Deep-learning boosted hadronic Higgs precise measurements at future e+e− Higgs factories

Chunxiang Zhu, Xinzhu Wang, Yifan Zhu, Ruoshui Yuan

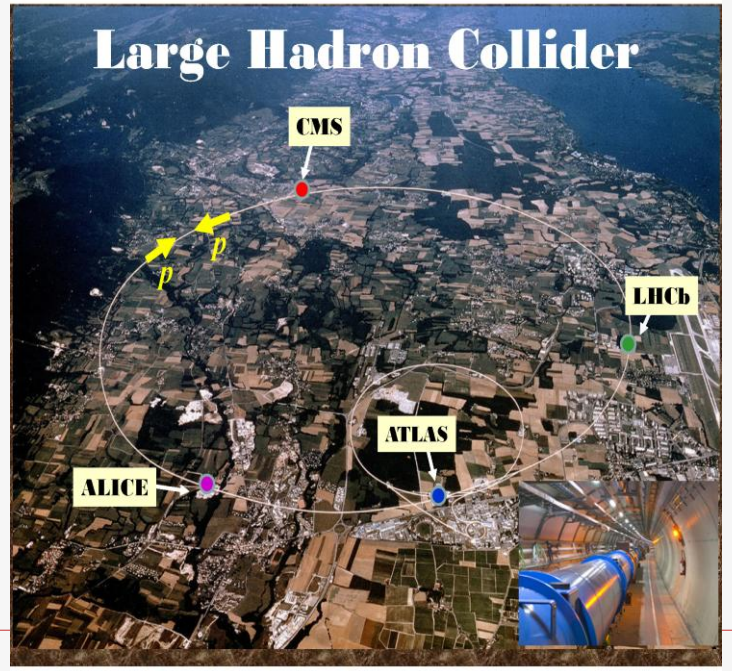
Kun Wang, Haijun Yang

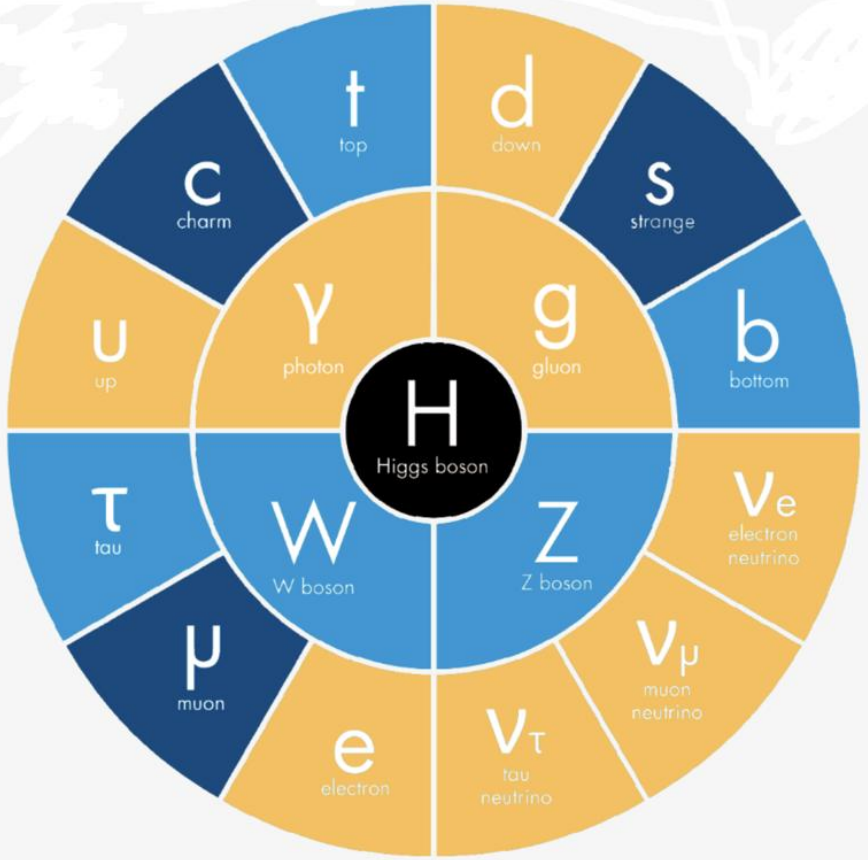
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Motivation

- Over ten years after Higgs discovery, it's still central to particle physics
- **Higgs Hadronic decays** is **Challenging** at LHC

- Better flavor ID enhances sensitivity in rare Higgs decay channels
- Test Higgs couplings across generations
- Search for signs of flavor violation beyond the SM

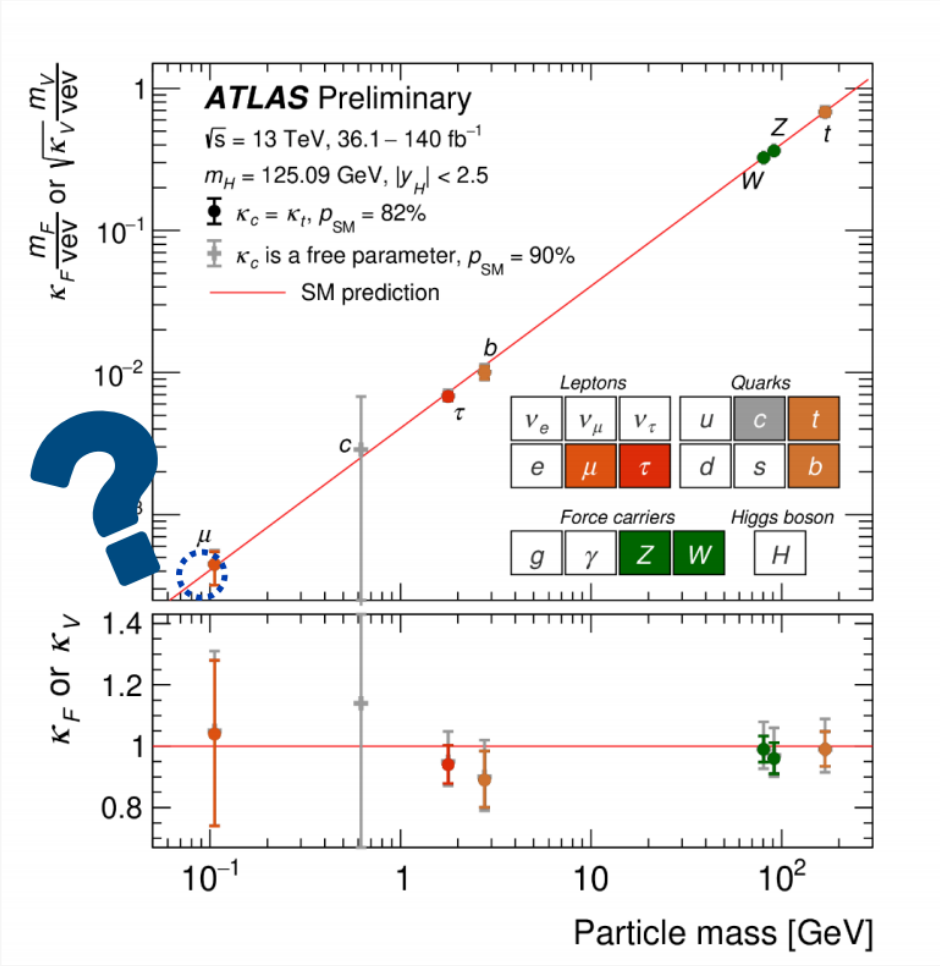




Motivation

- **3rd** generation fermions & **vector bosons**: observed
- **c quark/μ** : towards evidence
- **s quark**: the next one?
  - Challenge: small BR(~10^{-4}), QCD bkg at LHC

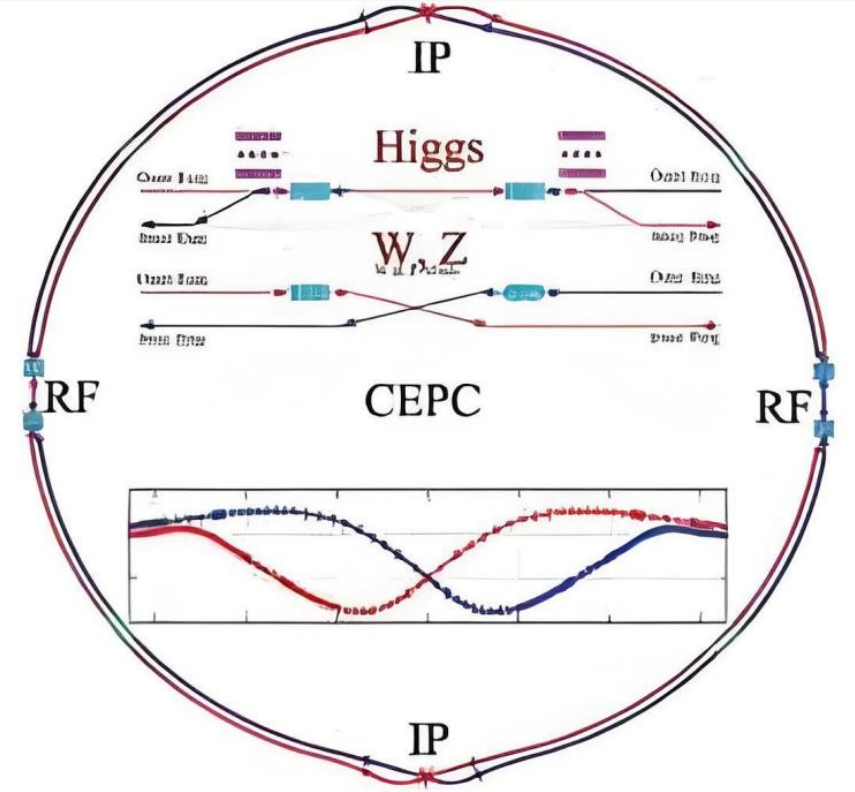
Decay channel	Reported quantity	Relative uncertainty	Reference
H → bb	$\mu_{bb} \approx 1.04 \pm 0.20$	**~19 %**	CMS-PAS-HIG-18-016
H → cc	$\kappa_c < 5.7 \times$ SM (95% CL upper limit)	—	Nature 607 (2022) 52
H → gg, ss	**Unobserved**	—	—
H → γγ	$\mu_{\gamma\gamma} = 1.18^{+0.17}_{-0.14}(stat) \pm 0.09(syst)$	~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

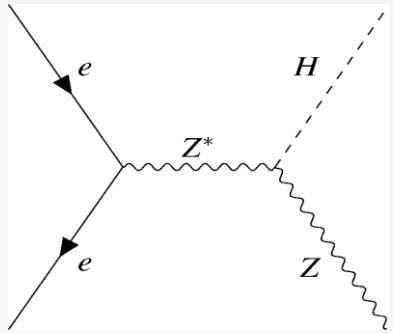


Nature volume 607, 52–59

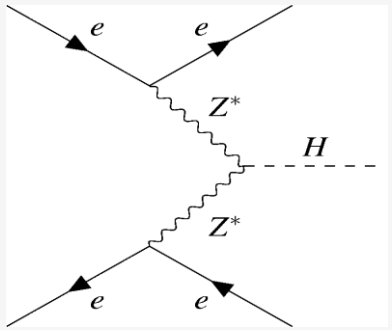
CEPC: New Opportunity for Higgs Physics

- Lepton colliders like CEPC may provide opportunities for even more precise measurements of Higgs physics
  - **~4M Higgs events** within 10 years
  - **Clean environment** from e^--e^+ collisions

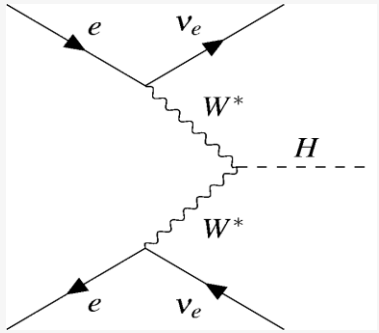




Higgs-Struhlung



Z Fusion

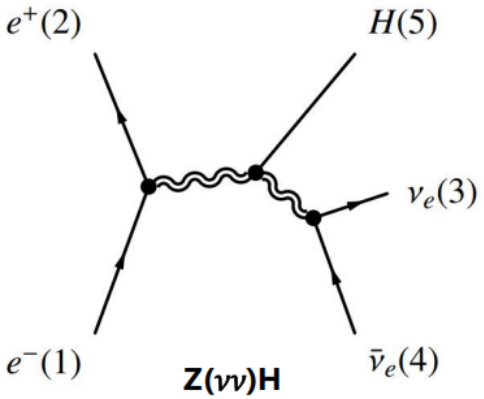


W Fusion

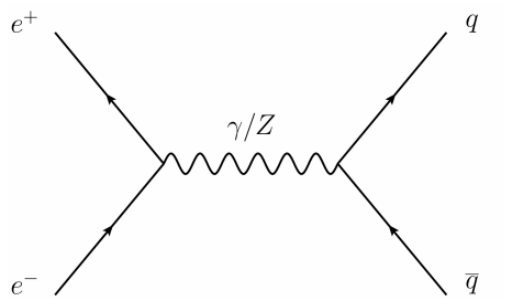
Operation mode	$\sqrt{s}$ (GeV)	SR power (MW)	$\mathcal{L}$ (10^{34} cm^{-2}s^{-1})	$\int \mathcal{L}$/year (ab^{-1}, 2 IPs)	Years	Total $\int \mathcal{L}$ (ab^{-1}, 2 IPs)	Event yields
H	240	50	8.3	2.2	10	21.6	4.3×10^6
Z	91	50	192(*)	50	2	100	4.1×10^{12}
W^+W^-	155-170	50	26.7	6.9	1	6.9	5.5×10^7
$t\bar{t}$	360	50	0.8	0.2	5	1.0	0.6×10^6

H→ss Pheno Search based on Advanced Taggers

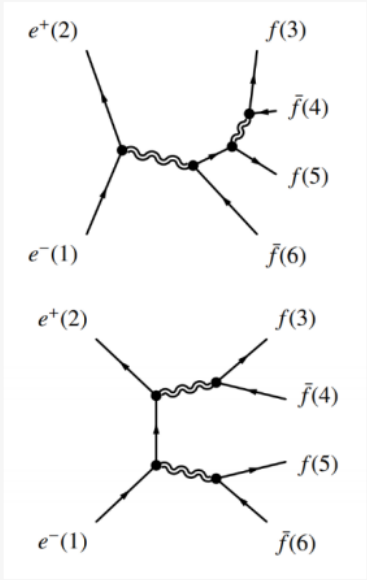
- **MadGraph3.6.3 + Pythia8.313 + Delphes** fast simulation
- **10M** events generated for each Higgs decay process, 25% for jet tagging training, 75% for event selection
- **Signal:** $e^+e^- \to ZH, Z \to \nu\bar{\nu}, H \to q\bar{q}$ and gg @ 240GeV
- **Background:** Dominated by 2 fermions and 4 fermions



Z(νν)H



2f



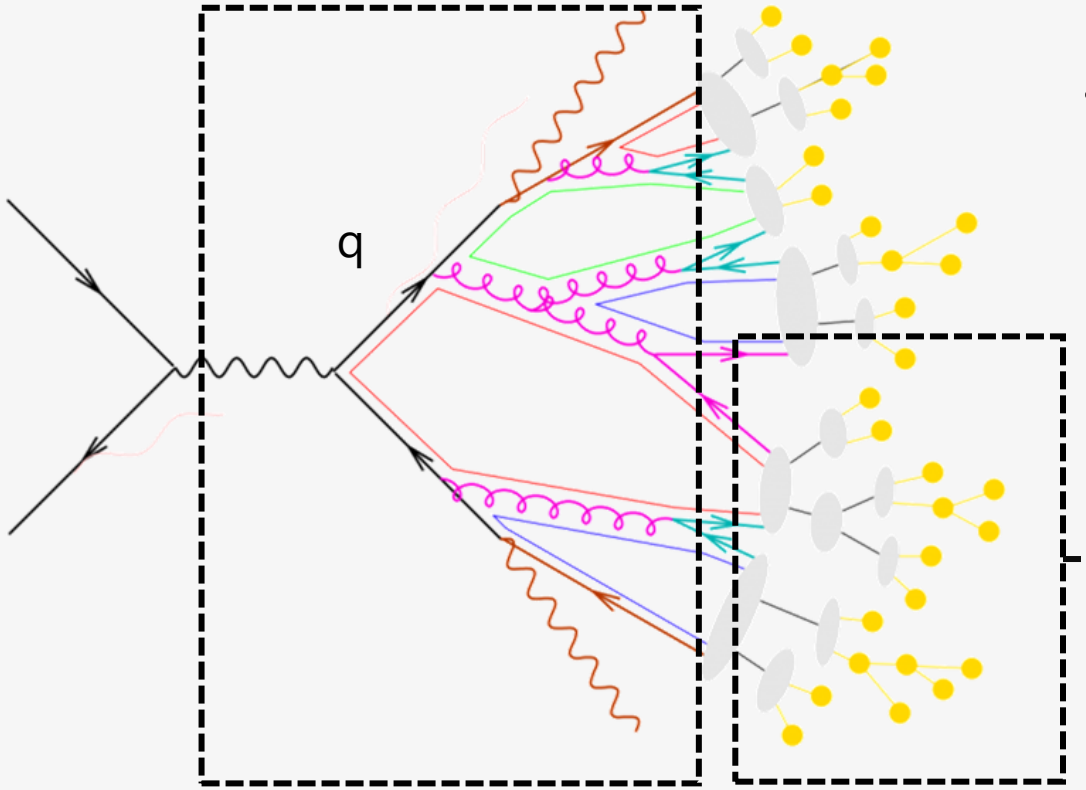
4f

Category	channel	cross section [fb]	expected events [M]	simulated events [M]
Signal	ZH, Z→νν, H–>bb	26.71	0.5342	10
	ZH, Z→νν, H–>cc	1.35	0.027	10
	ZH, Z→νν, H–>ss	0.01	0.0002	10
	ZH, Z→νν, H–>gg	3.97	0.0794	10
Background	ZH, Z→νν, H–>ZZ; Z–>νν, Z–>qq	0.34	0.0068	10
	4f	369.71	7.3942	40
	2f	46490	929.8	25
		1320	26.4	

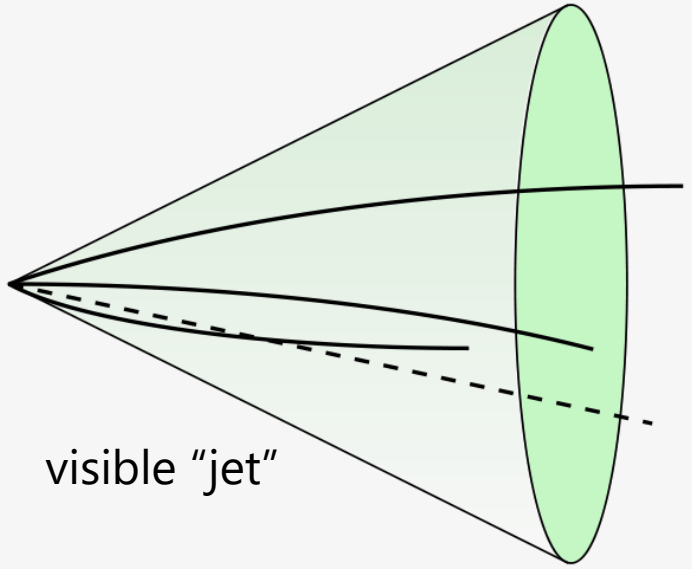
add generation cut

Jet is important physics objects

- >90% of ZH events contains jets
- Isolated quarks are not detectable in detectors → color confinement
- **Jet**: cluster of secondary particles/constituents detected from quark/gluon **parton shower**

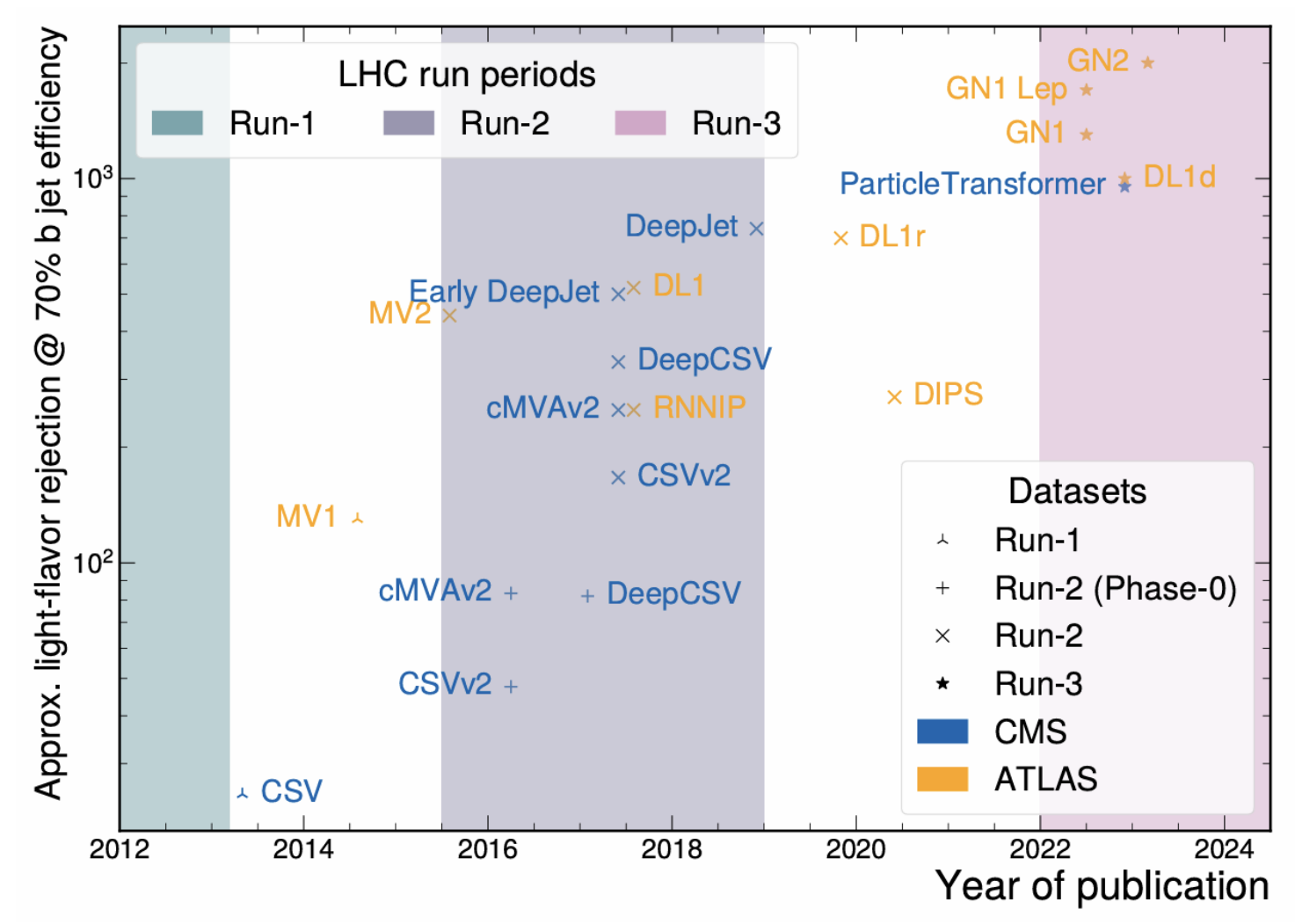


- The internal structure of jets carries information about their origin -> **jet tagging**

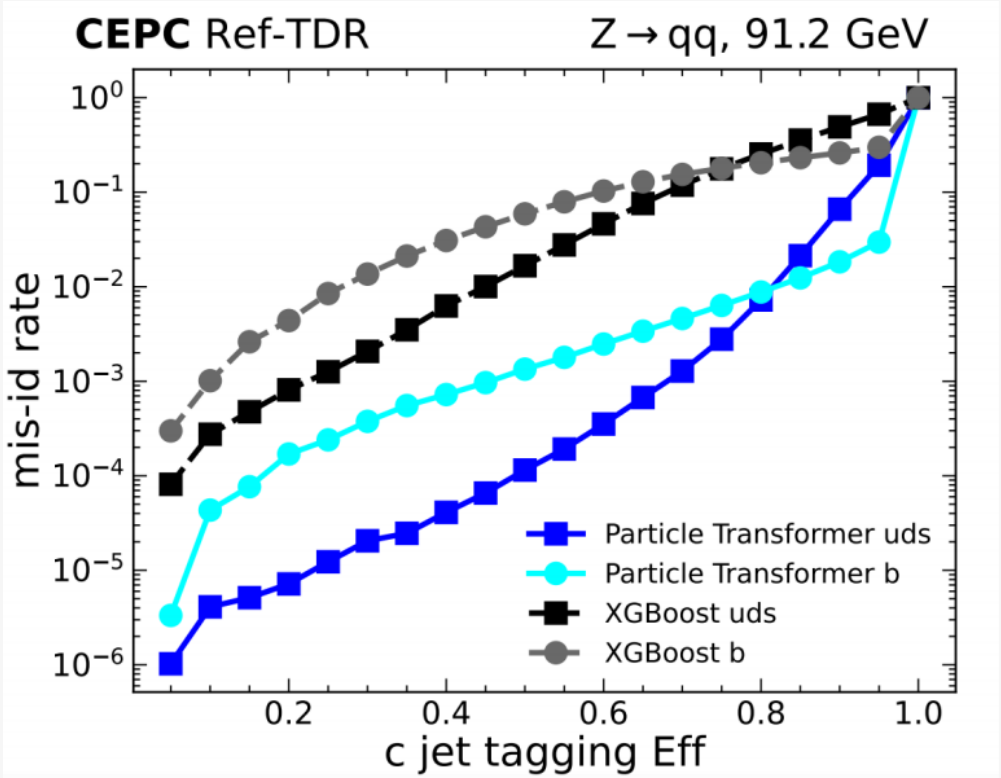


Physics

Jet is important physics objects

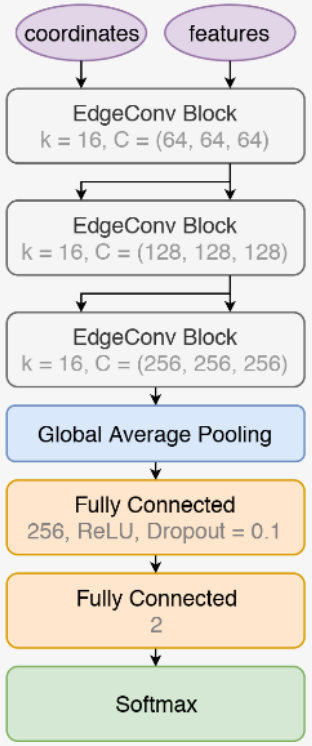


- Higgs couplings to quarks measurements are boosted by **particle level information** at jet level

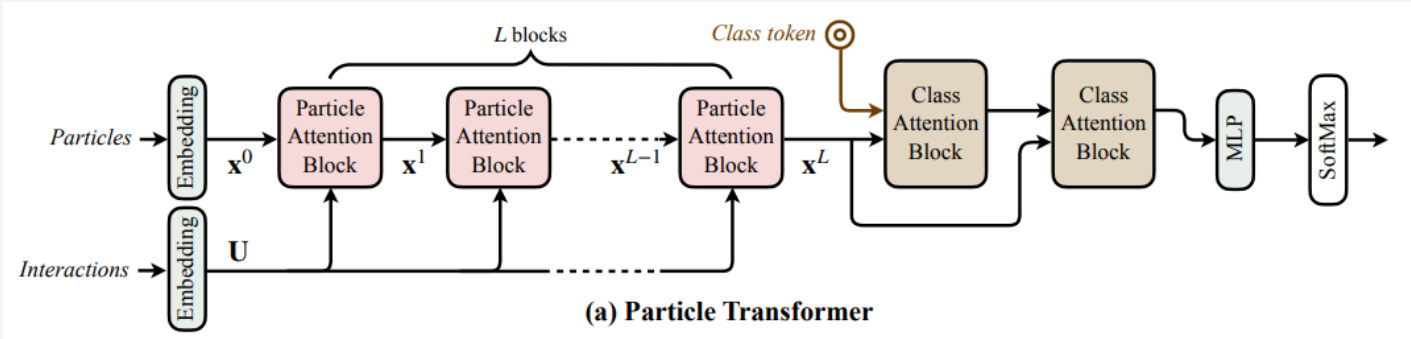


3 advanced jet taggers

- **ParticleNet** (PN): Uses dynamic graph convolutions to learn local & global jet substructure
- **Particle Transformer** (ParT): Based on Attention Mechanism, capturing long-range correlations among jet constituents
- **More-Interaction Particle Transformer** (MIParT): A reduced version of ParT

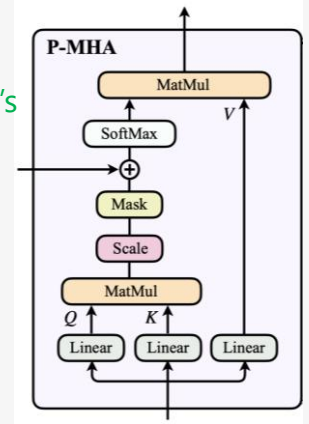


PN (1902.08570)



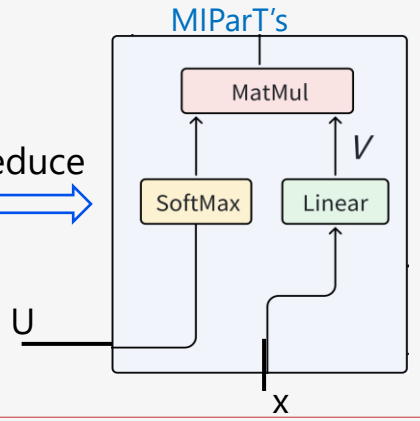
ParT (2202.03772)

ParT's



reduce

MIParT's

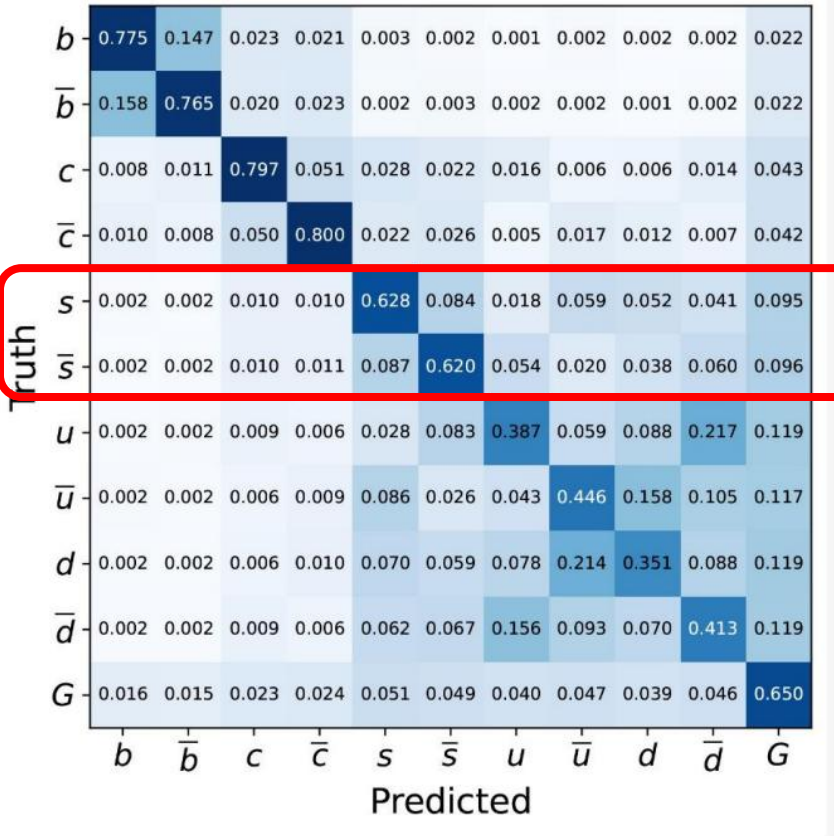


network	Params
ParticleNet	370k
ParT	2.14M
MIParT	720.9k

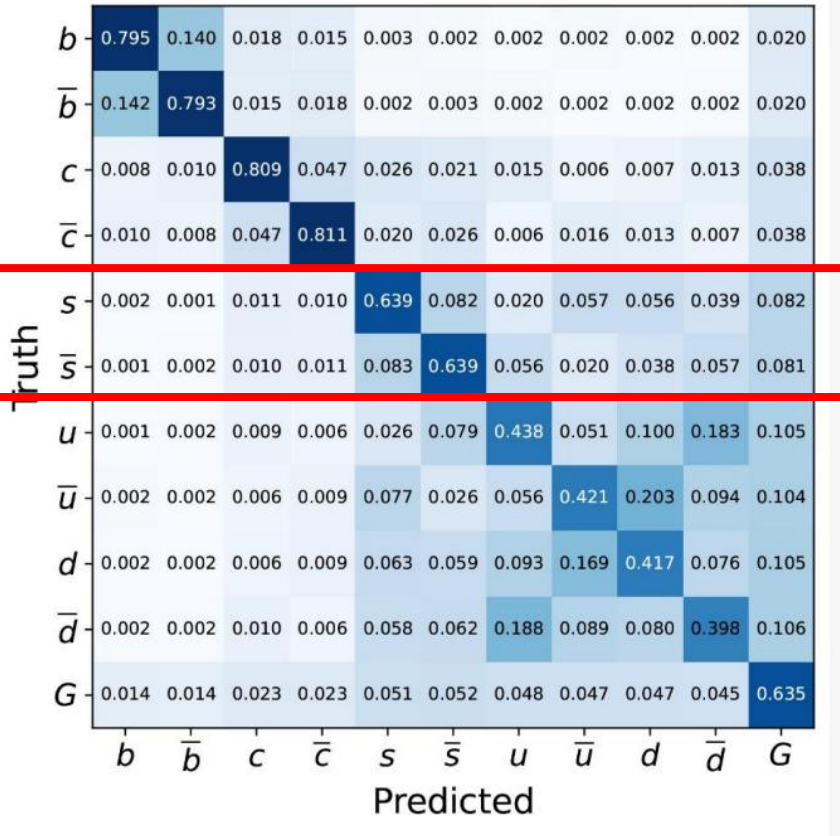
30%

Jet Tagging at CEPC

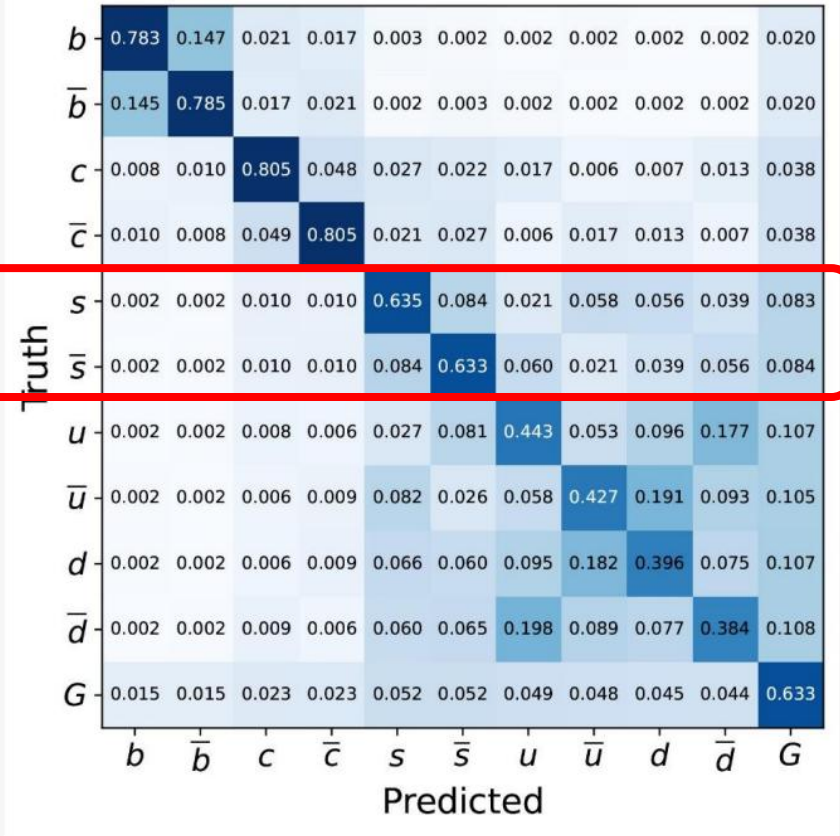
- Possibility to tag s-jets at CEPC
- 2.5M events each channel (H→bb/cc/ss/uu/dd/gg) for training , validation and test



PN



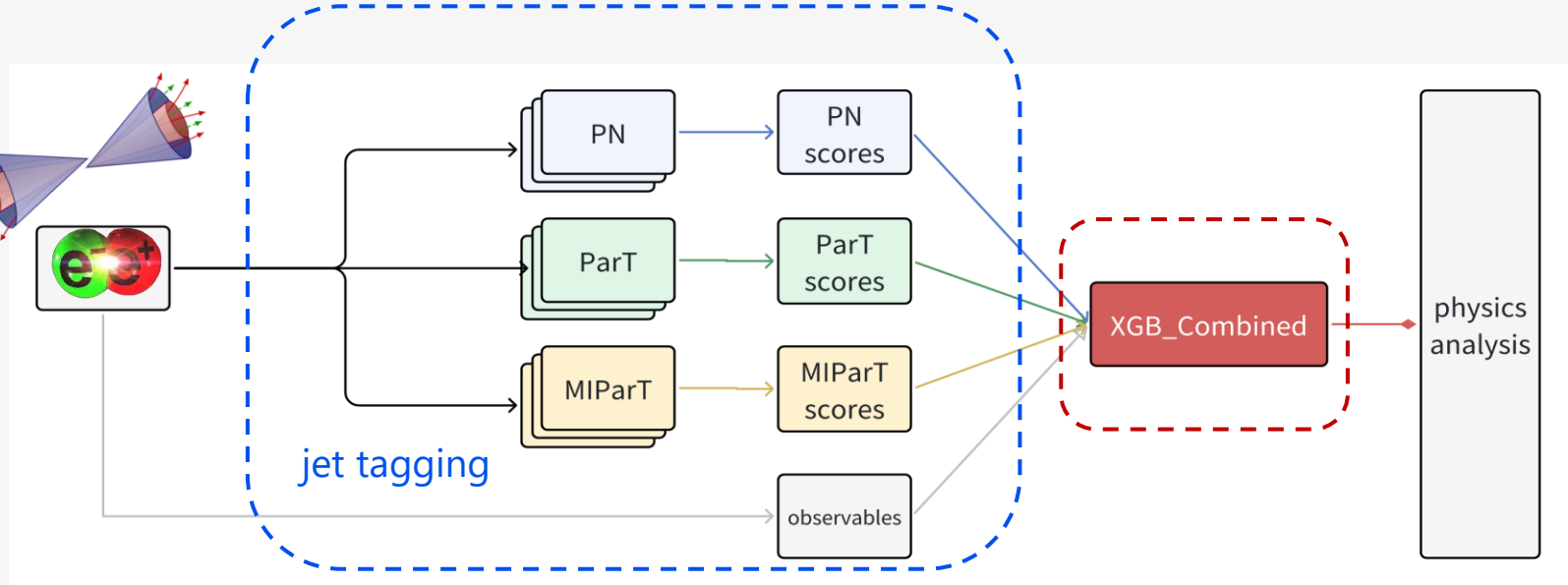
ParT



MIParT

H→ss Pheno Search based on Advanced Taggers

- At event level, train an XGBoost multi-class classifier combining jet scores with other observables
  - > 200 input features
  - 3 × 3 tagging models -> estimate uncertainties from models
- A bb/cc/gg region + a dedicated ss region



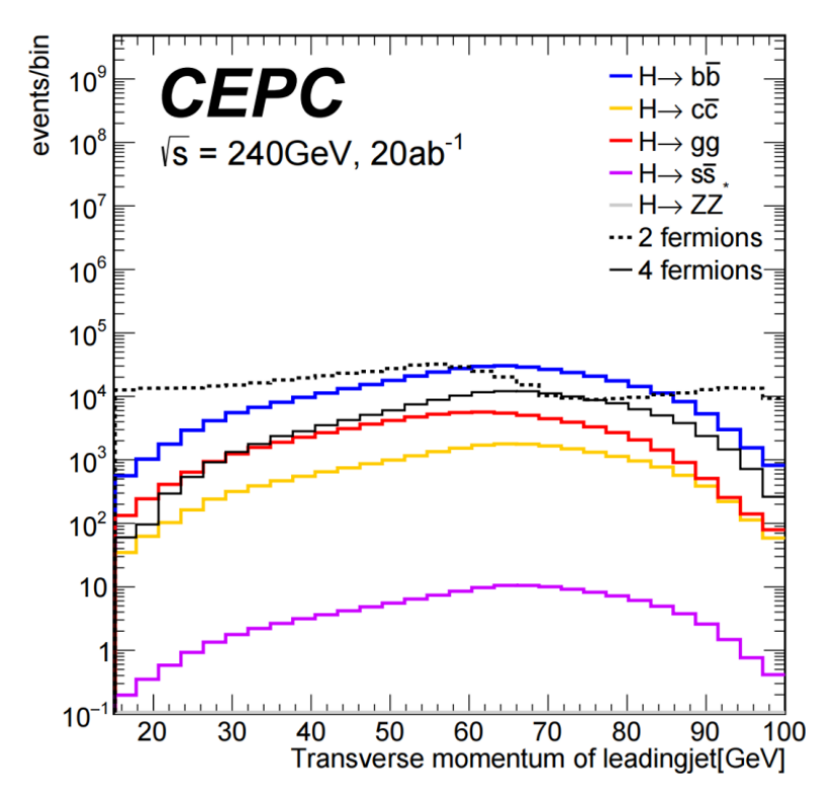
overview of the analysis strategy

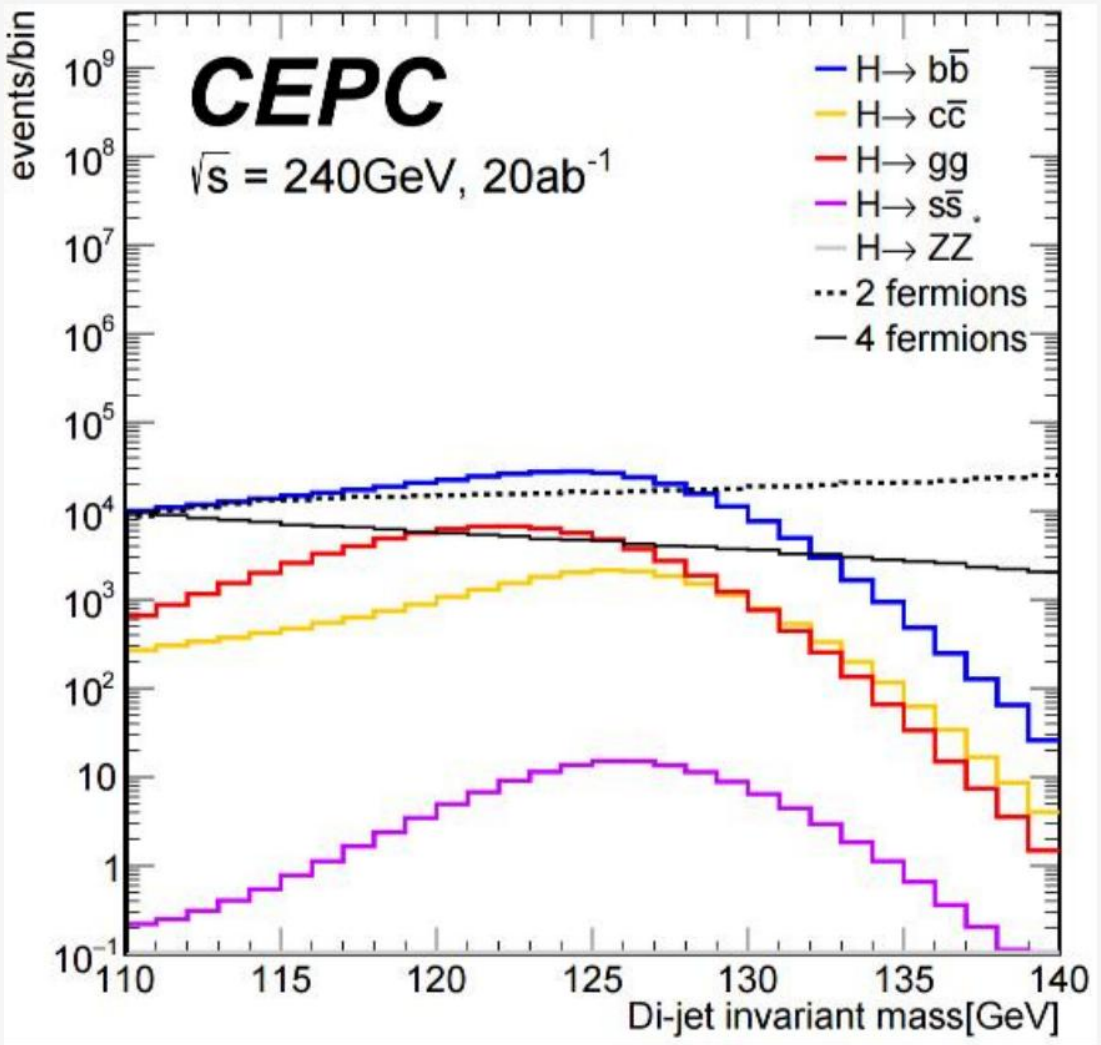
Category	Features
Single-jet kinematics	p_T, p_z, η, θ, ϕ, energy
Jet shape and composition	$n_{\text{particles}}$, ΔR, Δp_T
Dijet kinematics	m_{jj}, $\Delta\eta_{jj}$, $\Delta\theta_{jj}$, $\Delta\phi_{jj}$
Missing energy	MET, η_{ME}, θ_{ME}, ϕ_{ME}, MEZ, MET/$p_T^{\text{otherobjects}}$
Jet–MET correlations	$\Delta\eta$, $\Delta\phi$, $\Delta\theta$ between each jet and MET
Jet flavor tagging scores	outputs from ParticleNet, ParT, and MIParT

Inputs for classification

Pre-cut

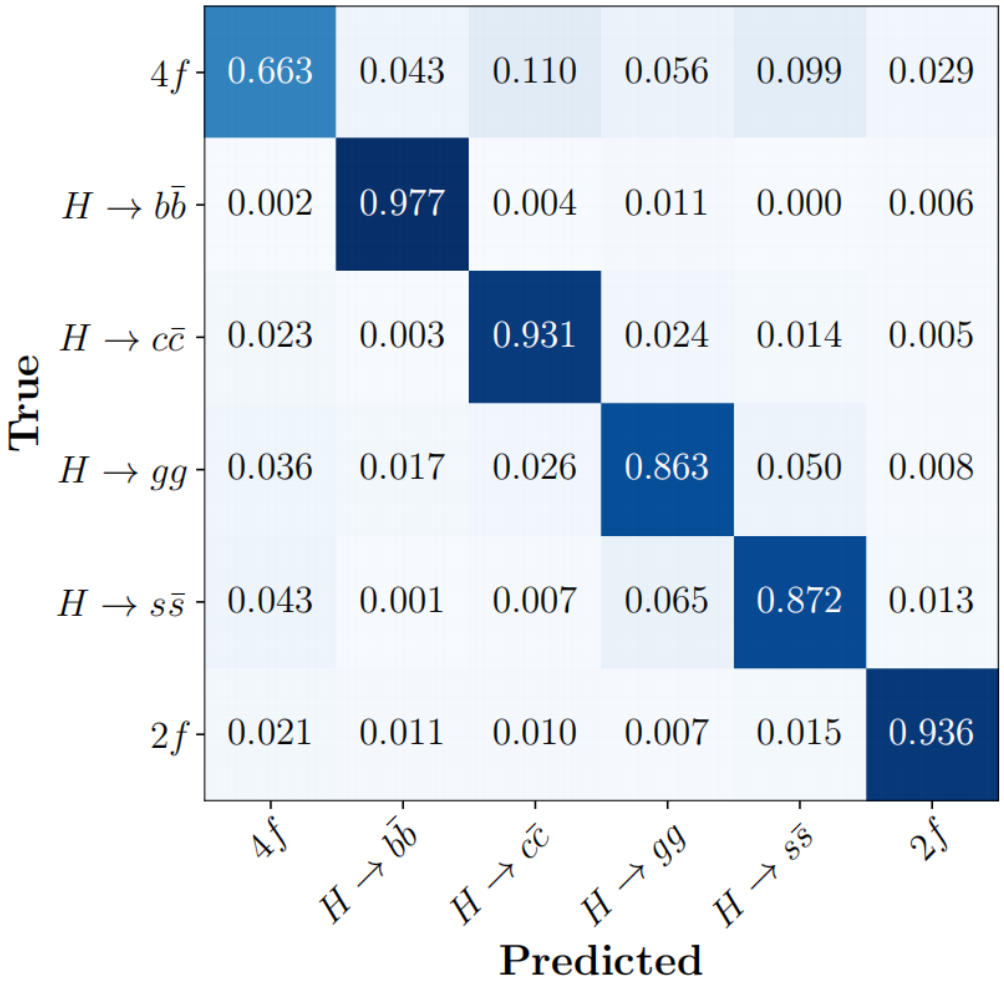
- bb/cc/gg, ss region
  - leading jet pz: (-95~95)GeV
  - leading jet pt: (15~100)GeV
  - MEZ: (-55,55)GeV
  - mass peak: (110, 140)GeV
  - leading jet b score < 0.2 (only for ss region)
  - leading jet c score < 0.2 (only for ss region)

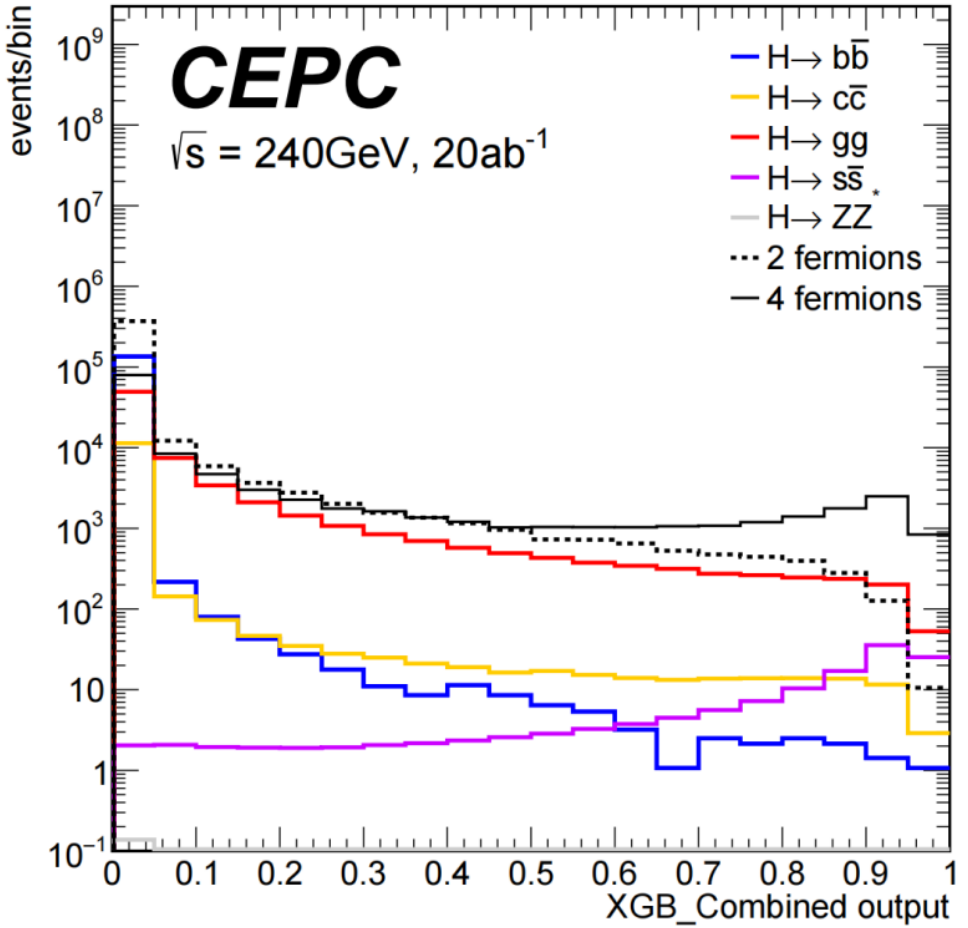




XGBoost Output

- Performance of XGBoost event classifier in the strange-enriched region





https://arxiv.org/abs/2512.21558
JHEP07(2026)079

H→bb/cc/gg Results

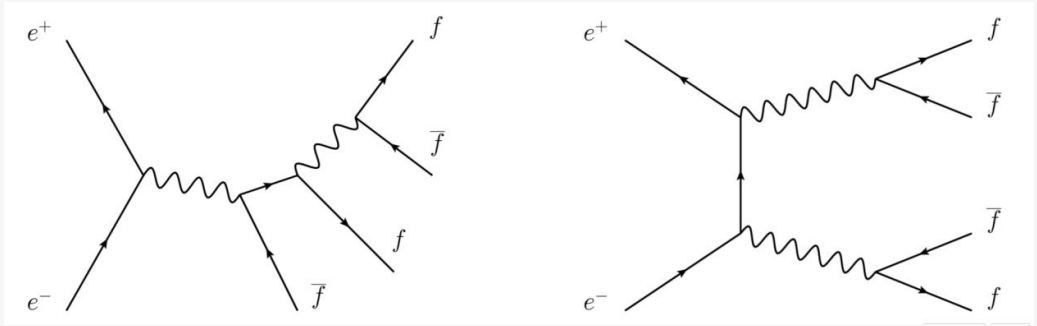
- Cut-and-Count based on XGBoost output score
- Promising performance in bb/cc/gg measurement (statistical only)

Target Channel	Channels	H->bb	H->cc	H->gg	H->ss	H->ZZ	4f	2f
H->bb	Efficiency [%]	**53.89**	2.73E-03	0.43	1.47E-03	8.39E-04	0.09	2.23E-04
	Event Yields [20/ab]	**287924.98**	0.73	347.03	0.003	0.06	7161.45	2414.79
H->cc	Efficiency [%]	0.01	**43.51**	0.36	5.14E-03	5.77E-04	0.07	8.11E-05
	Event Yields [20/ab]	61.25	**11747.07**	283.73	0.01	0.04	5824.03	878.10
H->gg	Efficiency [%]	0.16	0.39	**50.17**	1.76	4.19E-04	0.04	1.62E-04
	Event Yields [20/ab]	853.22	107.21	**39836.00**	3.52	0.030	3099.98	1756.21

H→ss Results

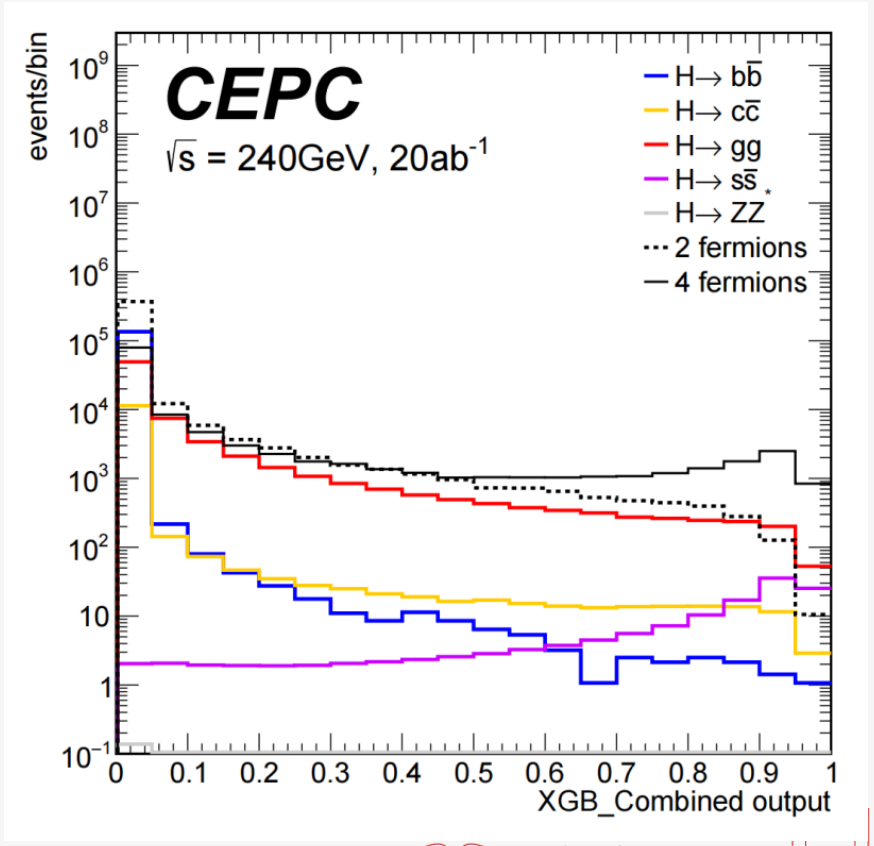
- Good classification performance among the channels
- ~**1.5σ** (statistical only) for H→ss search
- Leading bkg: 4f

Leading background 4f process



Channels	H->bb	H->cc	H->gg	**H->ss**	H->ZZ	4f	2f
Efficiency [%]	6.00E-04	0.07	0.44	**45.99**	0.00	0.04	8.00E-04
Event Yields [20/ab]	3.21	20.05	346.85	**91.97**	0.00	**3288.52**	211.25

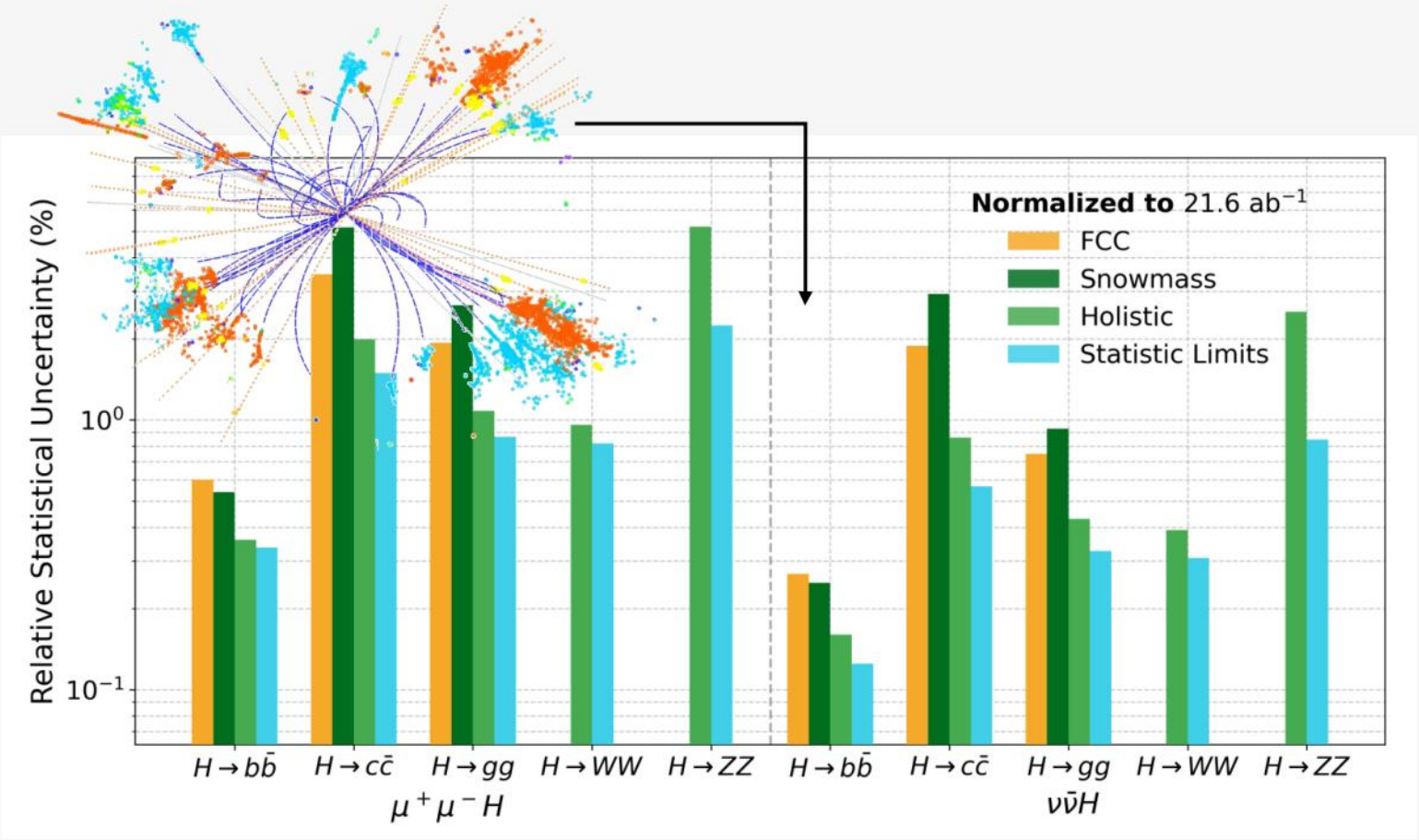
Channel	CEPC	FCC-ee	This work	Imp. vs CEPC
$Z \to \nu\bar{\nu},\ H \to b\bar{b}$	0.20%	0.28%	0.17%	15%
$Z \to \nu\bar{\nu},\ H \to c\bar{c}$	1.85%	1.95%	1.06%	43%
$Z \to \nu\bar{\nu},\ H \to gg$	0.70%	0.78%	0.50%	29%
$Z \to \nu\bar{\nu},\ H \to s\bar{s}$	—	117%	68%	—



https://arxiv.org/abs/2512.21558
JHEP07(2026)079

Even More Particle Level Information

- While indirect info from jet tagging boosts sensitivity, how about using particles directly?
- **"Holistic"** approach: event classifier from particles to events w/o jets



Channel	This work	Holistic
$Z \to \nu\bar{\nu},\ H \to b\bar{b}$	0.17%	0.14%
$Z \to \nu\bar{\nu},\ H \to c\bar{c}$	0.78%	0.72%
$Z \to \nu\bar{\nu},\ H \to gg$	0.46%	0.46%
$Z \to \nu\bar{\nu},\ H \to s\bar{s}$	23%	29%

- Only the four Higgs decay modes are considered
- Now jet scores + jets show competitive performance

10.53941/hihep.2026.100005

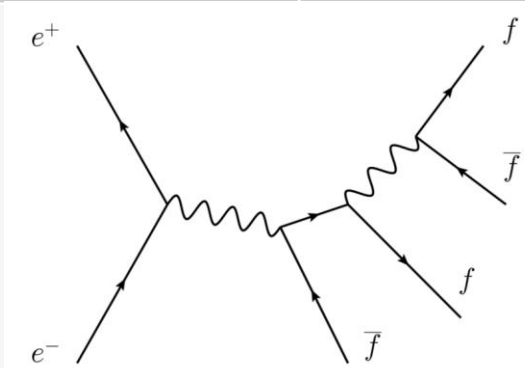
mmH channel

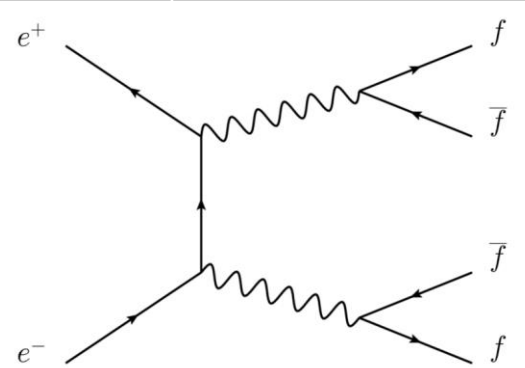
- Signal and background sample

	Channel	X-section [fb]	Simulation [k]	Expected [k]
Signal Z(mu+ mu-) H	Higgs→bb	3.91	1000	78.2
	Higgs→cc	0.197	1000	3.94
	Higgs→gg	0.58	1000	11.6
	Higgs→ss	0.001354	1000	2.7e-2
background	Z→mu+mu-, Higgs→WW	1.46	1000	29.1
	Z→mu+mu-, Higgs→ZZ	0.179	1000	3.57
	ZZ, mu+ mu- uu/cc	87.39	1000	1747.8
	ZZ, mu+ mu- dd/ss/bb	136.14	1000	2722.8
	WW, mu ν_{mu} q q	2423.43	5000	48468.6

Table 3. Standard model predictions of the decay branching ratios and total width of a 125 GeV Higgs boson [31-33]. The quoted uncertainties include contributions from both theoretical and parametric sources.

decay mode	branching ratio	relative uncertainty
$H \to b\bar{b}$	57.7%	+3.2%, −3.3%
$H \to c\bar{c}$	2.91%	+12%, −12%
$H \to \tau^+\tau^-$	6.32%	+5.7%, −5.7%
$H \to \mu^+\mu^-$	2.19×10^{-4}	+6.0%, −5.9%
$H \to WW^*$	21.5%	+4.3%, −4.2%
$H \to ZZ^*$	2.64%	+4.3%, −4.2%
$H \to \gamma\gamma$	2.28×10^{-3}	+5.0%, −4.9%
$H \to Z\gamma$	1.53×10^{-3}	+9.0%, −8.8%
$H \to gg$	8.57%	+10%, −10%
Γ_H	4.07 MeV	+4.0%, −4.0%



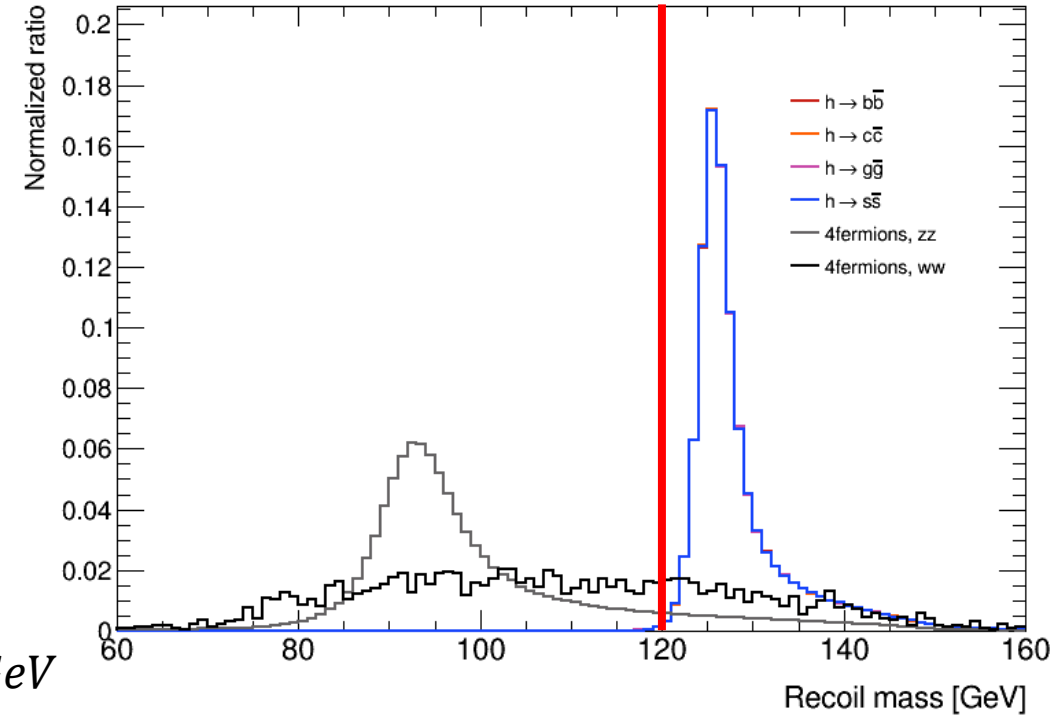


4f feynman diagrams

Fenfen An *et al* 2019 *Chinese Phys. C* **43** 043002

mmH channel

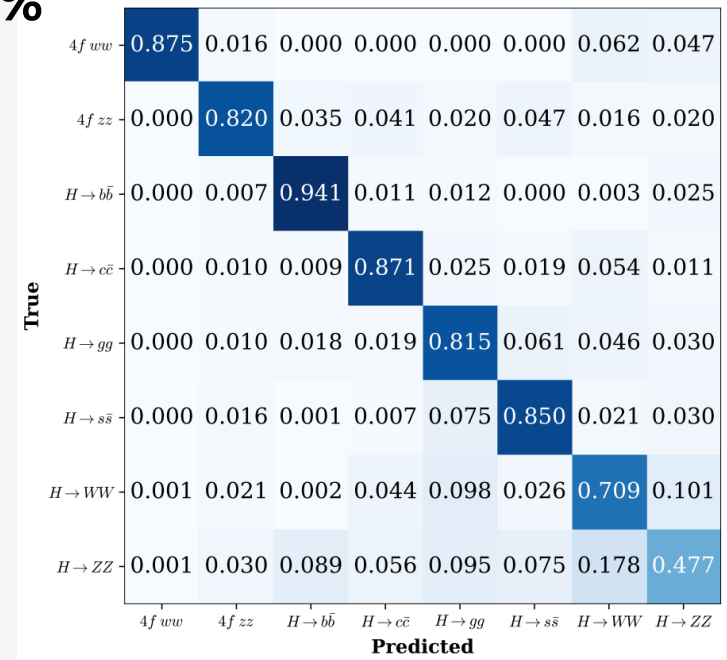
- signal region
- Pre-cut
  - Good muon conditions :
    - Muon pt > 10 GeV
    - Muon charge : +1&-1
    - M{mumu} more close to Z peak
  - Z mass range(71-111 GeV)
  - Recoil mass > 120 GeV
  - $M_{rec} = \sqrt{s + M^2_{\mu^+\mu^-} - 2\sqrt{s}\left(E_{\mu^+} + E_{\mu^-}\right)}$, $\sqrt{s} = 240\ GeV$
- The events number is normalized to 20ab^{-1}

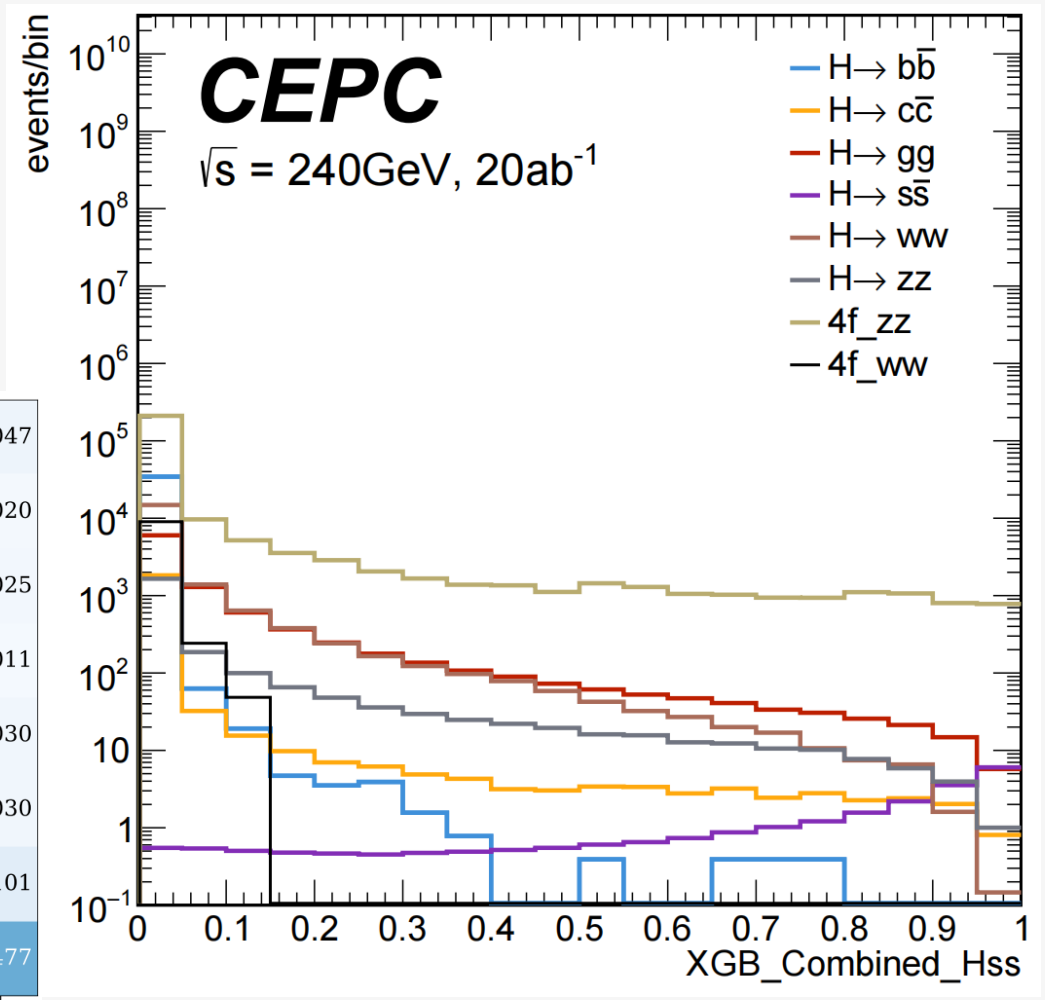


	Hbb	Hcc	Hgg	Hss	HWW	HZZ	4f_zz	4f_ww
total	78200	3940	11600	27	29200	3580	4470600	48468600
Good muon+Z mass cut	72816.0	3666.5	10818.6	25.1	27230.7	3337.2	3329043.5	41498.8
Recoil mass	72674.1	3660.0	10771.2	25.1	27090.7	3322.0	340791.6	11613.1

mmH channel Results

- Good classification performance among the channels
- **0.26σ** (statistical only) for H→ss search
- Relative uncertainty : **384%**
- Leading bkg: 4f



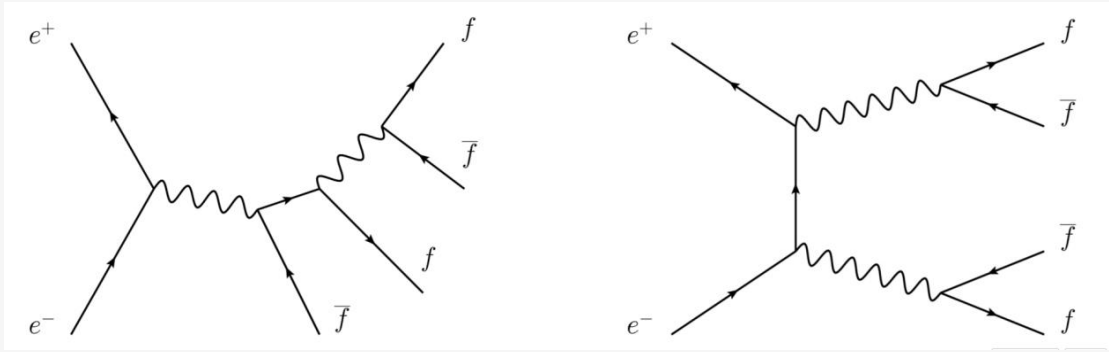


	Hbb	Hcc	Hgg	Hss	HWW	**HZZ**	**4f_zz**	**4f_ww**
Total events num	78200	3940	11600	27	29200	3580	4470600	48468600
Total eff	0	6.4e-4	0.0014	0.33	3e-5	0.001	2.6e-4	0
Events after ML	0	2.5	16.56	9.05	0.88	3.82	1179.86	0

mmH channel Results

- Good classification performance among the channels
- **0.26σ** (statistical only) for H→ss search
- Relative uncertainty : **384%**
- Leading bkg: 4f

Leading background 4fermions zz process



- Relative uncertainty : **66%** (preliminary result)
  - Assume that eeH and mmH have the same level of precision
  - Combining all the three processes (ZH channel, Z decay to $e^+e^-/\mu^+\mu^-/\nu\bar{\nu}$)

	Hbb	Hcc	Hgg	Hss	HWW	**HZZ**	**4f_zz**	**4f_ww**
Total events num	78200	3940	11600	27	29200	3580	4470600	48468600
Total eff	0	6.4e-4	0.0014	0.33	3e-5	0.001	2.6e-4	0
Events after ML	0	2.5	16.56	9.05	0.88	3.82	1179.86	0

Conclusion

- We explore the limit of Higgs couplings to quarks in a combined approach
  - Jet level tagging -> jet scores in event-level classification

- Relative uncertainty : **66%** (preliminary result, combine three channel)

Channel	CEPC	FCC-ee	This work	Imp. vs CEPC
$Z \to \nu\bar{\nu},\ H \to b\bar{b}$	0.20%	0.28%	0.17%	15%
$Z \to \nu\bar{\nu},\ H \to c\bar{c}$	1.85%	1.95%	1.06%	**43%**
$Z \to \nu\bar{\nu},\ H \to gg$	0.70%	0.78%	0.50%	29%
$Z \to \nu\bar{\nu},\ H \to s\bar{s}$	—	117%	**68%**	—

- Improve lepton channel result and work on qqH process
- Combining nnH, llH and qqH channel
- More approach
  - "**Holistic**" approach

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Thanks

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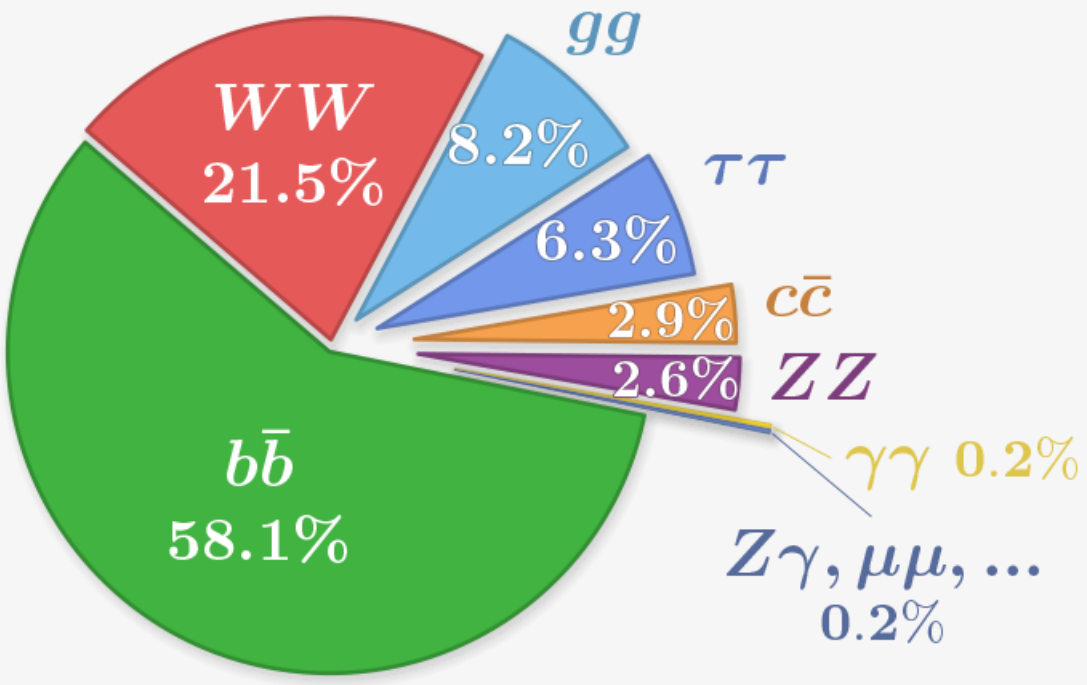
Back up

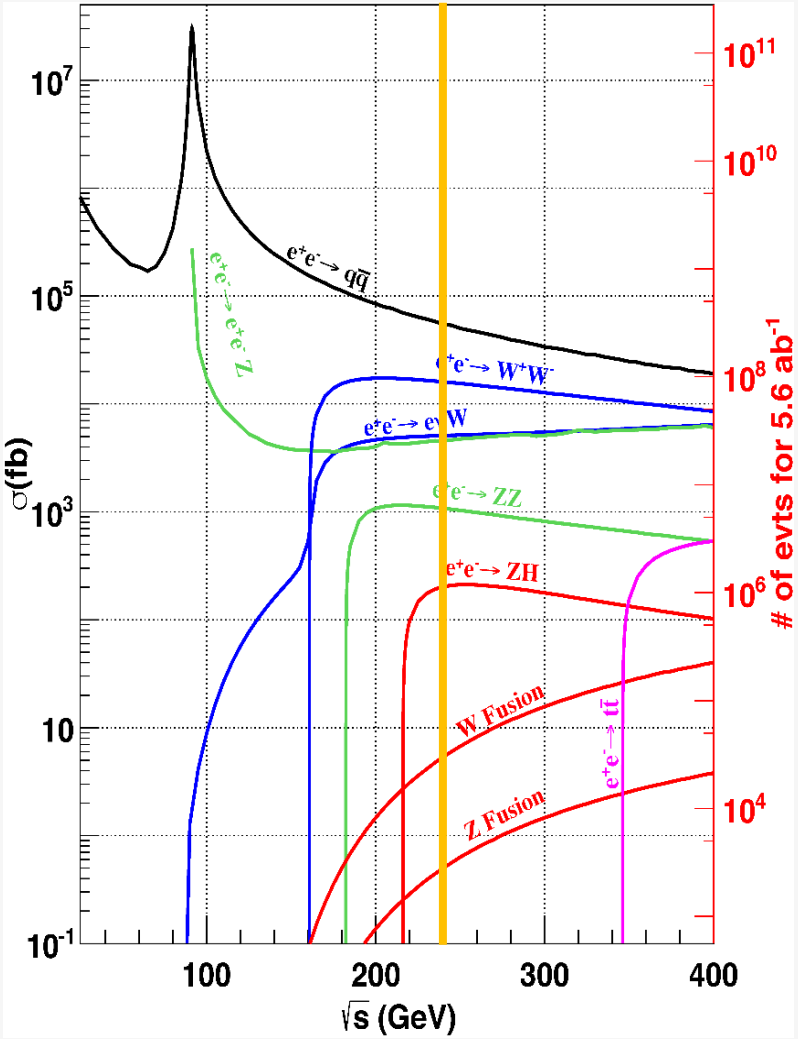
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Higgs decay modes and background processes

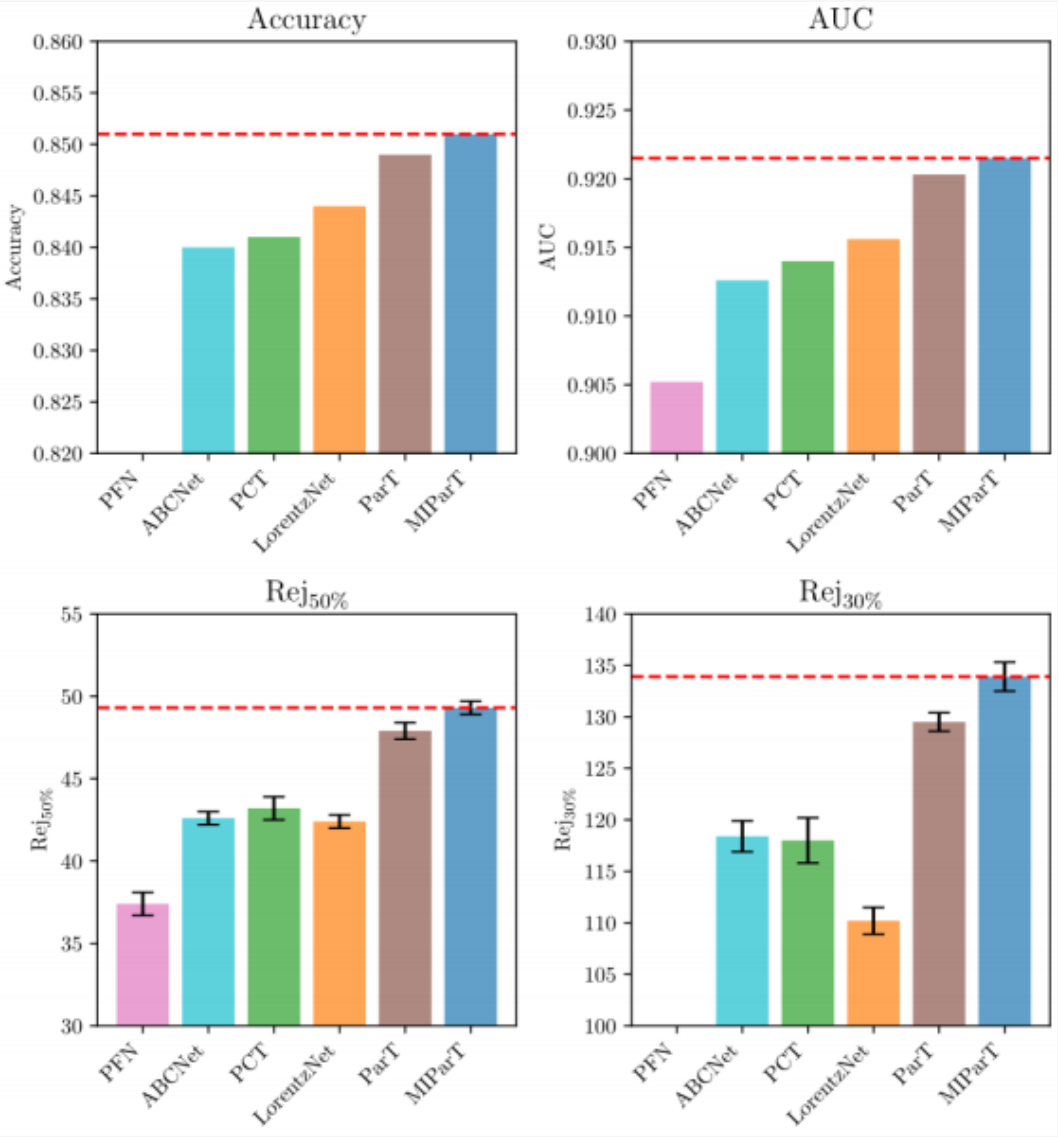
- Higgs to leptons: τ
  to vector bosons: W, Z
  to **quarks**: **t, b …**

- Most of the Higgs couplings can be determined with great precision





Performance



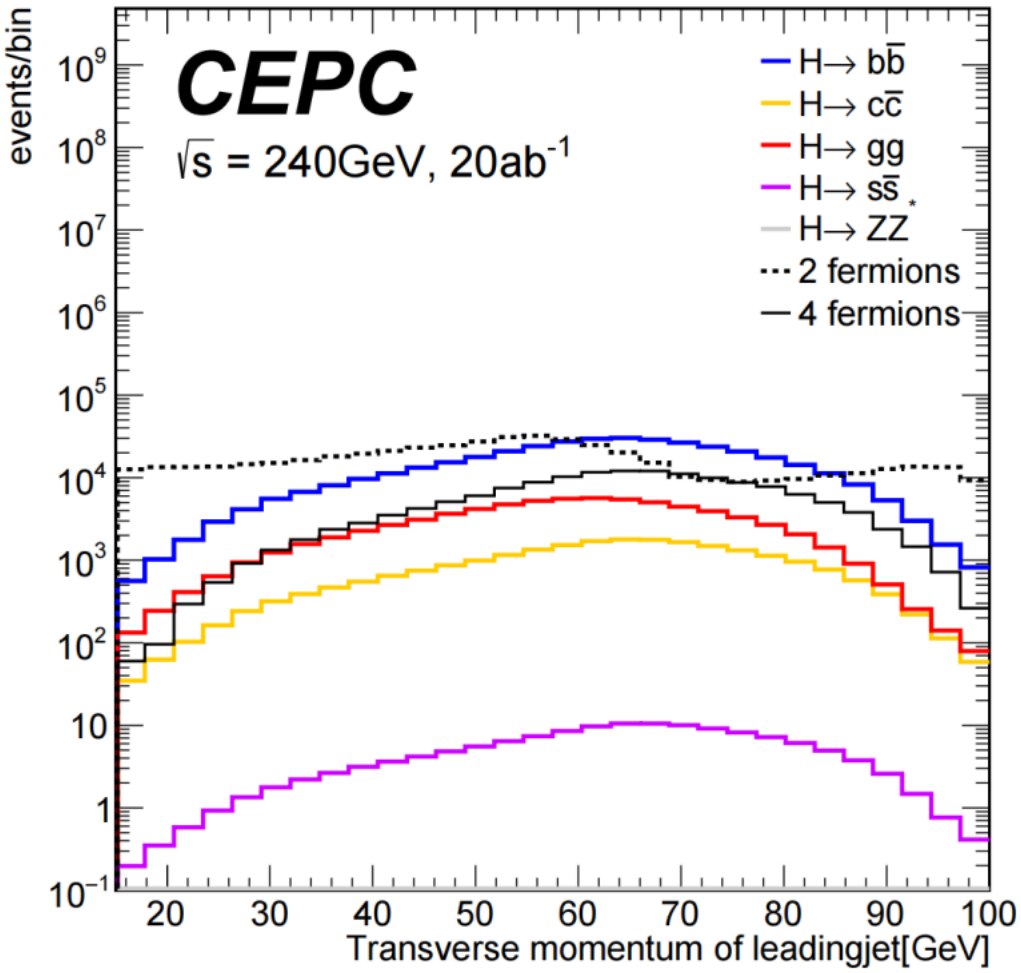
- Jet level kinematics + PID from Quark-gluon tagging dataset
- Representation suit with model structure

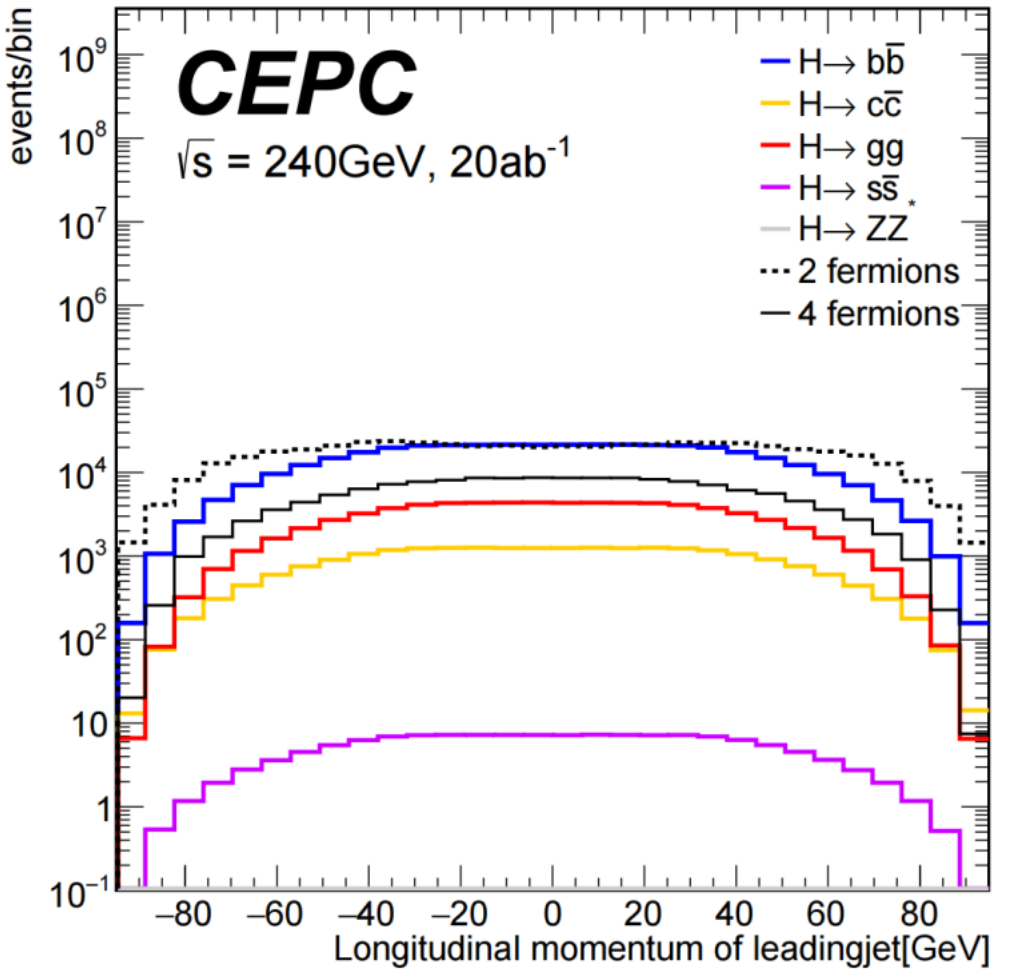
$$\text{Rej}_{50\%} = \frac{1}{\text{bkg mis–id rate}}\Big|_{\text{signal efficiency [\%]}}$$

	Accuracy	AUC	$\text{Rej}_{50\%}$
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**

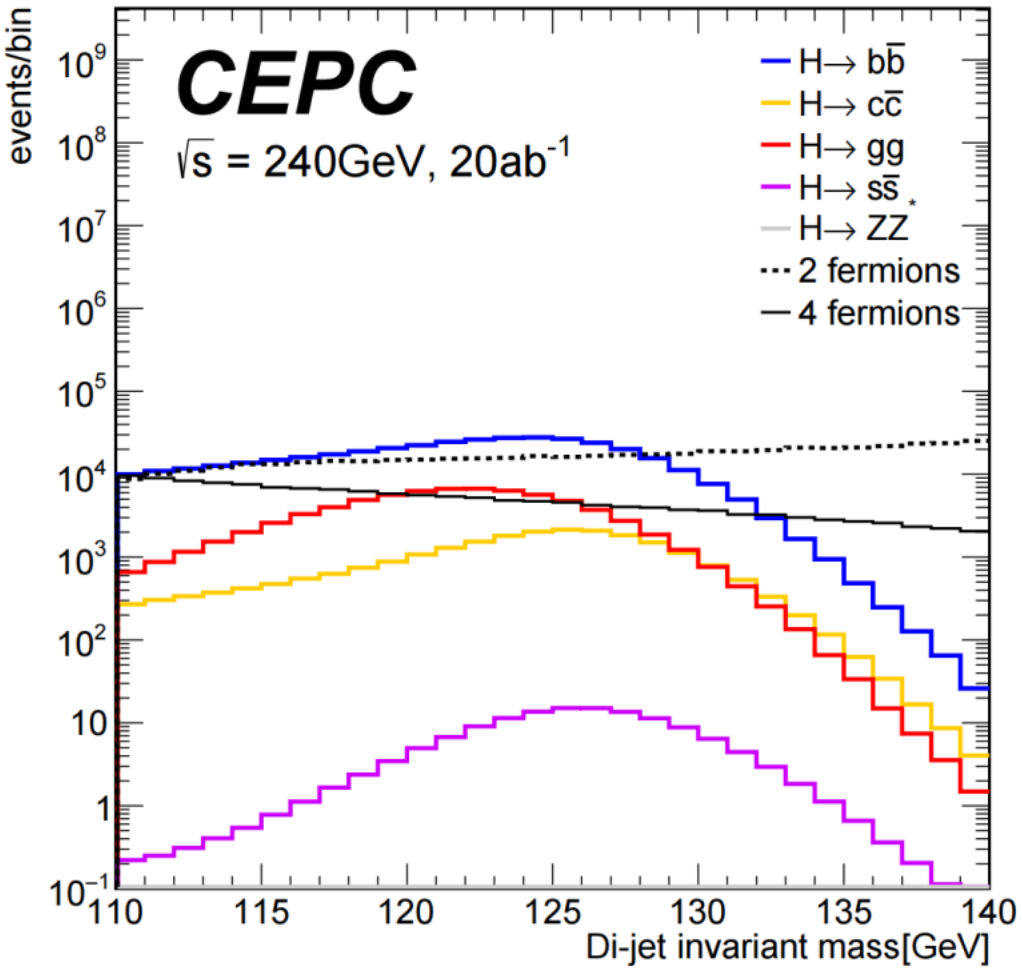
arXiv:2407.08682

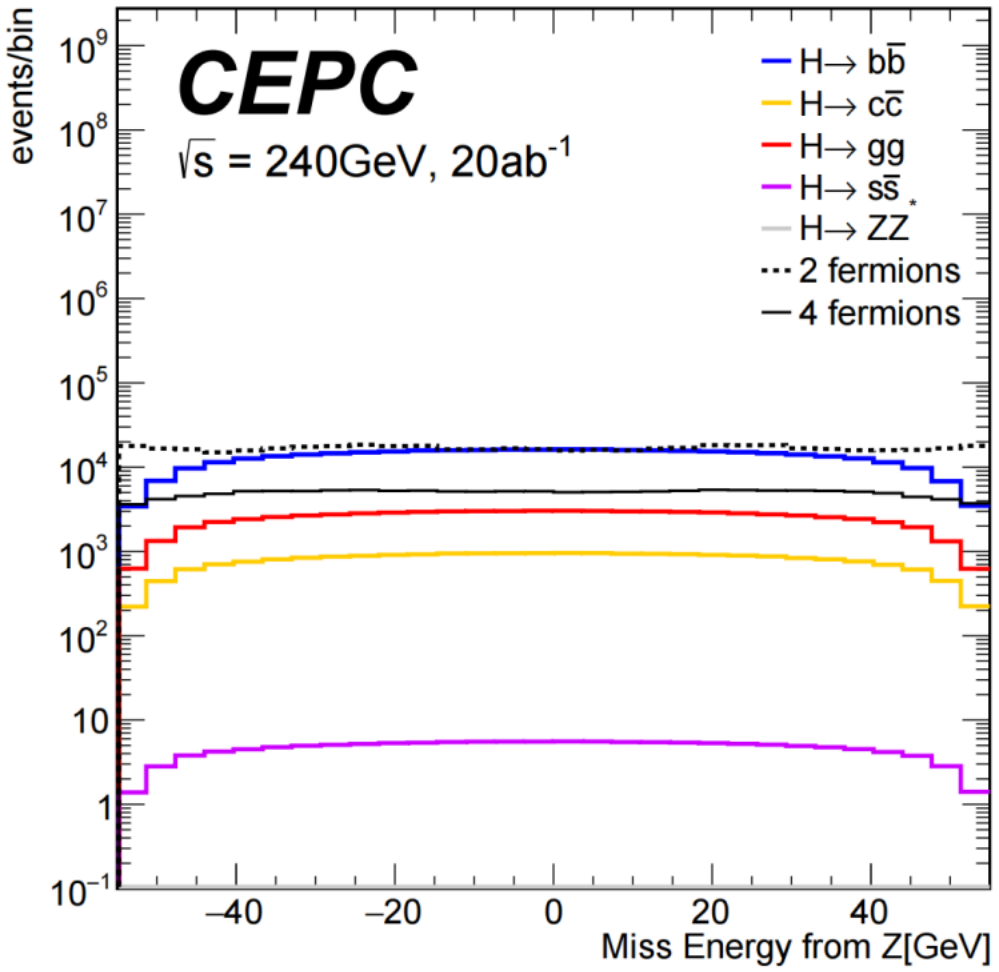
Some Characteristic Distributions for Event Classifier





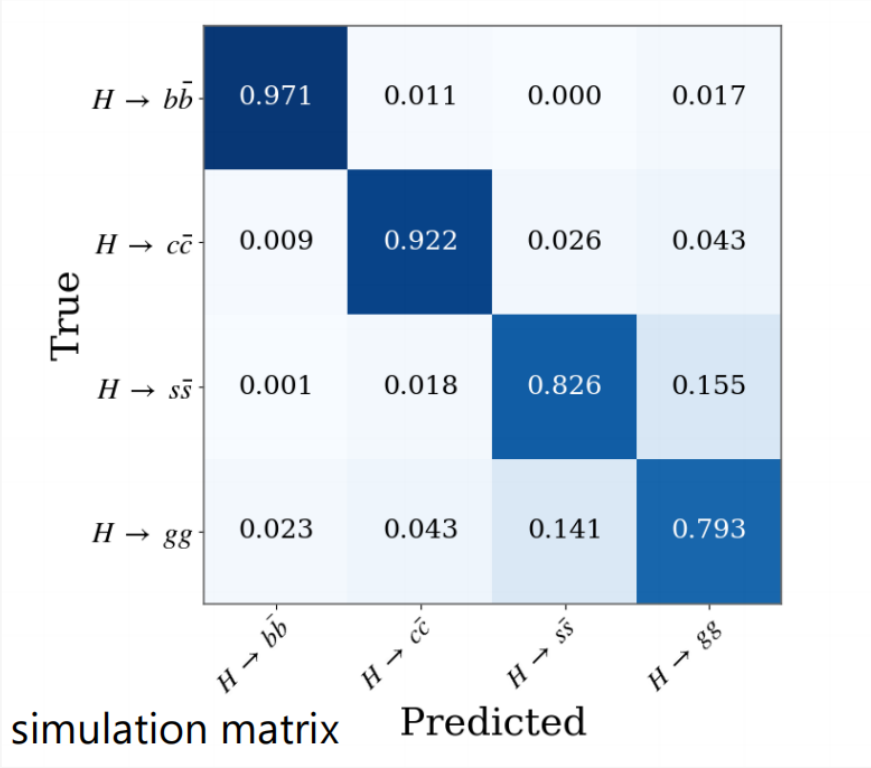
Some Characteristic Distributions for Event Classifier



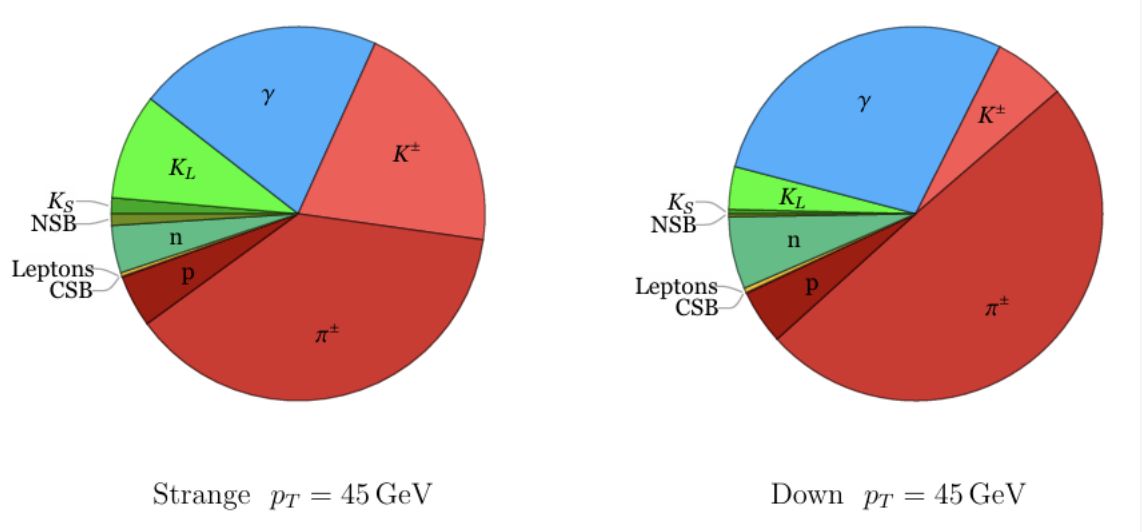


From Pheno to Realistic

- Various uncertainties are considered
  - **PID** plays a leading role in tagging s and light jets -> signal loss considering realistic PID in current CEPC design
  - Other systematic sources at ~1% or negligible



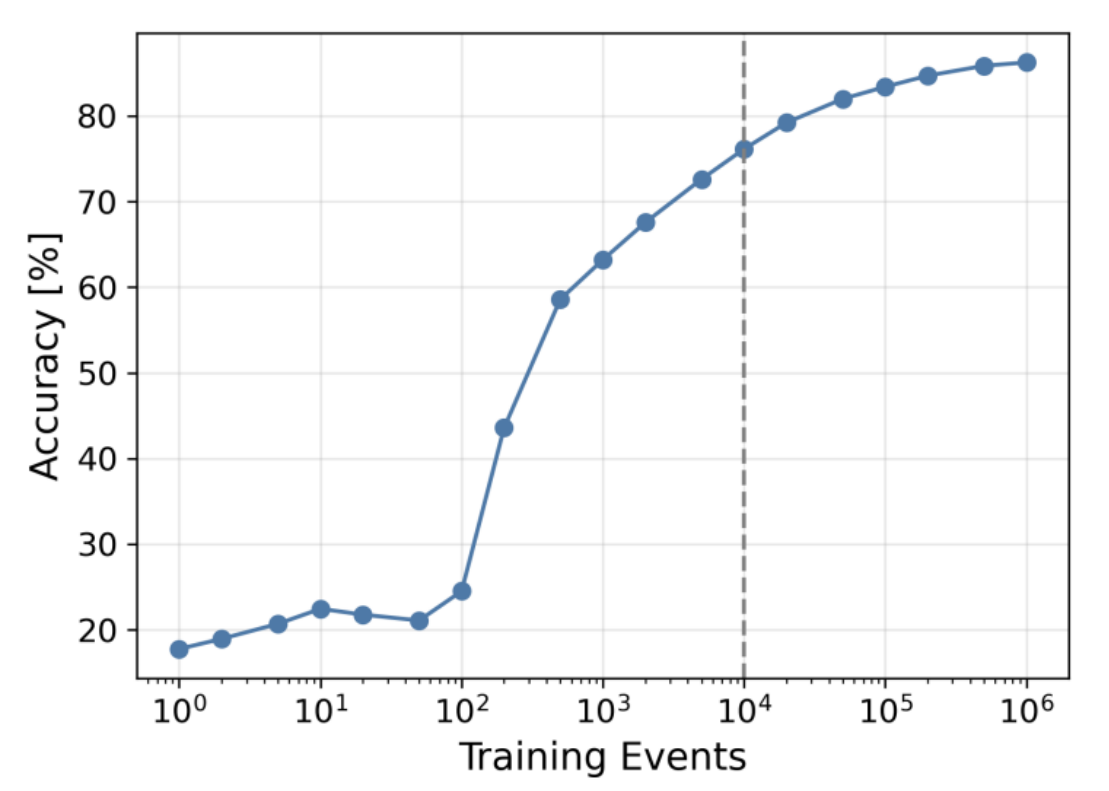
Full simulation matrix

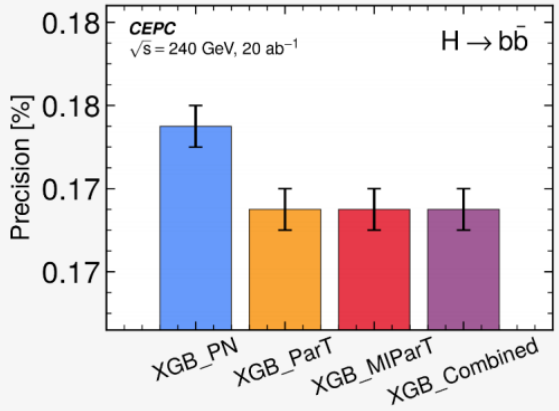


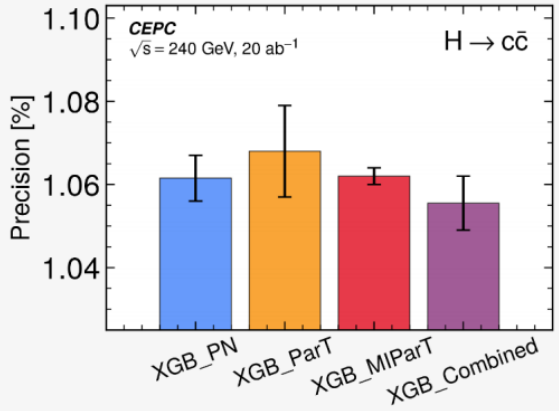
arXiv:2003.09517

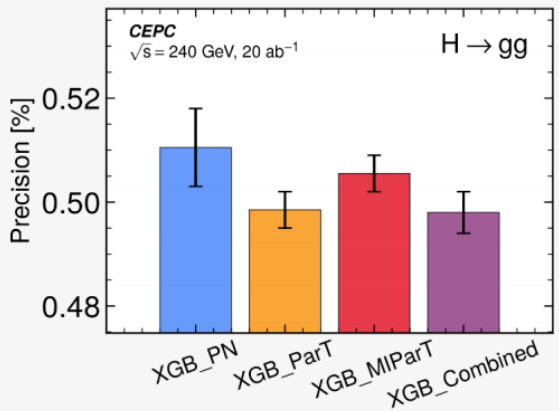
What Beyond Our Knowledge

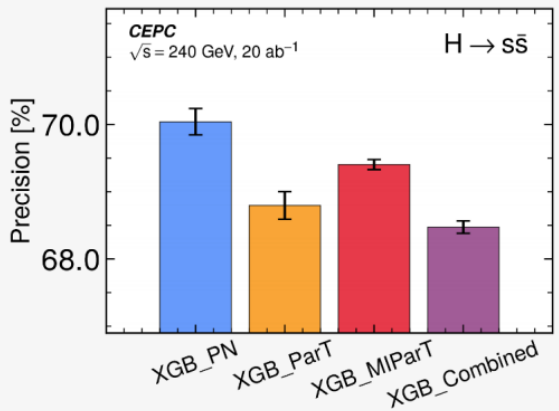
- Only **H→ss precision** improved from multiple jet experts?
  - Scaling law: will the sensitivity be further improved with > 10M evts?







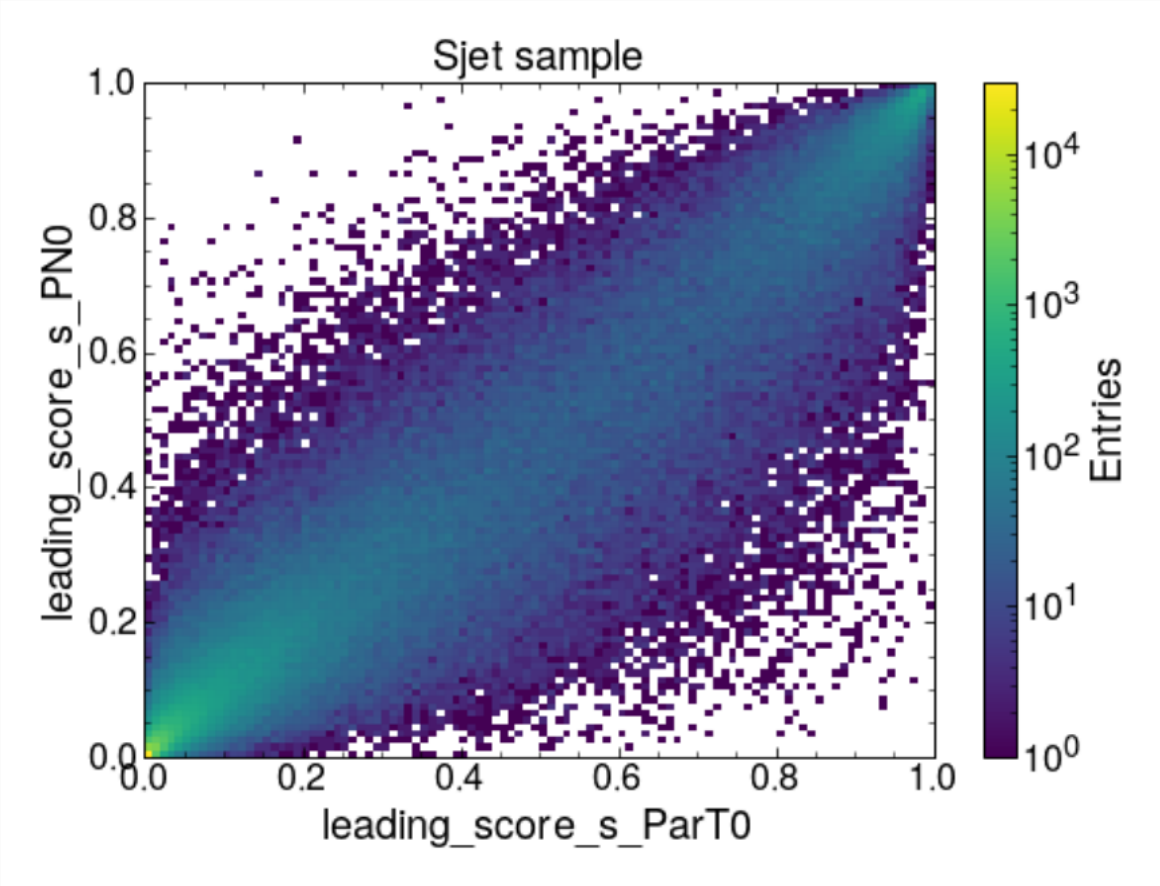


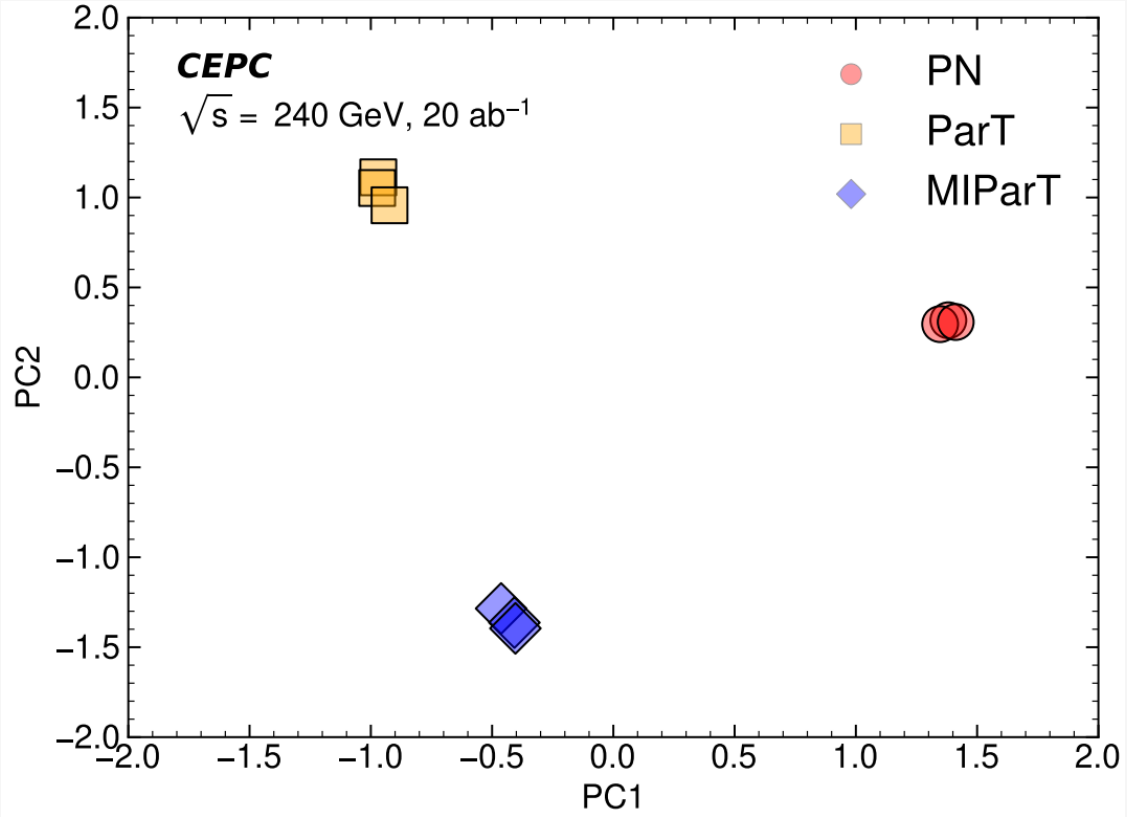


10.53941/hihep.2026.100005

Correlations of Models

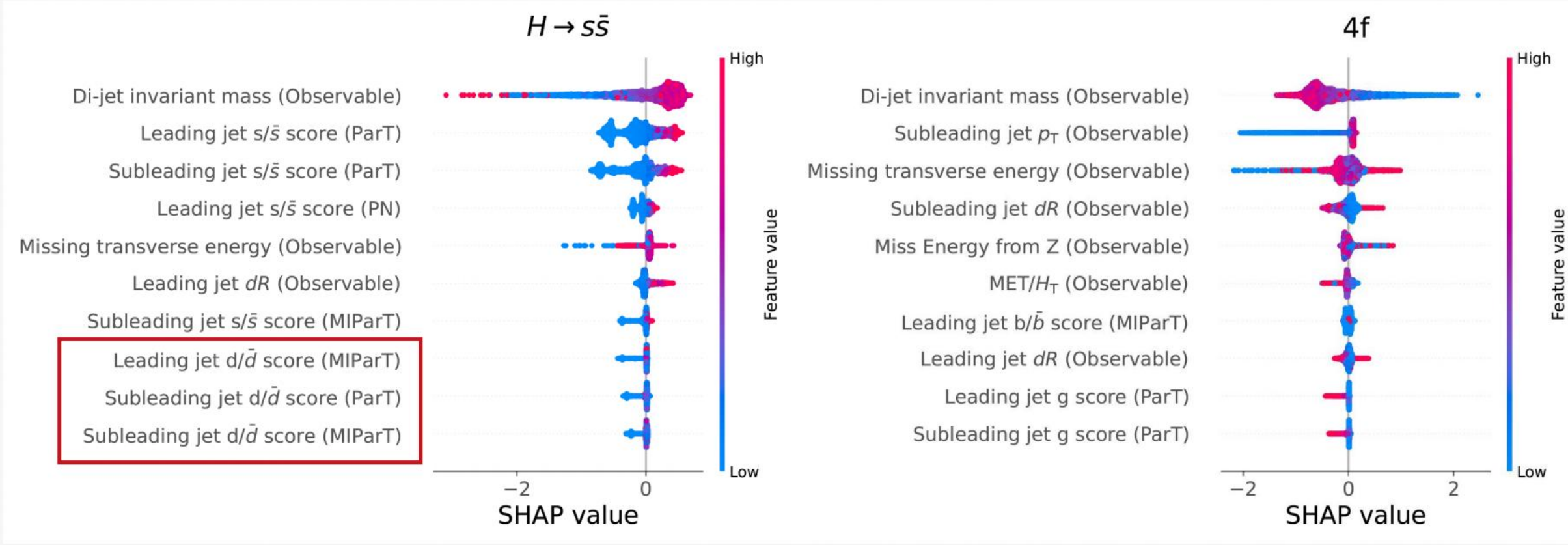
- Do Different Models Learn Different Representations?



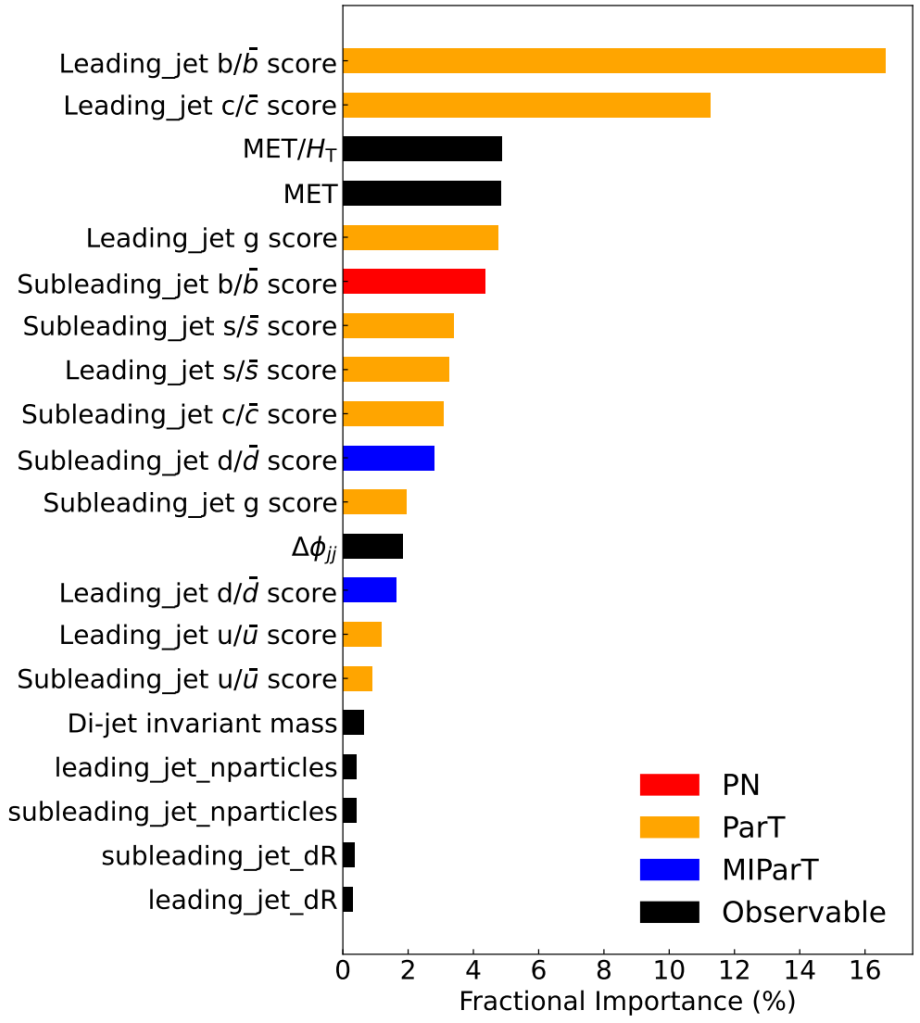


Interpretations of the Results

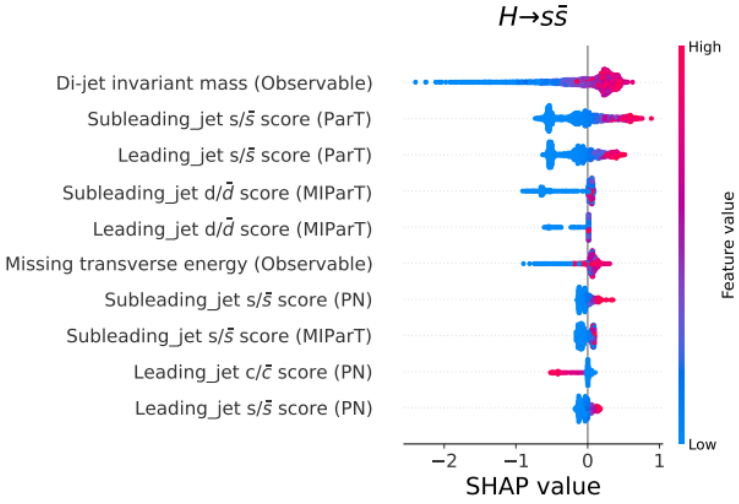
- **SHapley Additive exPlanations**: how features contribute to the results event by event
- **d-tagging** plays an important role in identifying H→ss



Physics interpretation



importance score



shape values (per class)

Feature(s)	Description
	Event- and jet-level kinematics
MET	Magnitude of the missing transverse energy
MET/H_{T}	MET to H_{T} ratio
m_{jj}	Invariant mass of the dijet system
$\Delta\phi_{jj}$	$\Delta\phi$ between the two jets
$\Delta\phi(j_2, \mathrm{MET})$	$\Delta\phi$ between subleading jet and MET
$\Delta R(j_1, j_2)$	Angular distance between the two jets
$n_{\mathrm{part}}(j_1)$, $n_{\mathrm{part}}(j_2)$	Leading/subleading jet particle multiplicities
	Jet-flavour tagging scores
ParT (leading jet): $\bar{b}, \bar{c}, \bar{s}, s, g$	ParT jet flavour scores for leading jet
ParT (subleading jet): $\bar{b}, b, \bar{c}, c, \bar{s}, s, g$	ParT jet flavour scores for subleading jet
PN (leading jet): $\bar{b}, g$	ParticleNet jet flavour scores for leading jet
PN (subleading jet): b, g	ParticleNet jet flavour scores for subleading jet
MIParT (subleading jet): c	MIParT jet flavour scores for subleading jet

Selected features