Precise Measurement of Higgs Hadronic Decay at CEPC

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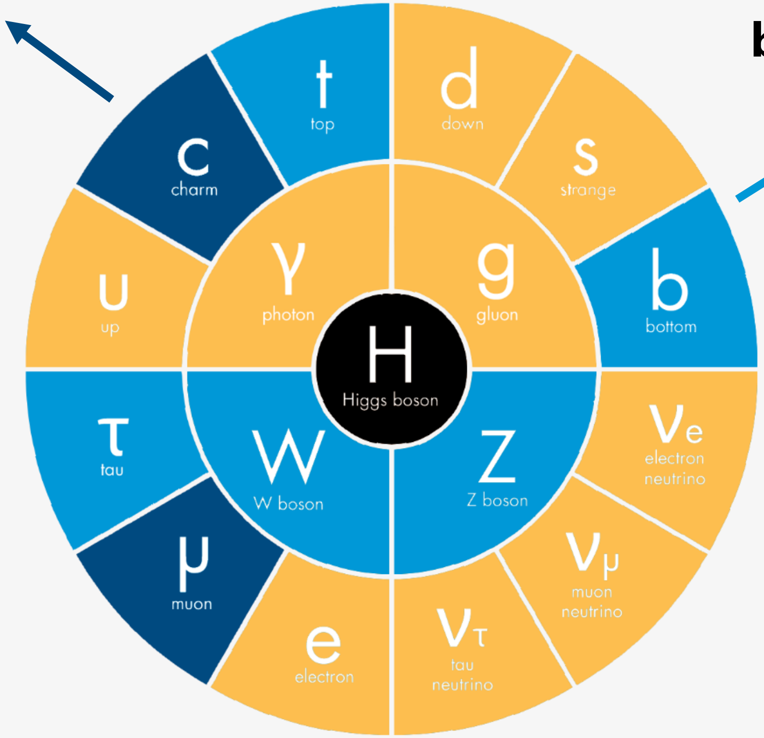
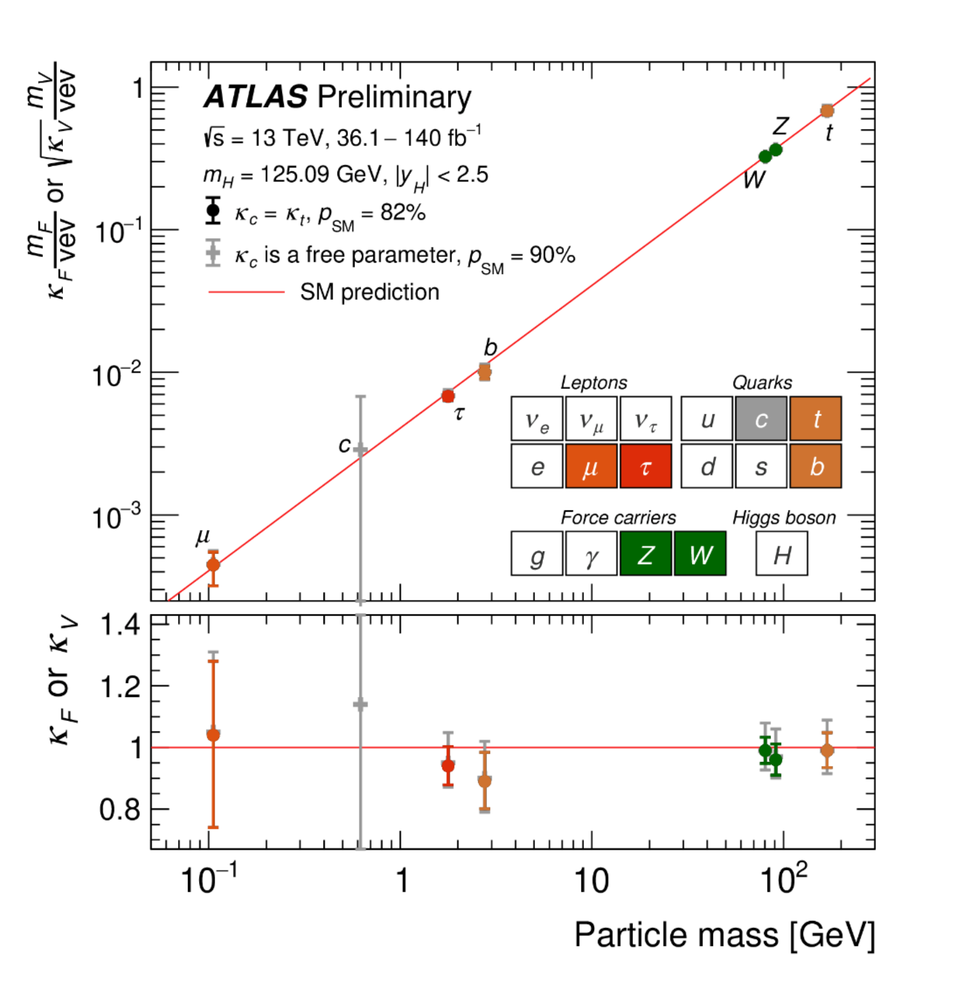
Higgs Couplings Overview

- Precision of Higgs boson couplings to SM particles reach **10%** at LHC

- **c quark/μ**: towards evidence

- **2rd** generation fermions & **vector bosons**: observed



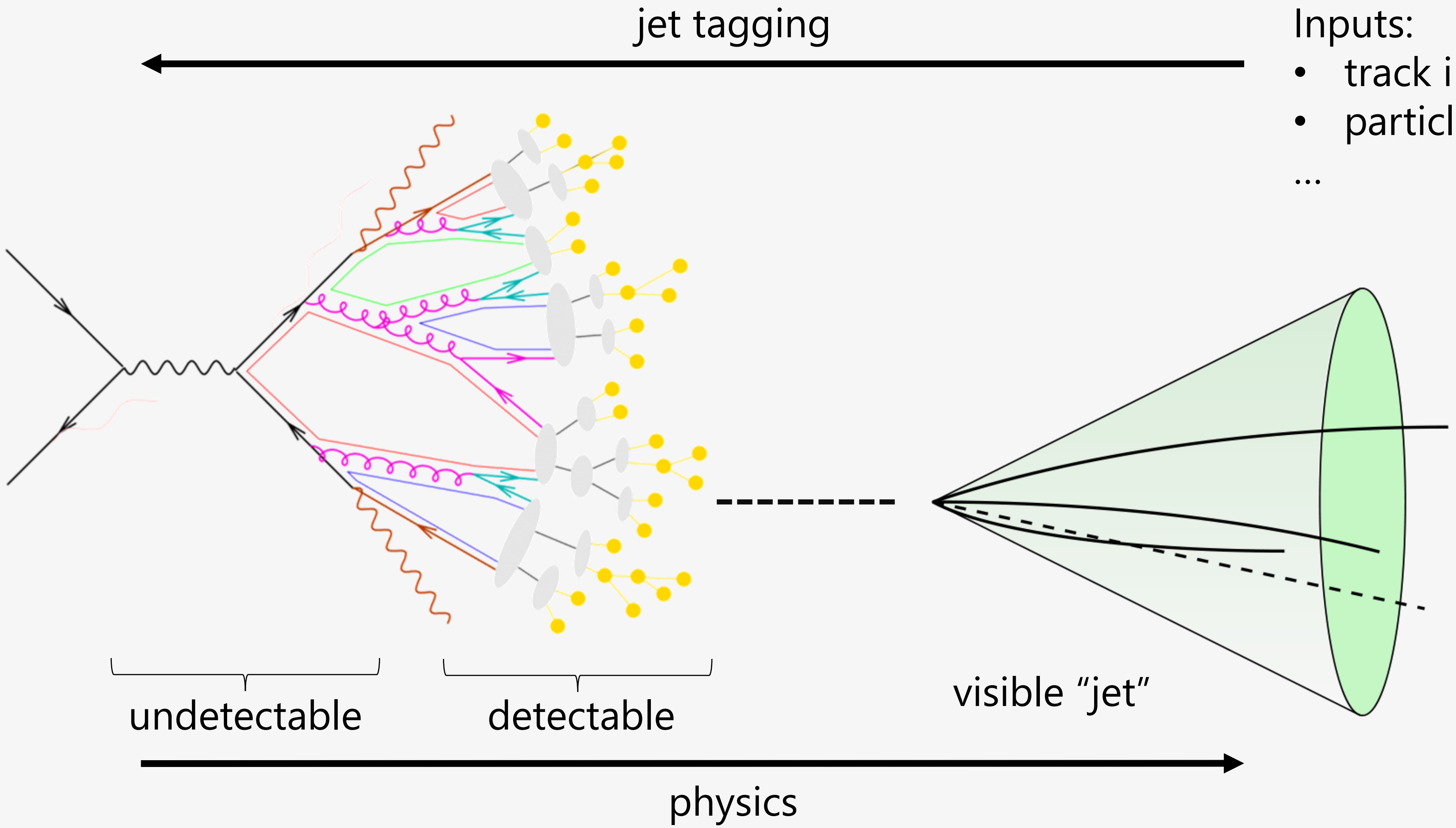


Jet Tagging

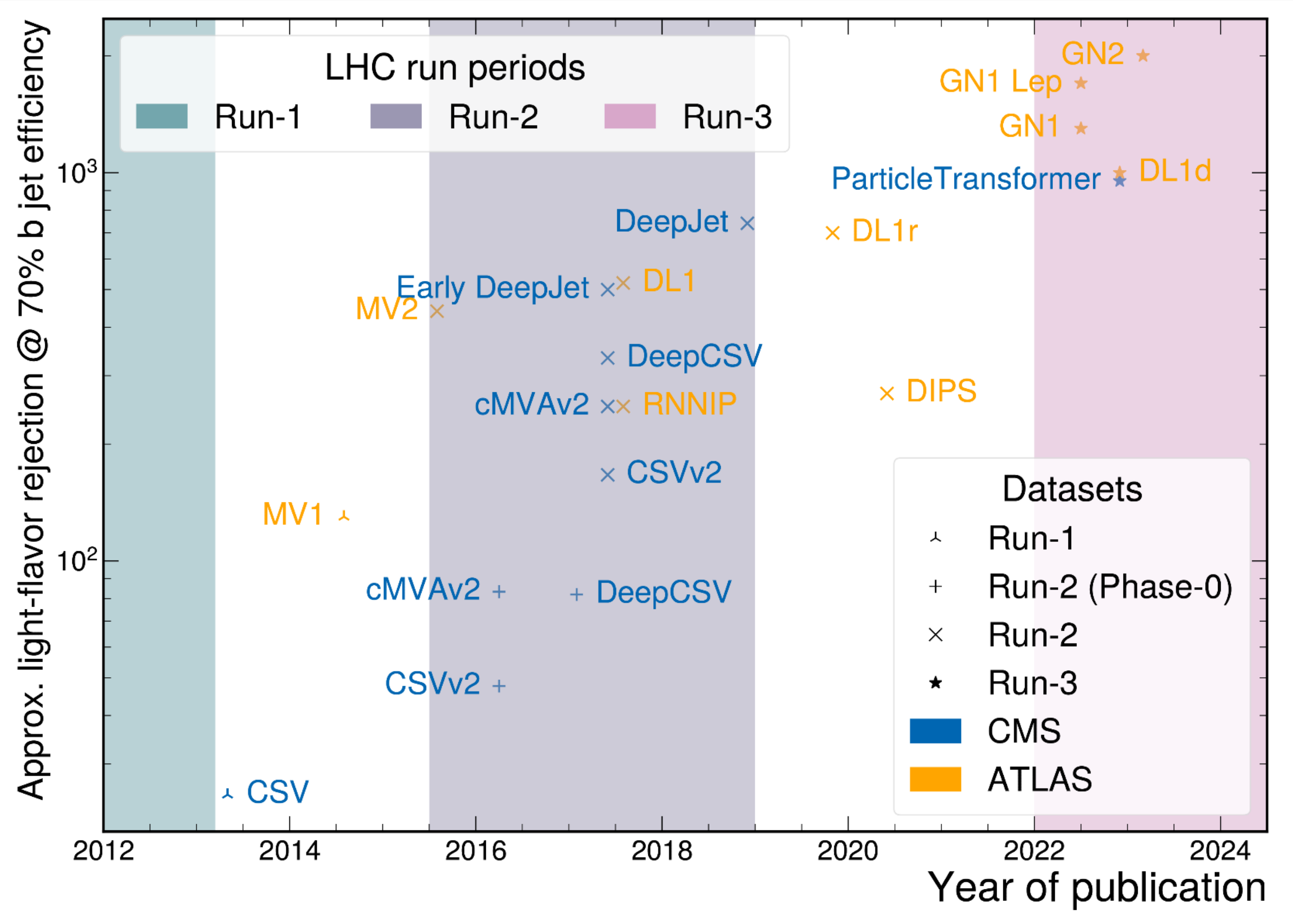
- Jet tagging is crucial to identify Higgs couplings to quarks

Inputs:
- track info
- particle level info

…



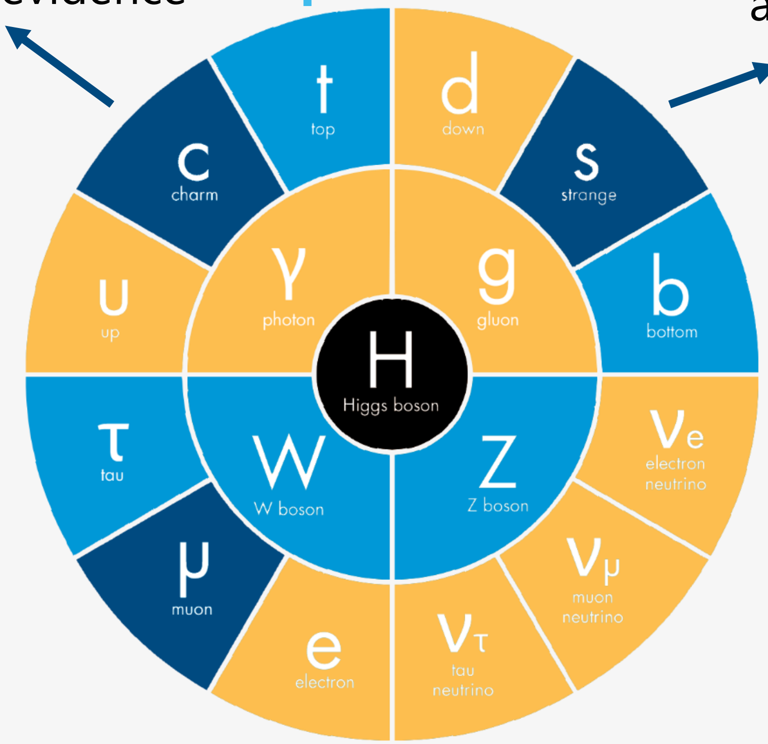
Jet Tagging based on ML

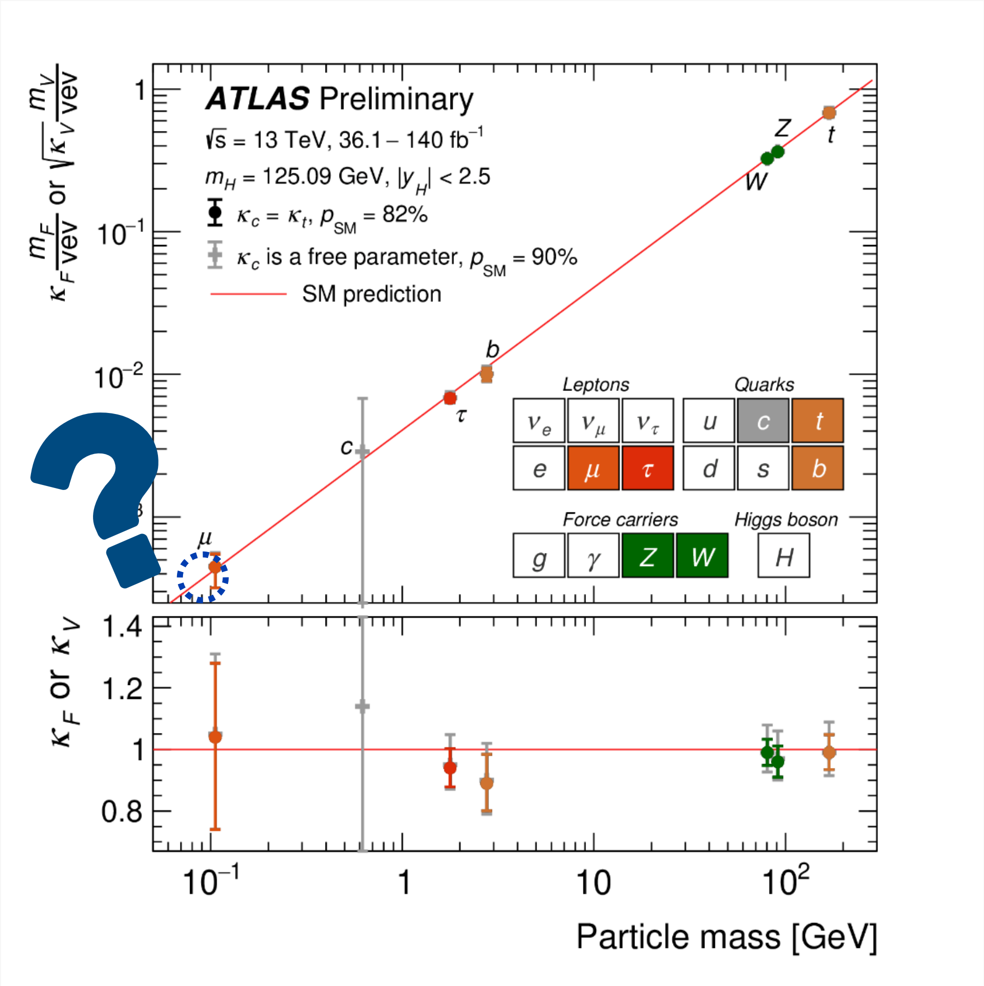


- Measurements of Higgs couplings to quarks are boosted by advanced jet tagging methods

What's Next?

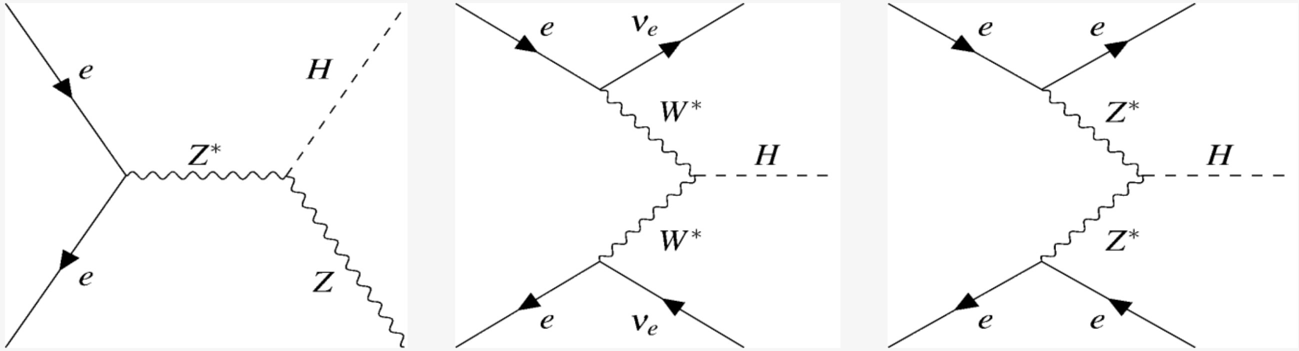
- **c quark/μ**: towards evidence
- **2rd generation fermions** & **vector bosons**: observed
- **s quark**: the next one?
- Challenge: small BR(~10^{-4}), QCD bkg at LHC

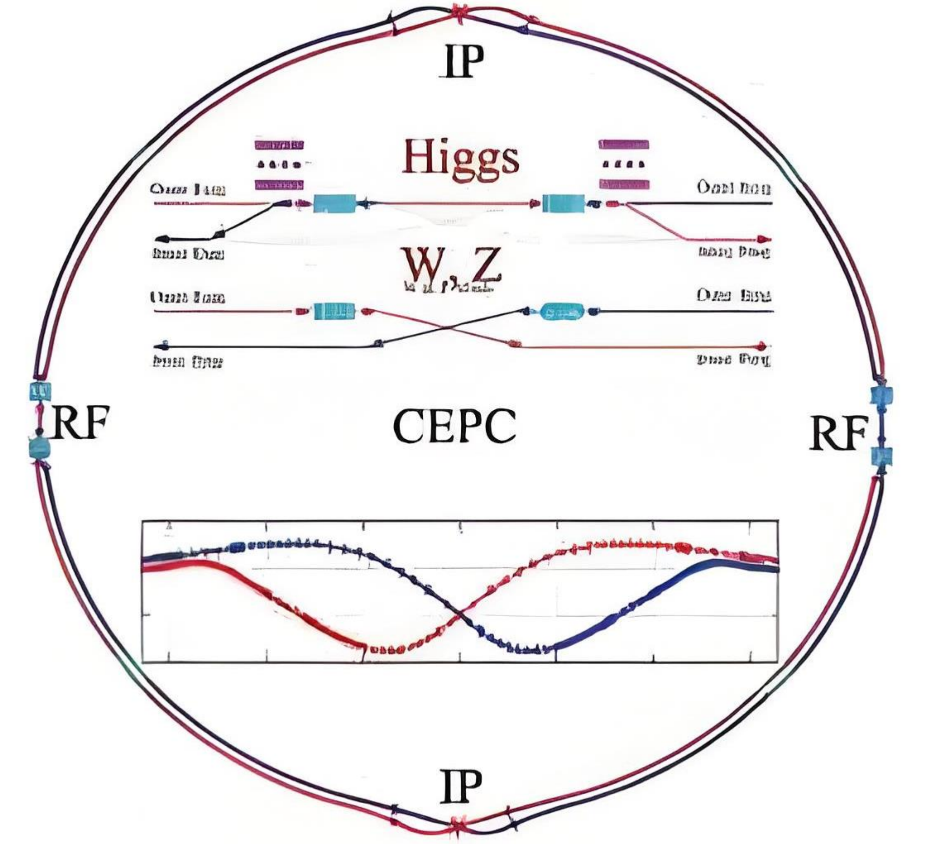




CEPC: New Opportunity for Higgs Physics

- 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



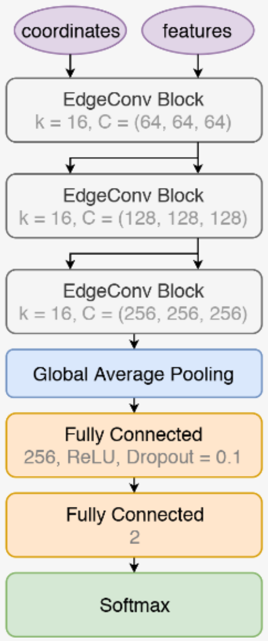


Operation mode	$\sqrt{s}$ (GeV)	SR power (MW)	$\mathcal{L}$ (10^{34} cm^{-2}s^{-1})	$\int \mathcal{L}$/year (ab^{-1}, 2 IPs)	Years	Total $\int \mathcal{L}$ (ab^{-1}, 2 IPs)	Event yields
H	240	50	8.3	2.2	10	21.6	4.3×10^6
Z	91	50	192(*)	50	2	100	4.1×10^{12}
W^+W^-	155-170	50	26.7	6.9	1	6.9	5.5×10^7
$t\bar{t}$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

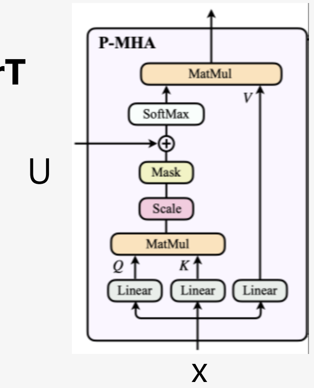
Jet Tagging at CEPC

- 3 advanced taggers
  - **ParticleNet (PN)**: Use dynamic graph convolutions to learn local & global jet substructure
  - **Particle Transformer (ParT)**: Based on attention, capturing long-range correlations among jet constituents
  - **More-Interaction Particle Transformer (MIParT)**: reduced ParT

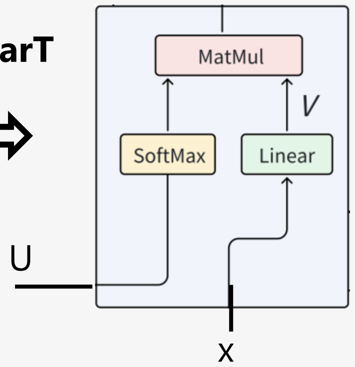
PN



ParT

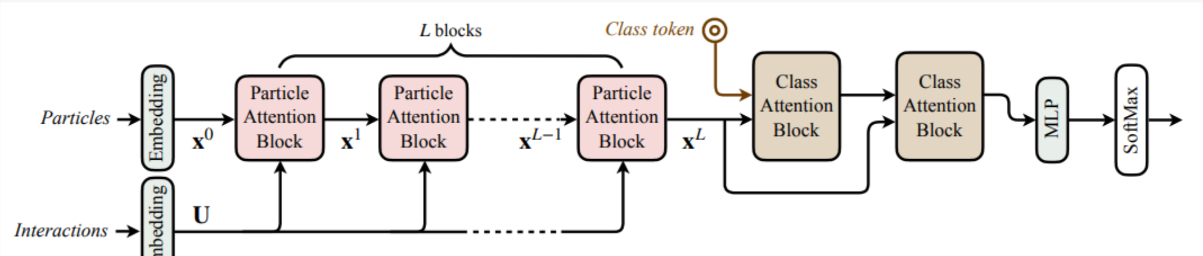


MIParT



Model	Params
ParticleNet	370k
ParT	2.14M
MIParT	720.9k

0.3x



(a) Particle Transformer

Jet Tagging at CEPC

- Possibility to tag s/jets at CEPC

True \ Predicted	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.736	0.144	0.029	0.022	0.004	0.003	0.002	0.002	0.002	0.002	0.055
$\bar{b}$	0.143	0.737	0.022	0.029	0.003	0.004	0.003	0.002	0.001	0.001	0.055
c	0.013	0.013	0.736	0.054	0.026	0.023	0.017	0.007	0.006	0.011	0.094
$\bar{c}$	0.013	0.013	0.052	0.739	0.022	0.027	0.007	0.017	0.011	0.006	0.093
s	0.004	0.003	0.017	0.016	0.522	0.087	0.019	0.065	0.045	0.034	0.188
$\bar{s}$	0.003	0.004	0.016	0.018	0.087	0.522	0.061	0.020	0.035	0.044	0.189
u	0.004	0.004	0.016	0.011	0.030	0.094	0.353	0.053	0.064	0.144	0.227
$\bar{u}$	0.004	0.004	0.011	0.016	0.091	0.031	0.051	0.358	0.144	0.063	0.228
d	0.004	0.004	0.012	0.016	0.071	0.068	0.071	0.197	0.267	0.061	0.229
$\bar{d}$	0.004	0.004	0.016	0.012	0.068	0.071	0.193	0.074	0.062	0.266	0.230
G	0.014	0.013	0.022	0.022	0.045	0.045	0.042	0.042	0.034	0.033	0.689

PN

True \ Predicted	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.754	0.137	0.027	0.019	0.004	0.003	0.002	0.002	0.002	0.002	0.048
$\bar{b}$	0.139	0.751	0.019	0.026	0.003	0.004	0.003	0.002	0.002	0.002	0.049
c	0.014	0.013	0.746	0.054	0.027	0.021	0.016	0.007	0.007	0.013	0.083
$\bar{c}$	0.013	0.013	0.050	0.751	0.022	0.026	0.007	0.017	0.013	0.007	0.082
s	0.004	0.003	0.018	0.017	0.531	0.084	0.021	0.066	0.051	0.040	0.164
$\bar{s}$	0.004	0.004	0.017	0.019	0.085	0.531	0.061	0.022	0.040	0.052	0.166
u	0.004	0.004	0.017	0.012	0.030	0.086	0.342	0.054	0.071	0.174	0.206
$\bar{u}$	0.004	0.004	0.011	0.017	0.085	0.030	0.051	0.353	0.169	0.071	0.206
d	0.004	0.004	0.013	0.017	0.067	0.065	0.072	0.178	0.308	0.066	0.207
$\bar{d}$	0.004	0.004	0.017	0.013	0.066	0.066	0.169	0.075	0.067	0.312	0.208
G	0.014	0.014	0.022	0.023	0.046	0.047	0.043	0.044	0.039	0.040	0.668

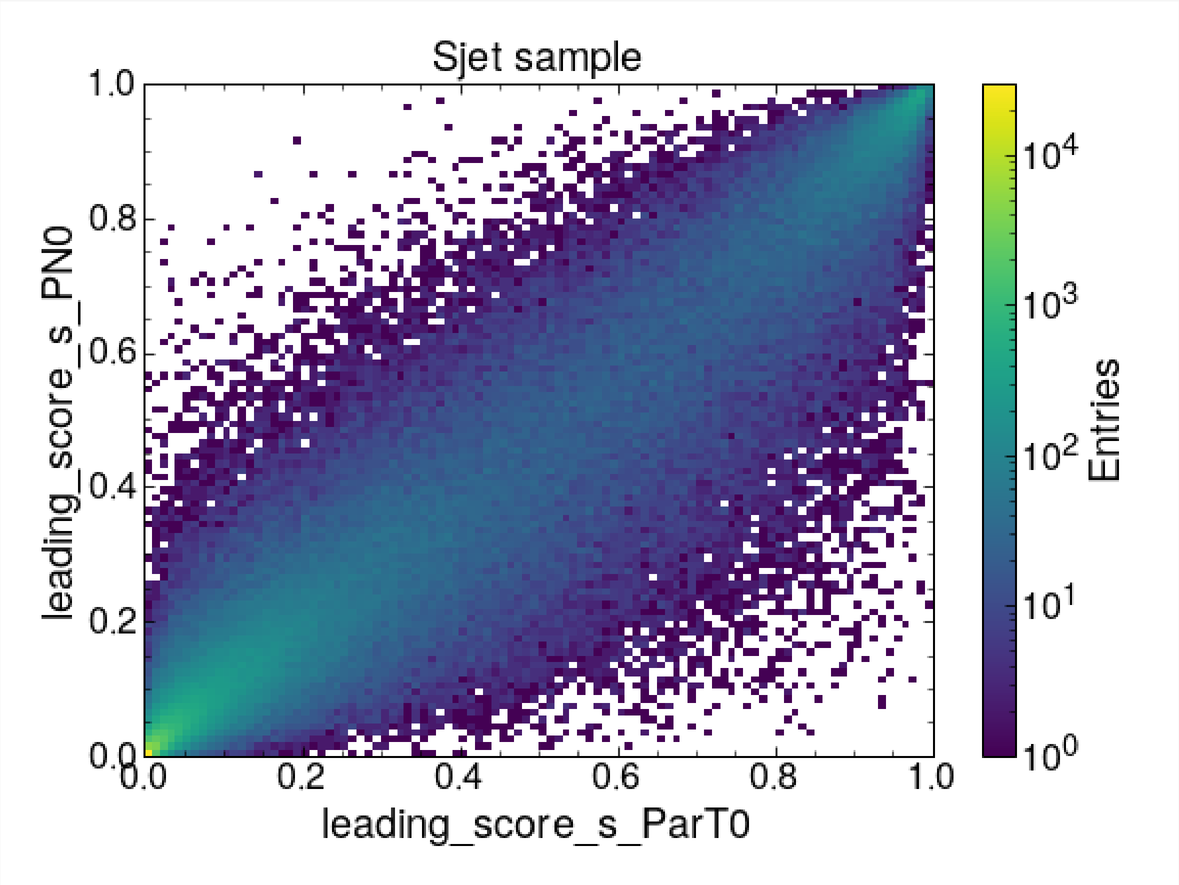
ParT

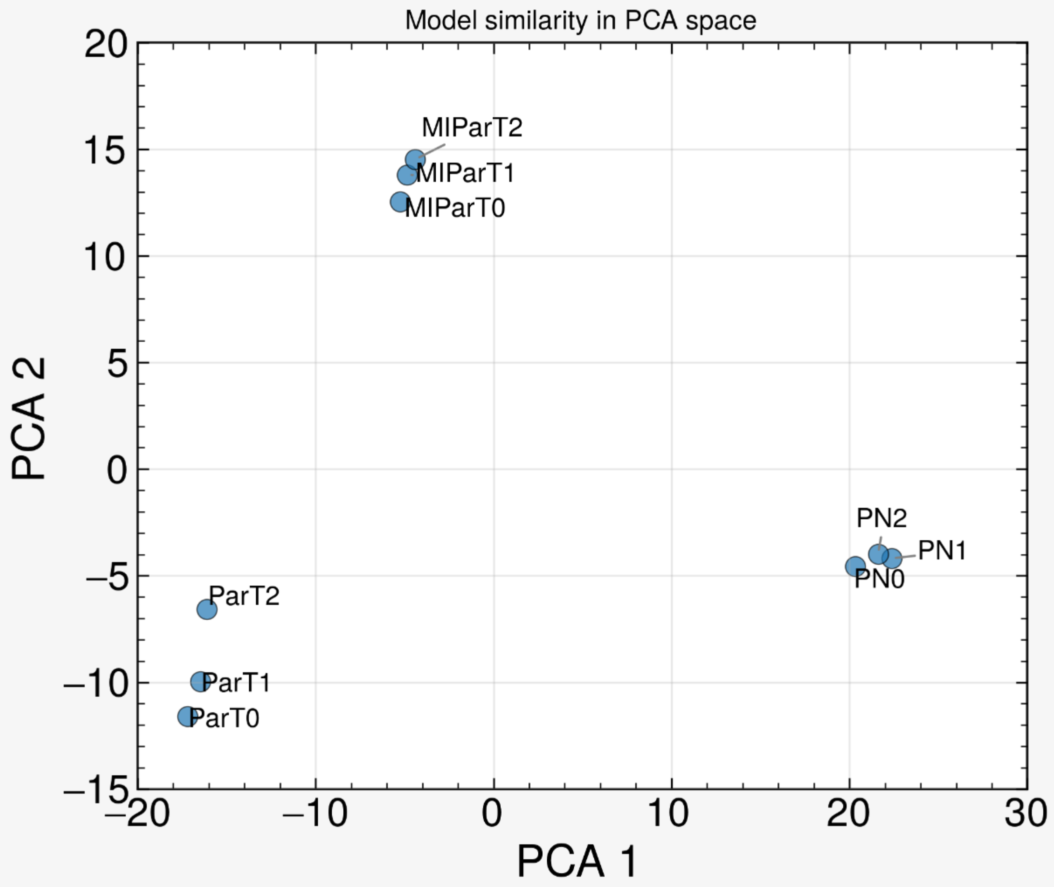
True \ Predicted	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.749	0.137	0.028	0.020	0.004	0.003	0.002	0.002	0.002	0.002	0.051
$\bar{b}$	0.141	0.744	0.021	0.027	0.003	0.004	0.003	0.002	0.002	0.002	0.051
c	0.013	0.012	0.744	0.053	0.027	0.022	0.017	0.007	0.007	0.013	0.086
$\bar{c}$	0.013	0.012	0.053	0.744	0.021	0.026	0.007	0.018	0.013	0.007	0.086
s	0.004	0.003	0.019	0.017	0.530	0.084	0.020	0.063	0.052	0.038	0.170
$\bar{s}$	0.003	0.004	0.017	0.018	0.084	0.528	0.062	0.021	0.040	0.051	0.170
u	0.004	0.004	0.017	0.012	0.030	0.088	0.335	0.056	0.068	0.180	0.207
$\bar{u}$	0.004	0.003	0.012	0.017	0.089	0.029	0.046	0.359	0.161	0.073	0.208
d	0.004	0.003	0.013	0.017	0.067	0.065	0.067	0.188	0.297	0.069	0.209
$\bar{d}$	0.003	0.004	0.017	0.013	0.068	0.067	0.166	0.077	0.065	0.310	0.210
G	0.014	0.013	0.022	0.022	0.047	0.047	0.042	0.045	0.038	0.041	0.670

MIParT

Correlations of Models

- Do different models focus on different features in a jet?





H→ss Pheno Search based on Advanced Jet Tagging

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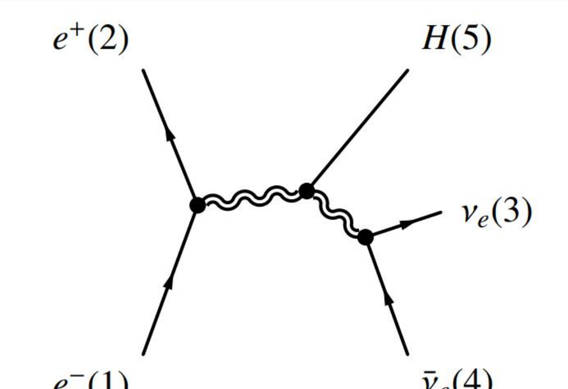
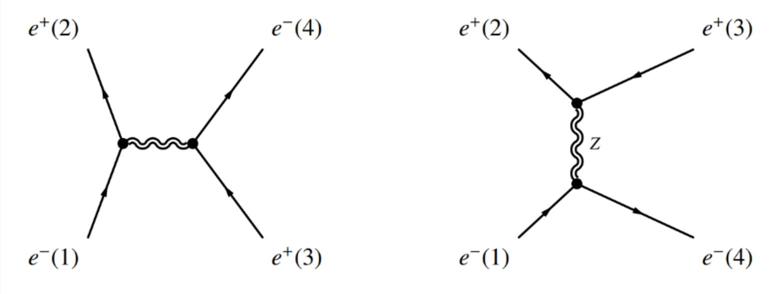
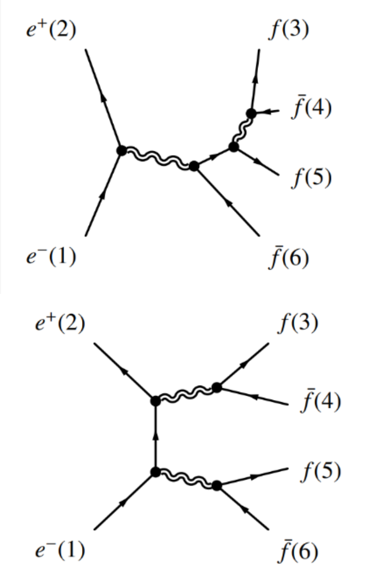
- **10M** Delphes events generated for each process
- **Signal**: ee→ZH, Z→$\nu\nu$, H→qq/gg @ 240GeV
- **Backgrounds**: Dominated by H→ZZ, 2 fermions and 4 fermions



Z($\nu\nu$)H



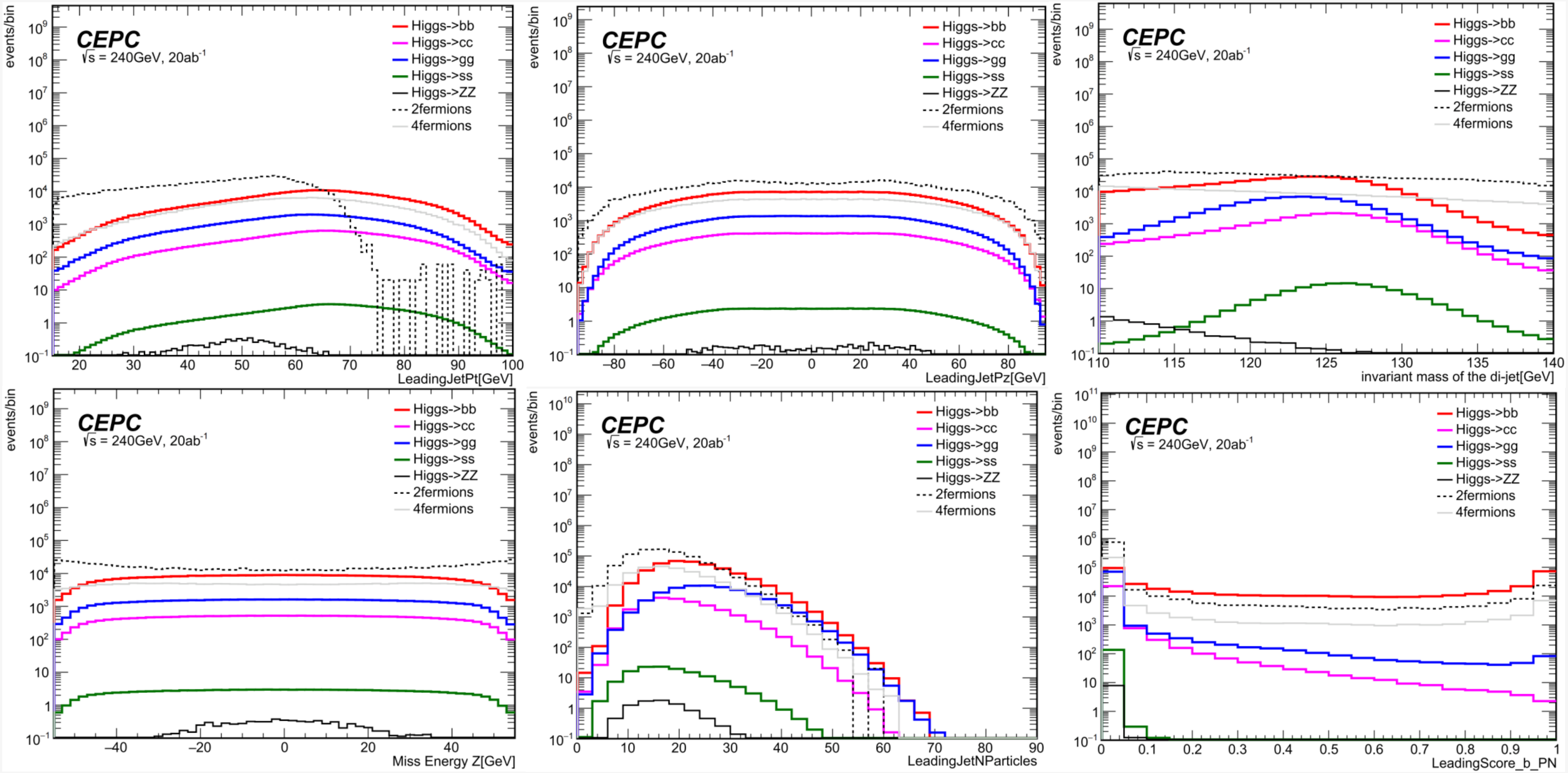
2f



4f

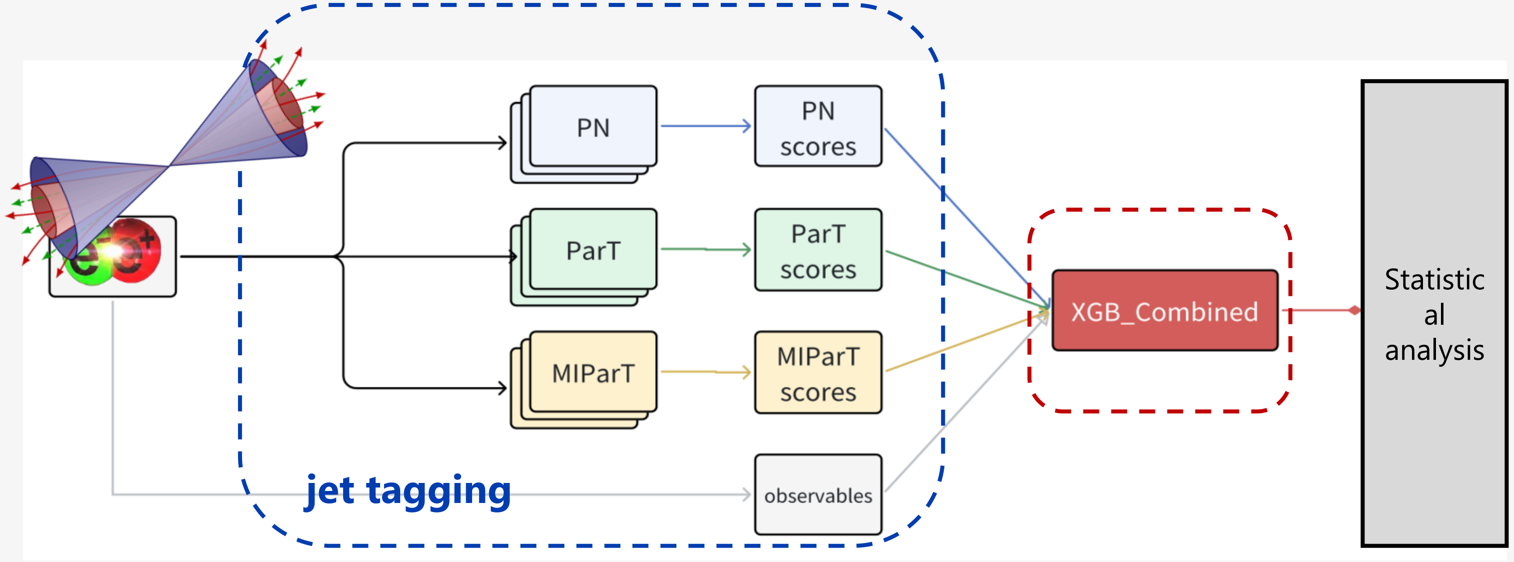
Category	Channel	Cross Section [fb]	Expected Events [M]	Simulated Events [M]
Signal	ZH, Z→νν, H->bb	26.71	0.5342	10
	ZH, Z→νν, H->cc	1.35	0.027	10
	ZH, Z→νν, H->ss	0.01	0.0002	10
	ZH, Z→νν, H->gg	3.97	0.0794	10
Background	ZH, Z→νν, H->ZZ; Z->νν, Z->qq	0.34	0.0068	10
	4f	369.71	7.3942	44
	2f	54106.86	1082.1372	6
		1213.25	24.2650	

Some Characteristic Distributions



H→ss Pheno Search based on Advanced Jet Tagging

- 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



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

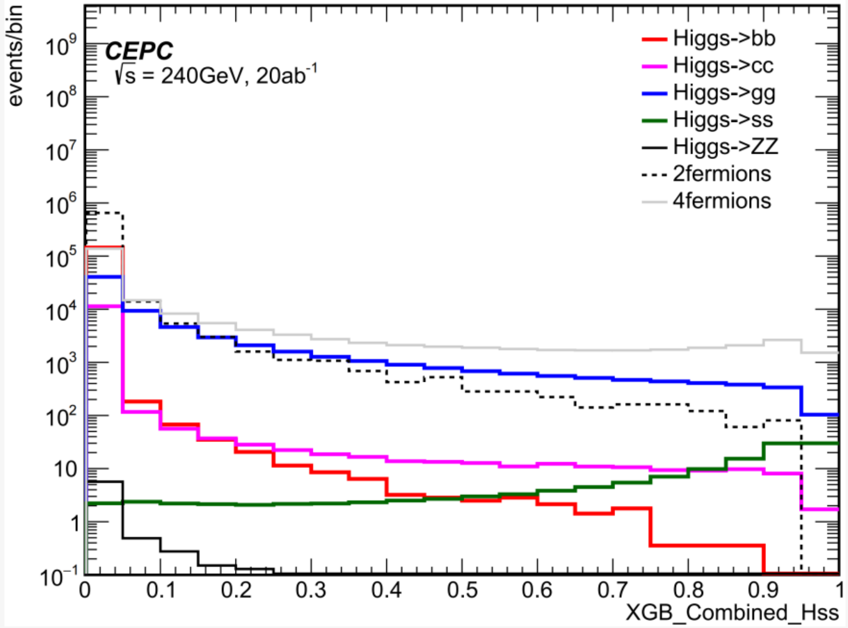
BDT inputs

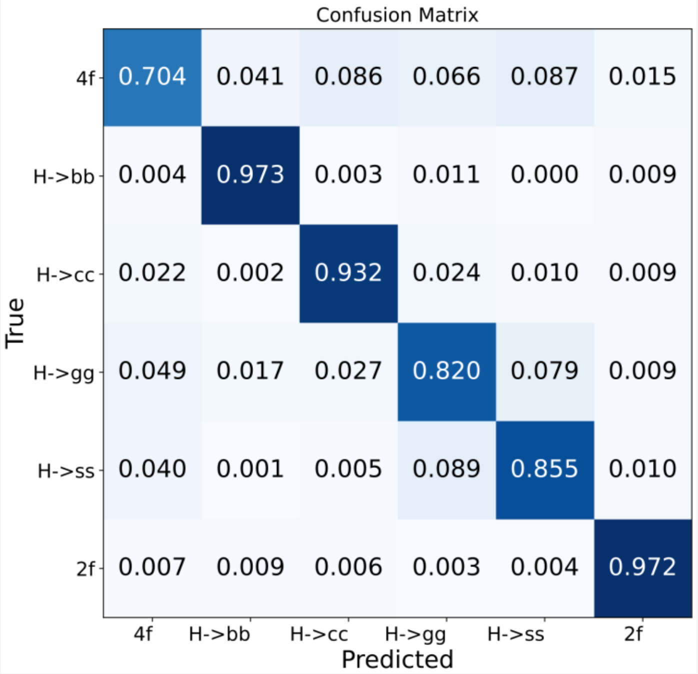
H→bb/cc/gg Results

- Promising performance in bb/cc/gg measurement (statistical only)
  - Observation of H→gg at CEPC?

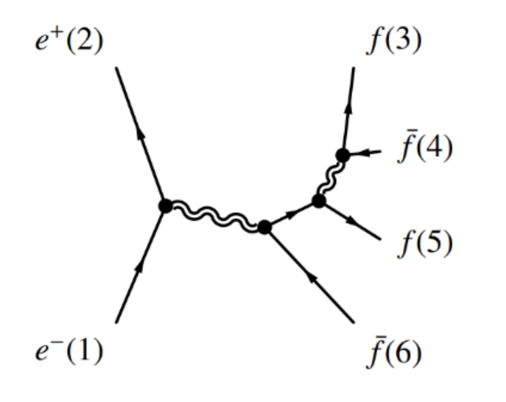
Target Channel	Channels	H->bb	H->cc	H->gg	H->ss	H->ZZ	4f	2f
H->bb	Efficiency [%]	**53.89**	2.73E-03	0.43	1.47E-03	8.39E-04	0.09	2.23E-04
	Event Yields [20/ab]	**287924.98**	0.73	347.03	0.003	0.06	7161.45	2414.79
H->cc	Efficiency [%]	0.01	**43.51**	0.36	5.14E-03	5.77E-04	0.07	8.11E-05
	Event Yields [20/ab]	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





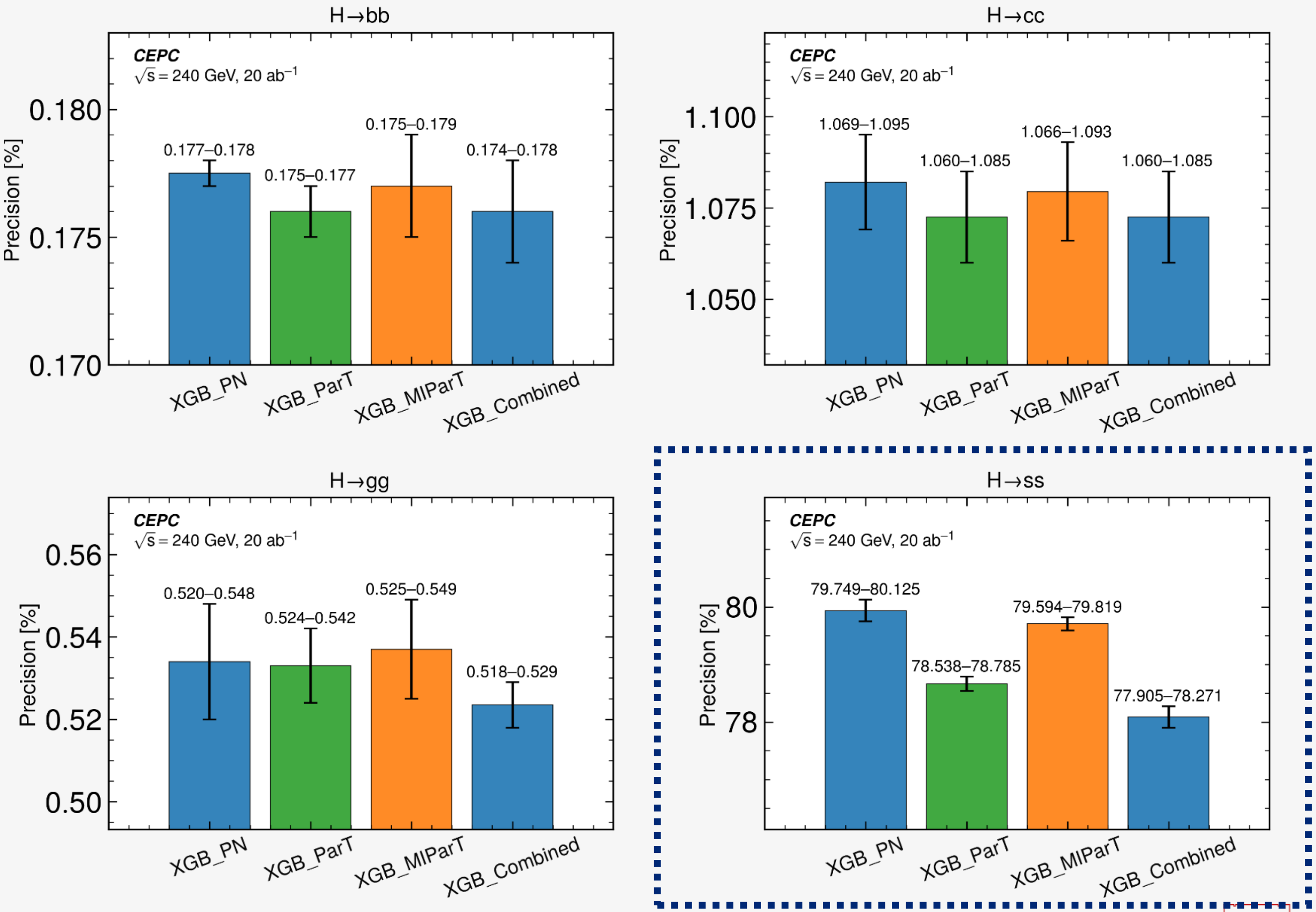
- Good classification performance among the channels
- ~**1.3σ** (statistical only) for H→ss search
- Leading bkg: 4f



Channels	H->bb	H->cc	H->gg	**H->ss**	H->ZZ	4f	2f
Efficiency [%]	6.67E-05	0.05	0.75	**44.68**	1.65E-04	0.05	4.16E-04
Event Yields [20/ab]	0.36	13.63	593.77	**89.36**	0.01	**4059.50**	101.05

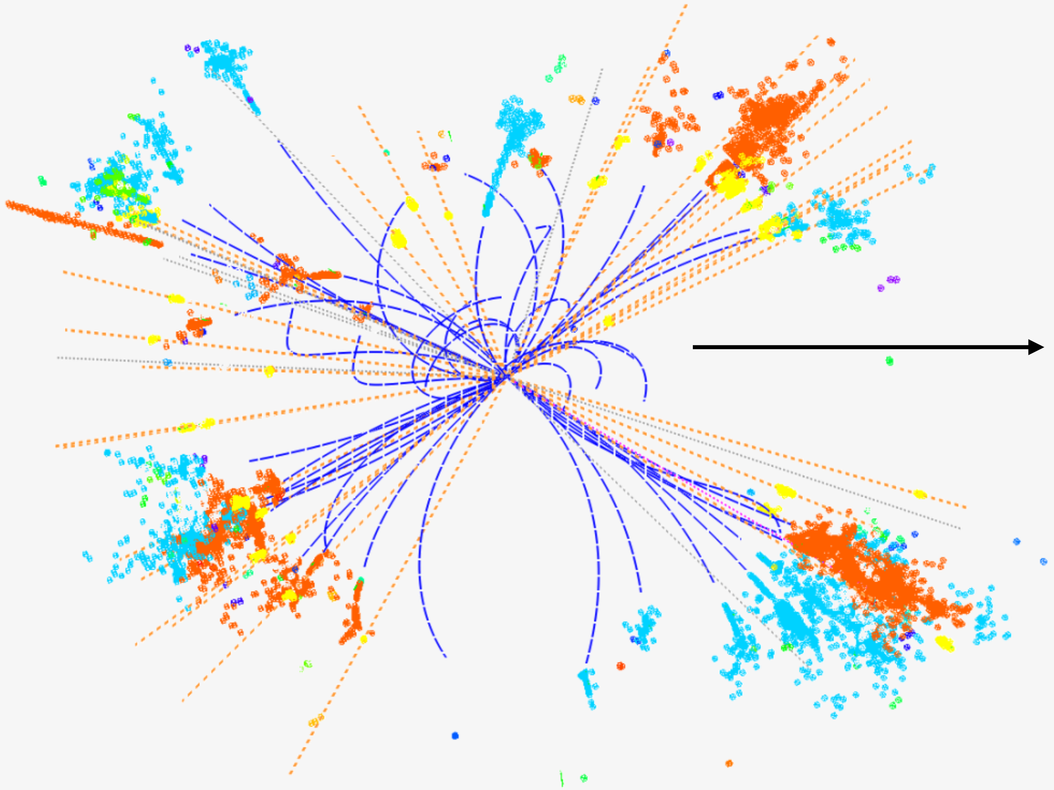
What Beyond Our Knowledge

- **Stable** results from all the scenarios
- **Slightly improved precision** from combination of different deep learning models in **H→gg/ss**
- Close performance among models from H→gg, **why**?



Even Better?

- A "holistic" approach: jet-free event classification (Manqi's slides)
- See also Congqiao's work @ CMS



H→bb

H→cc

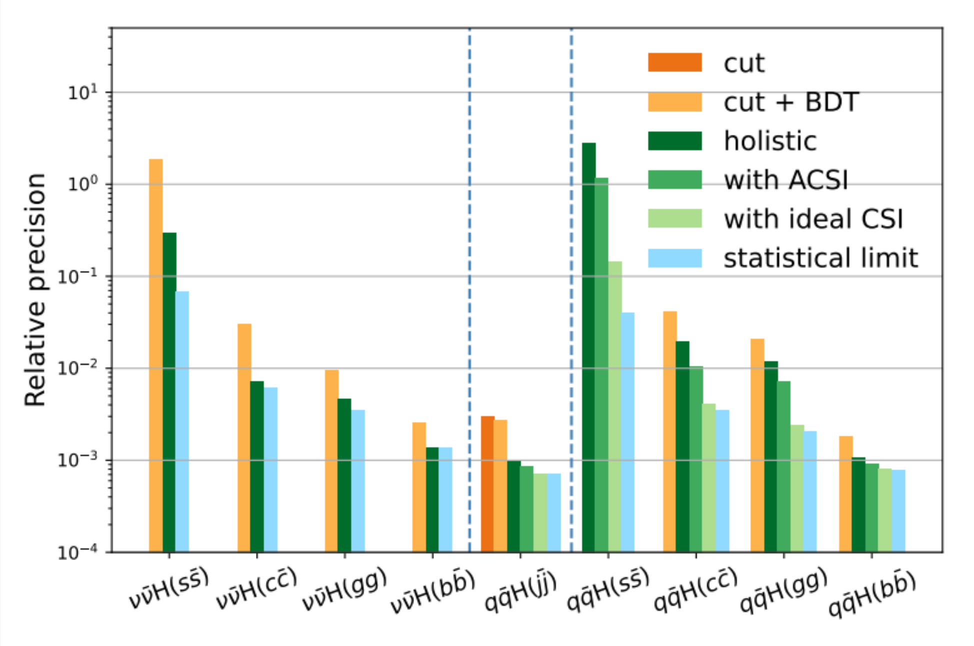
H→ss

H→gg

H→ZZ

…

	$\nu\bar{\nu}H$			
	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$	$H \to s\bar{s}$
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%



Conclusions

- We explore the limit of Higgs couplings to quarks in a more "traditional" approach
  - Jet level tagging -> event level classification

Channels	Published*	Ours	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%**	—

* Precision Higgs Physics at CEPC (2018)

- There exists a "Holistic" jet-free approach
  - Event level tagging!

- There remains many questions as well
  - Impacts from theory (generators), further improve the separation performance, better understanding of models, …

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Thank You!

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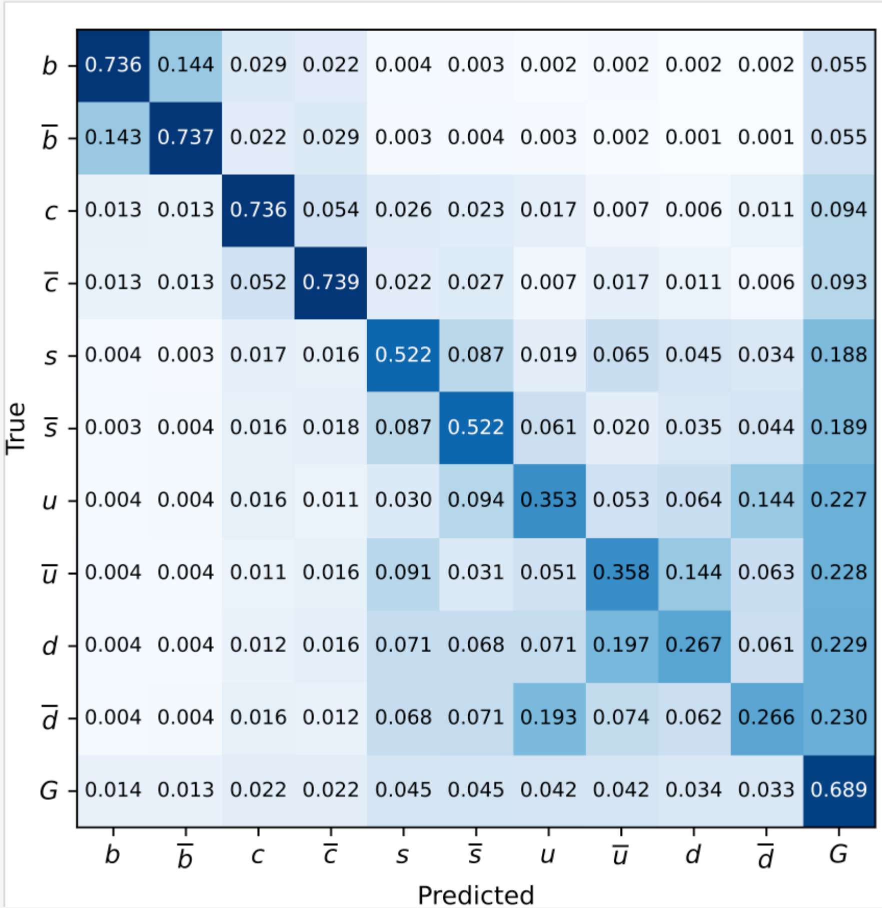
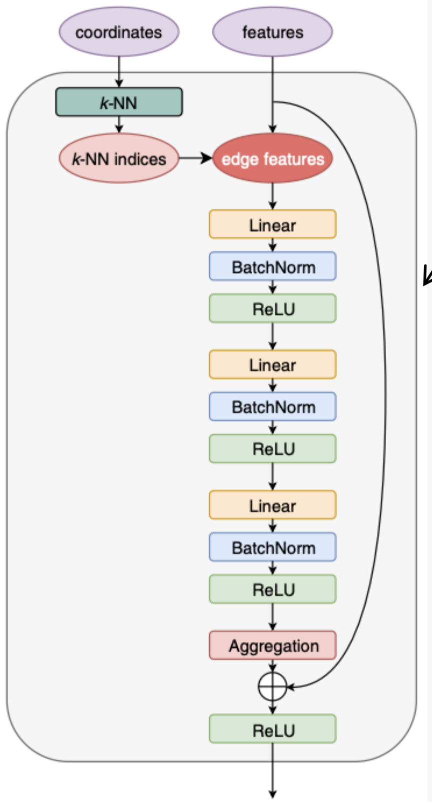
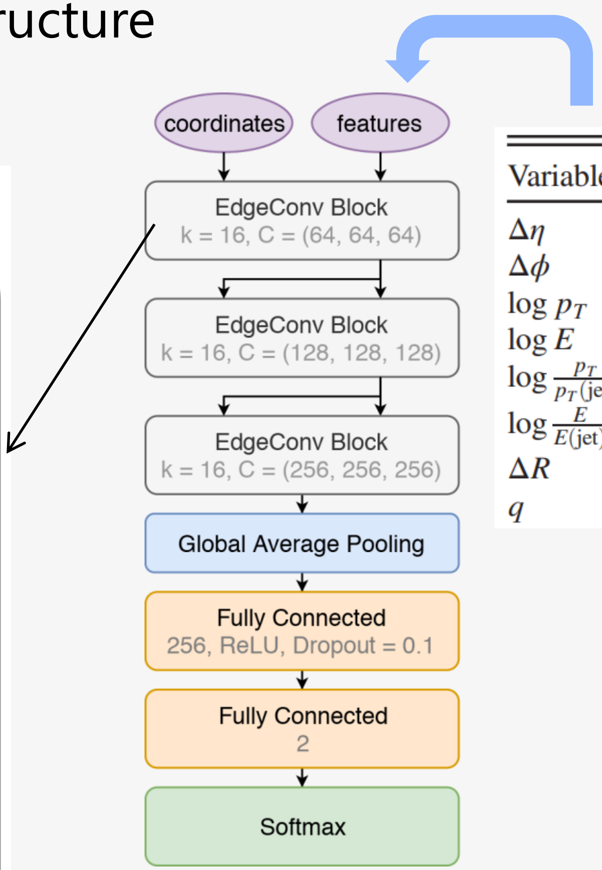
ParticleNet

- Treat a jet as a particle cloud
  - Use dynamic graph convolutions to learn local & global jet substructure





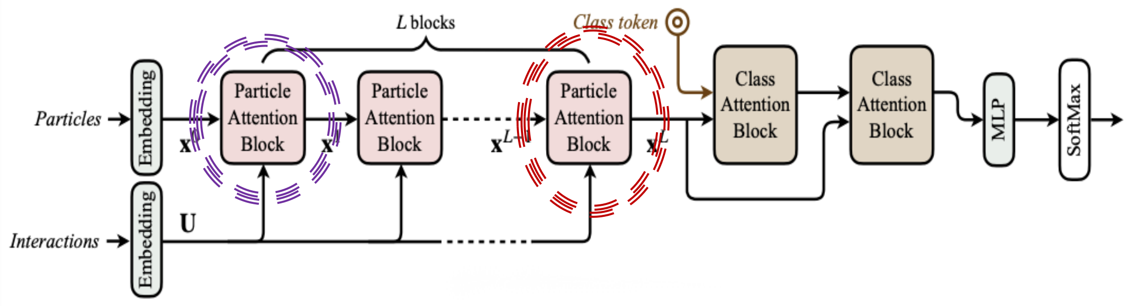


Variable
$\Delta\eta$
$\Delta\phi$
$\log p_T$
$\log E$
$\log \frac{p_T}{p_T(\text{jet})}$
$\log \frac{E}{E(\text{jet})}$
ΔR
q

Particle Net

ParT & MI-ParT

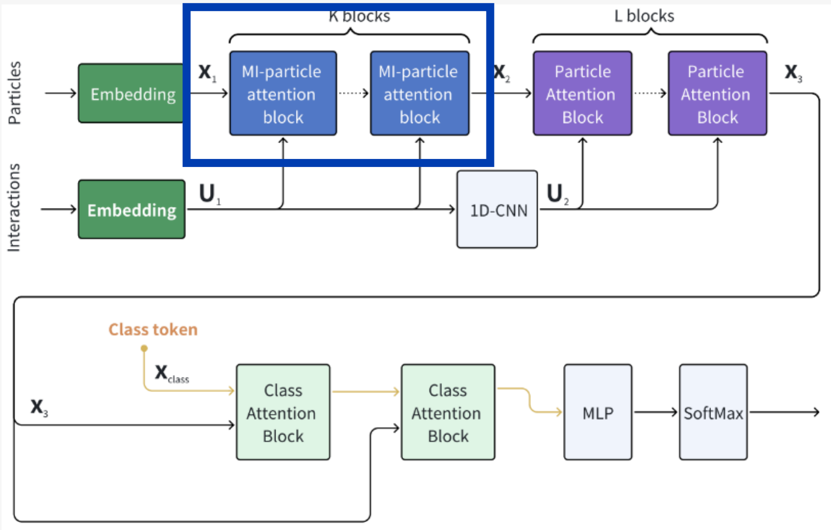
- Attention on particle and their "interactions"
  - Particle attention: particle <-> particle
  - Class attention: particles <-> class/jet flavor
  - More-Interaction attention: reduces model complexity compared with ParT



Particle Transformer

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

"interactions"



More-Interaction Particle Transformer

model	Params
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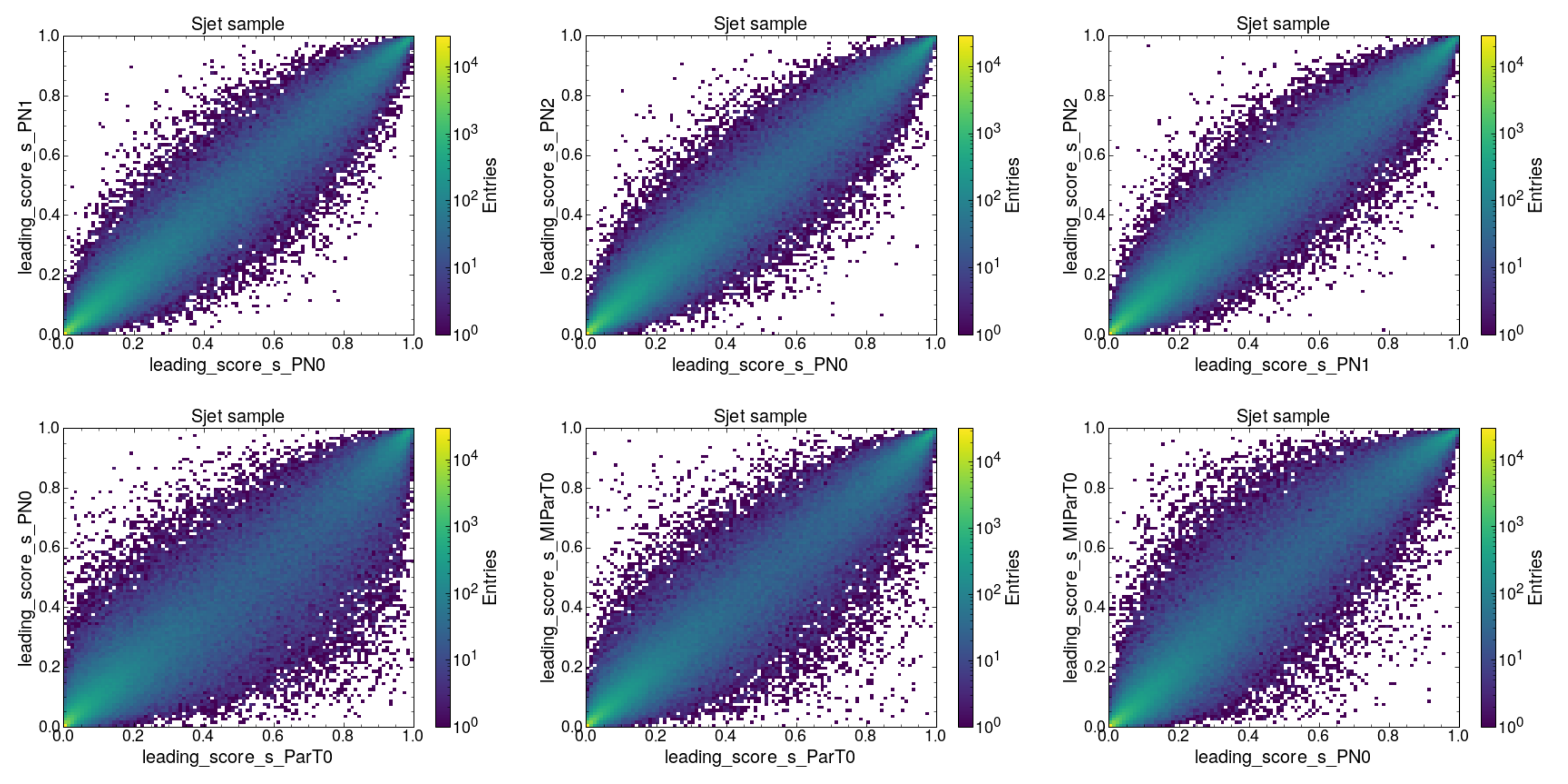
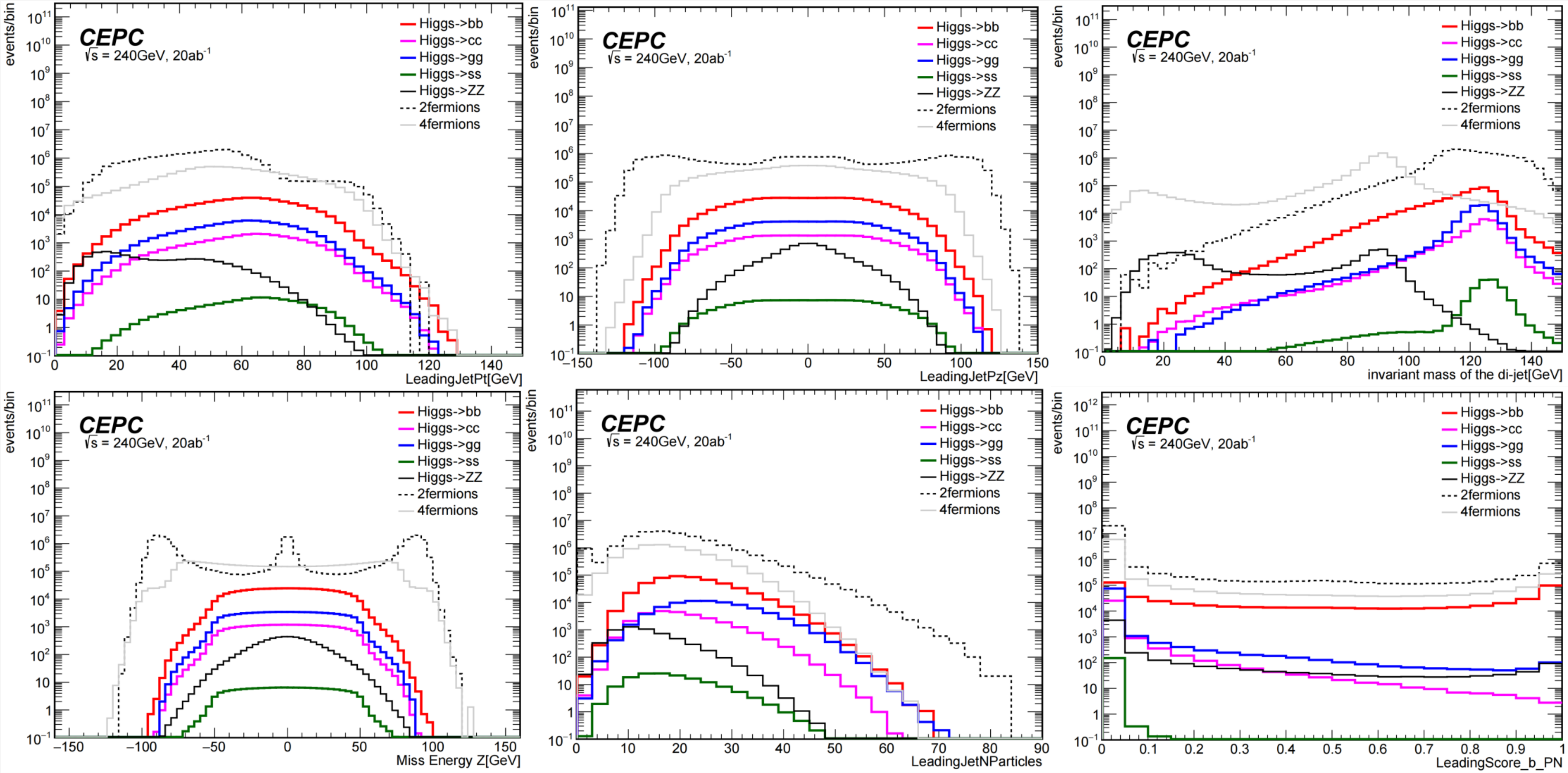
ParT	2.14M
MIParT	720.9k

0.3x

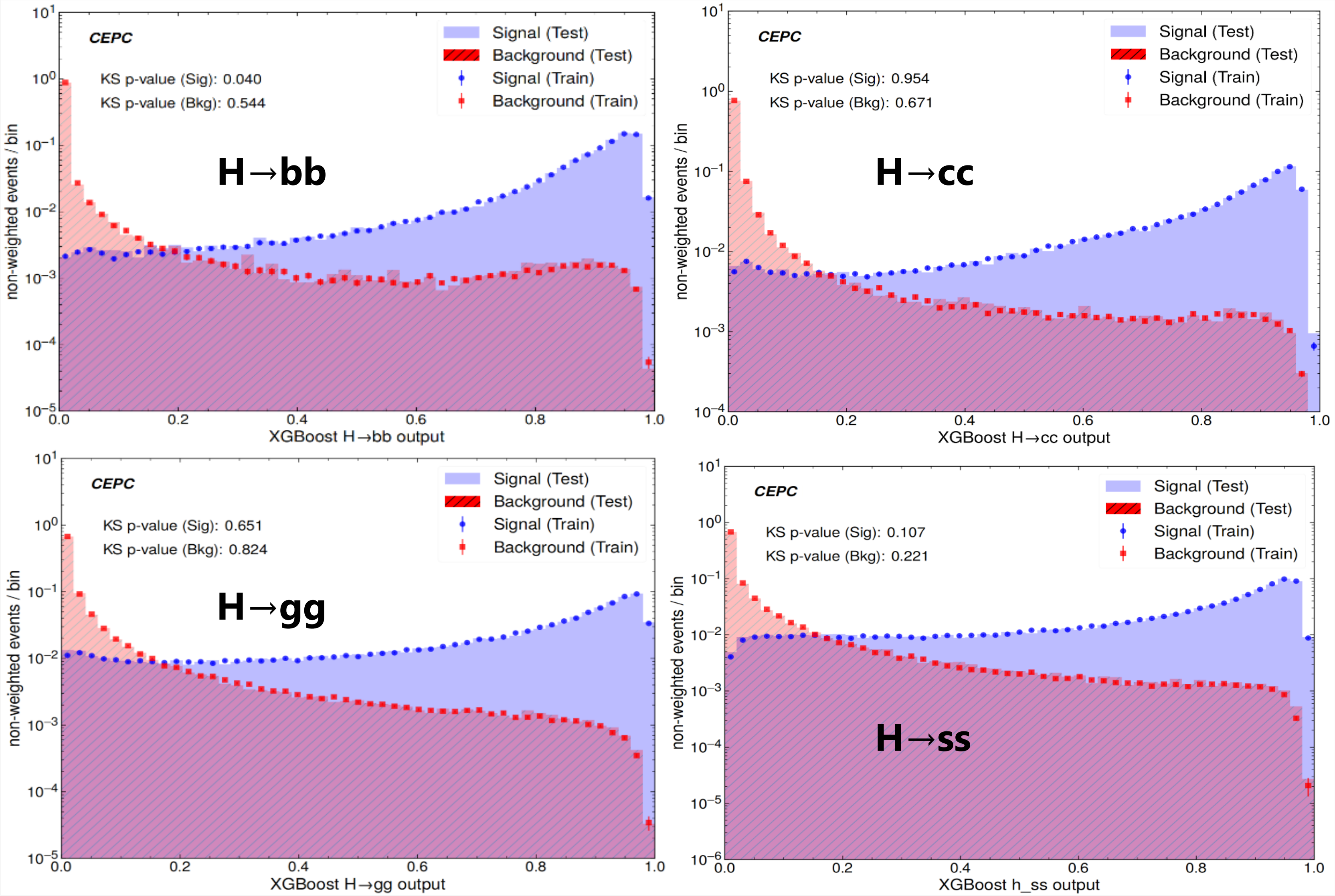
Correlations of Models



Some Characteristic Distributions



BDT outputs



CEPC
Signal (Test)
Background (Test)
Signal (Train)
Background (Train)
KS p-value (Sig): 0.040
KS p-value (Bkg): 0.544
H→bb
non-weighted events / bin
XGBoost H→bb output
CEPC
KS p-value (Sig): 0.954
KS p-value (Bkg): 0.671
H→cc
XGBoost H→cc output
CEPC
KS p-value (Sig): 0.651
KS p-value (Bkg): 0.824
H→gg
XGBoost H→gg output
CEPC
KS p-value (Sig): 0.107
KS p-value (Bkg): 0.221
H→ss
XGBoost h_ss output

Comparison of Holistic Approach

- Comparison between our results and the holistic approach
  - Bkg free estimate

	$\nu\bar{\nu}H$			
	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$	$H \to s\bar{s}$
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%

Channels	Z →νν, H->bb %	Z →νν, H->cc %	Z →νν, H->gg %	Z →νν, H->ss %
Stat. Unc.	0.17	0.77	0.47	28.54%