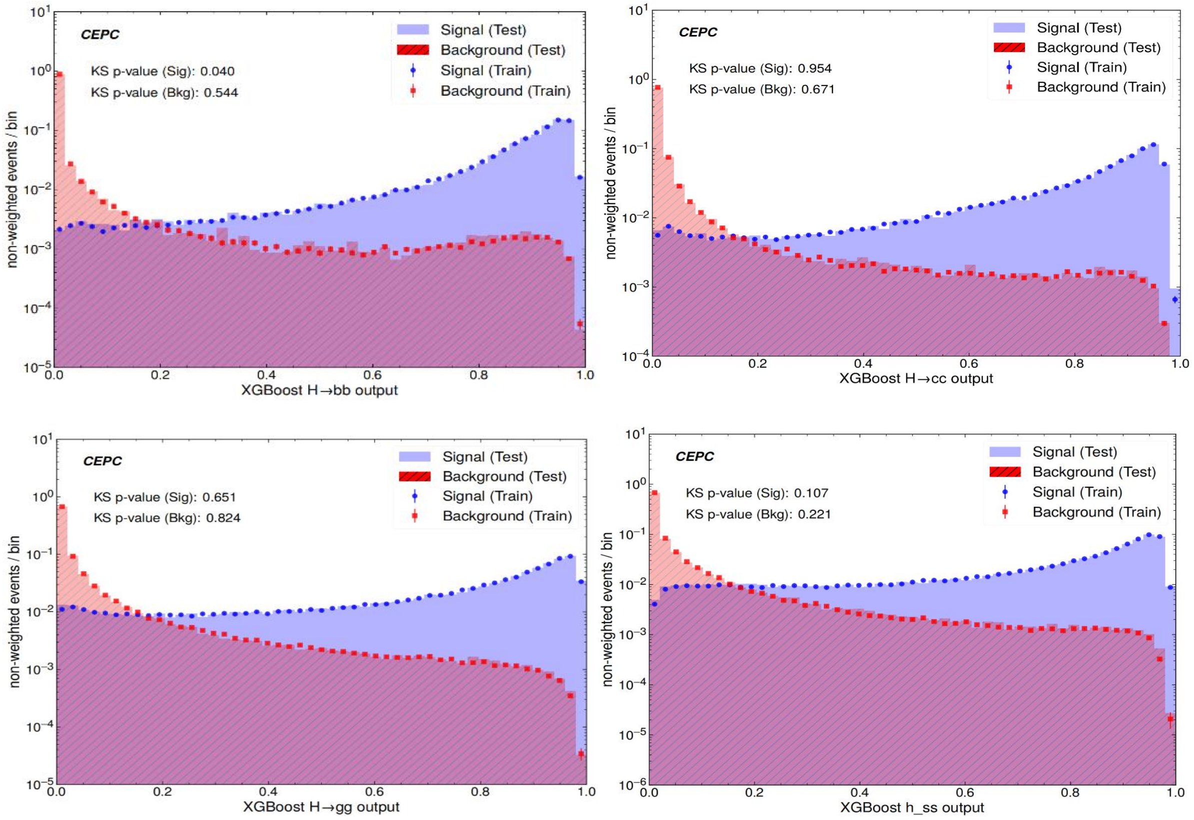


Overfitting-check

- Distribution is consistent, no obvious overfitting

H−>bb

H−>cc



H−>gg

H−>ss

CEPC-TDR draft

- ParticleTransformer deeply used in TDR research

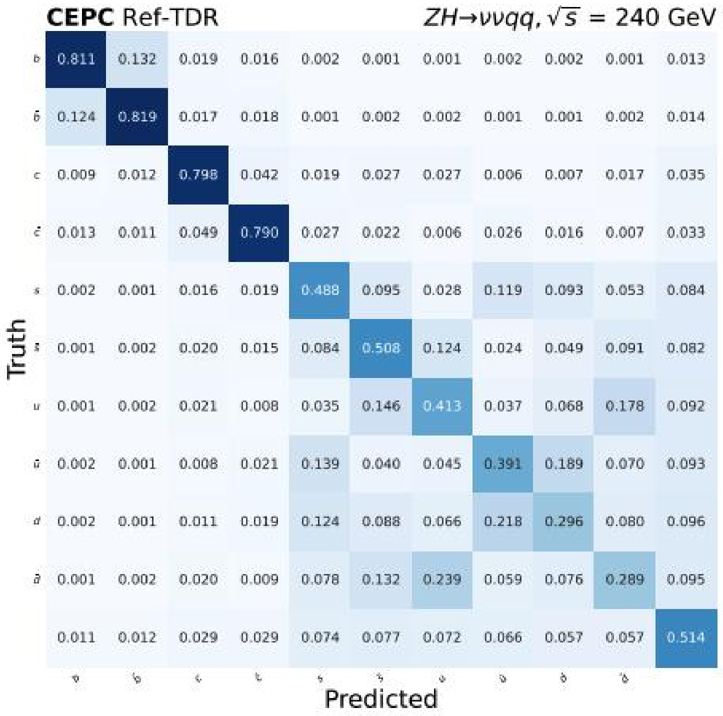


Figure 15.15: The confusion matrix M_{11} of JOI using realistic PID of leptons and charged hadrons for $\nu\bar{\nu}H$, $H\to qq$ events at $\sqrt{s}$ = 240 GeV, with the reference detector. The matrix is normalized to unity for each truth label.

Jet Origin Identification (JOI)

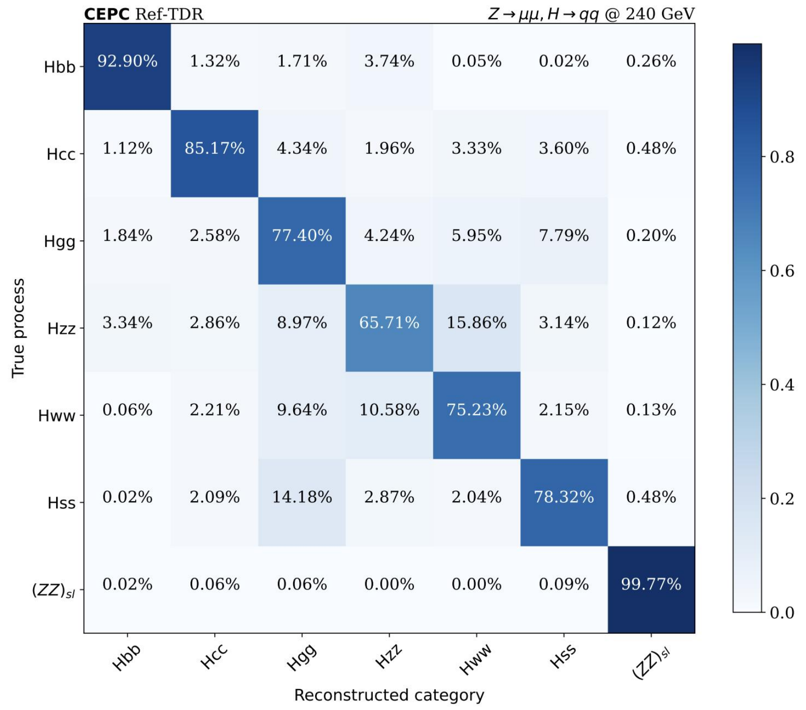


Figure 15.20: The migration matrix for the seven classes is shown. The horizontal axis represents the prediction of the model for each event in the test set, while the vertical axis indicates the true labels. The sum of values in each row equals 1.

Higgs hadronic decay

Compare with the lastest holistic result

- Compare with the lastest holistic result
- Only considered process H->bb/cc/gg/ss
- Beyond “cut+BDT”
- Comparable result

https://arxiv.org/pdf/2506.11783

$20\ \mathrm{ab}^{-1}$

	$\nu\bar{\nu}H$			
	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$	$H \to s\bar{s}$
cut + BDT	0.26%[21]	3.04%[21]	0.96%[21]	190.00%[19]
holistic	0.14%	0.72%	0.46%	29.34%
holistic with CSI	-	-	-	-
holistic with ideal CSI	-	-	-	-
statistical limit	0.14%	0.61%	0.36%	6.91%

model	Z →ν ν , H−>bb %	Z →ν ν , H−>cc %	Z →ν ν , H−>gg %	Z →ν ν , H−>ss %
XGB_Combined	0.17	0.77	0.47	28.54%