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Precision Higgs Measurements and Light Scalar Searches with Particle-Level Transformers

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arXiv: 2407.08682, in collaboration with Yifan Wu, Congqiao Li, Huilin Qu, and Jingya Zhu
arXiv: 2510.24662, in collaboration with Yabo Dong, Manqi Ruan, Haijun Yang, and Jingya Zhu
arXiv: 2512.21558, in collaboration with Xinzhu Wang, Yifan Zhu, Chunxiang Zhu, Jianfeng Jiang, Manqi Ruan, Haijun Yang, and Yongfeng Zhu

2026年新物理前沿与交叉科学研讨会

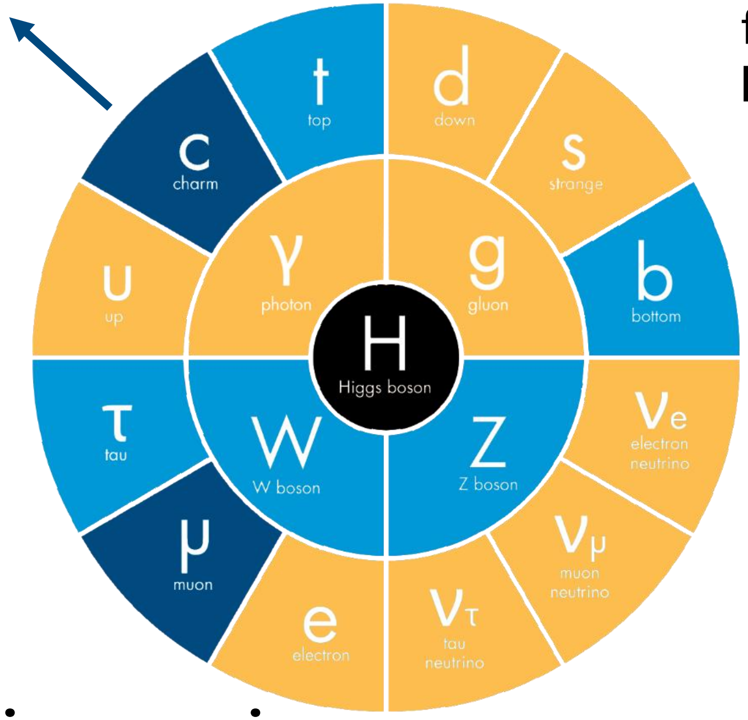
2026年5月18日 南京

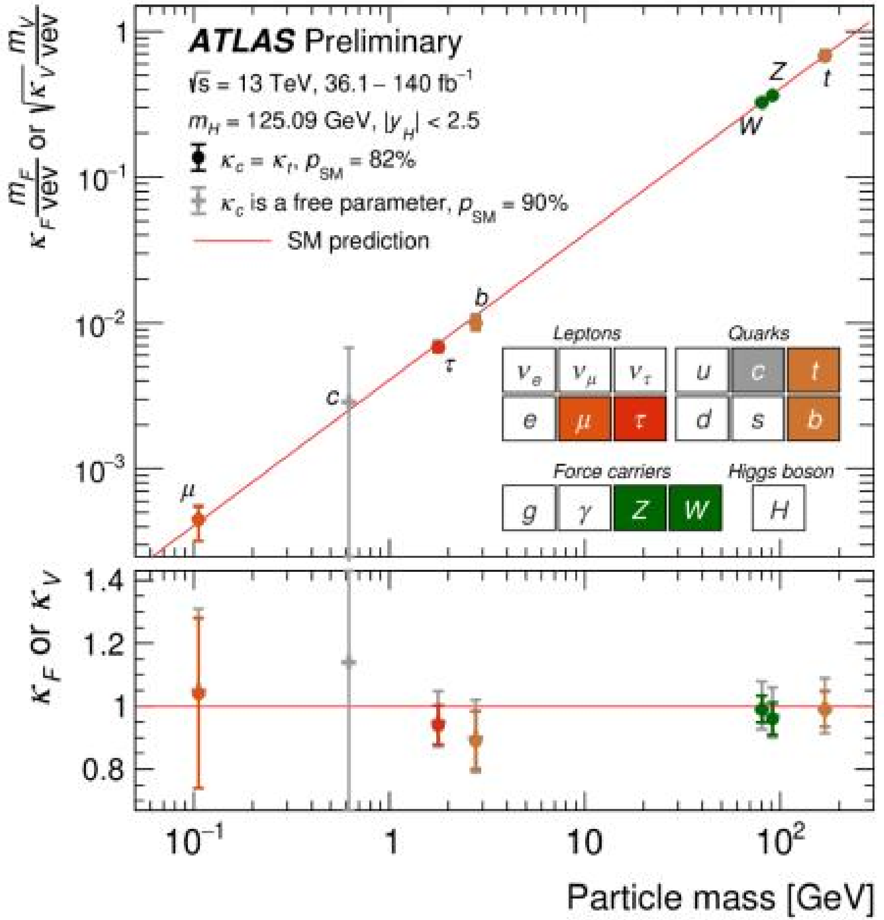
Outline

- **Motivation:** Precision Measurement & Search for a light Scalar
- **Technical Tools**： MIParT (Our Innovation) （arXiv: 2407.08682）
- **Application 1**: Precision Hadronic Higgs Measurements （arXiv: 2512.21558)
- **Application 2**: Search for New Physics （arXiv: 2510.24662)
- **Summary & Outlook**

Why the Higgs sector is the frontier

- **Higgs coupling measurement**
  - **c quark/μ**: towards evidence
  - **3rd** generation fermions & **vector bosons**: observed

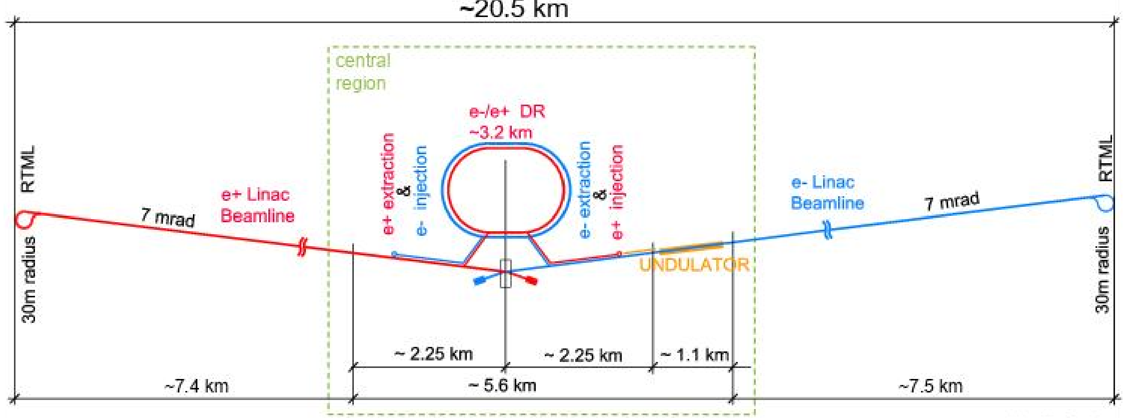




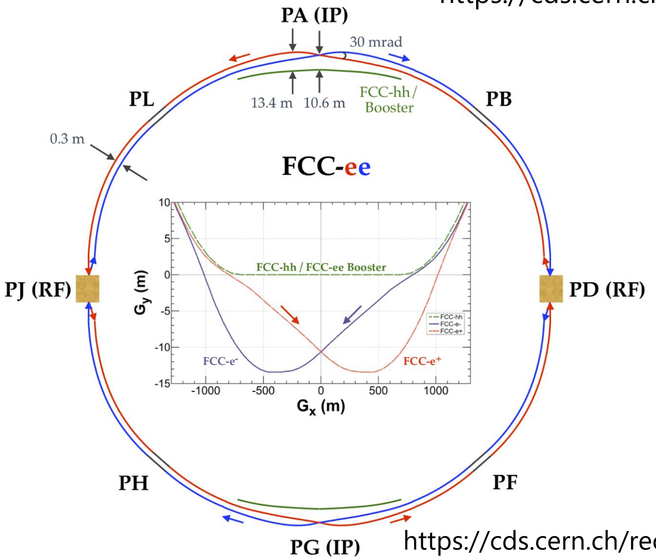
- **Key questions remain:**
  - Are Higgs couplings exactly SM? (precision frontier)
  - Does the Higgs sector have additional states? (discovery frontier)
  - What is the Yukawa structure for 2nd generation (c, s, μ)?

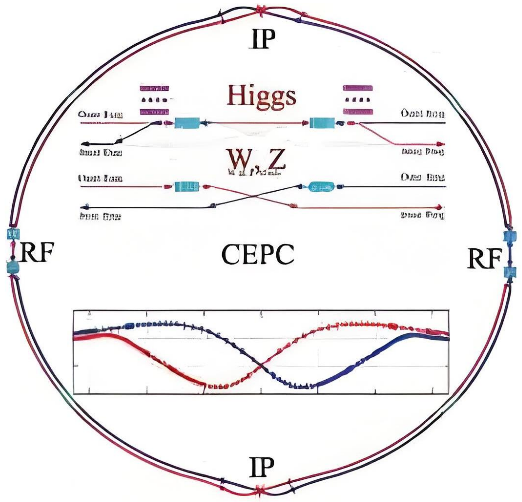
Future Higgs Factories

- **A New Era of Precision Measurement**
  - Clean environment: low QCD backgrounds, no pileup, precise initial state
  - Millions of Higgs
- **New Opportunity for Higgs Physics**
  - **Precision Measurement**
  - **Search for New Physics**



https://cds.cern.ch/record/2655225/plots





https://cds.cern.ch/record/2775933/plots

Collider	**Center-of-mass Energy**	**Integrated Luminosity**	**Number of Higgs**
CEPC	240 GeV	20 ab^{-1}	~4M
FCC-ee	240 GeV	5 ab^{-1}	~1M
ILC	250 GeV	2 ab^{-1}	~0.5M

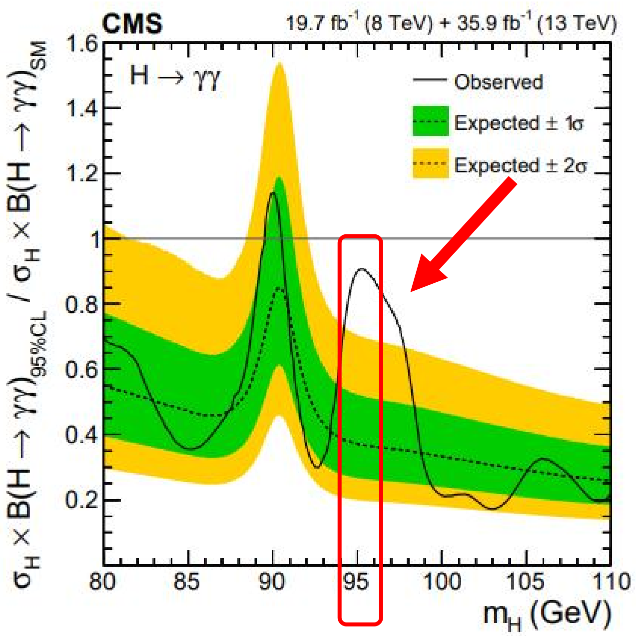
Two physics targets & The shared challenge

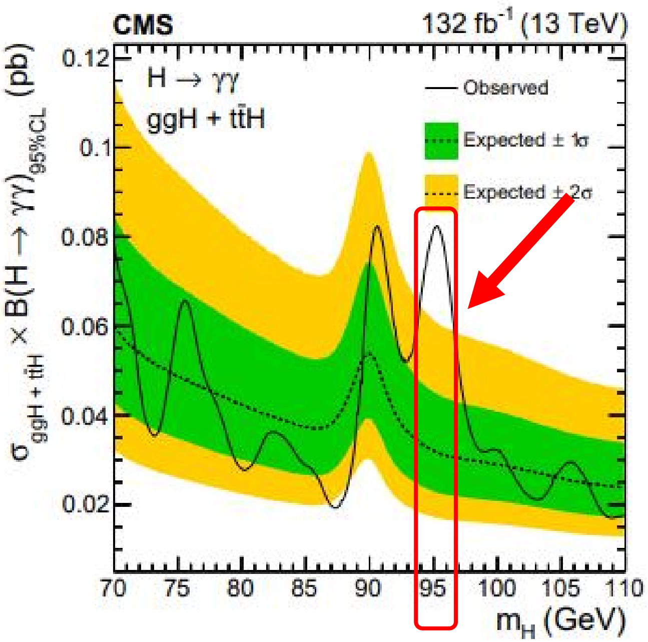
- **Precision Measurement:**
  - Measurements of Br(H→cc, gg, ss)

Decay channel	Reported quantity	Relative uncertainty	Reference
H → bb	μ_{bb} ≈ 1.04 ± 0.20	**~19 %**	CMS-PAS-HIG-18-016
H → cc	κ_c< 5.7 × 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	μ = 1.002 ± 0.057 (combined fits)	~5.7 %	arXiv:2207.00043

Two physics targets & The shared challenge

- **Search for New Physics:**
  - Search for a light scalar S





a. 95.3 GeV dipohoton channel 2.8σ
CMS 2018. arXiv: 1811.08459.

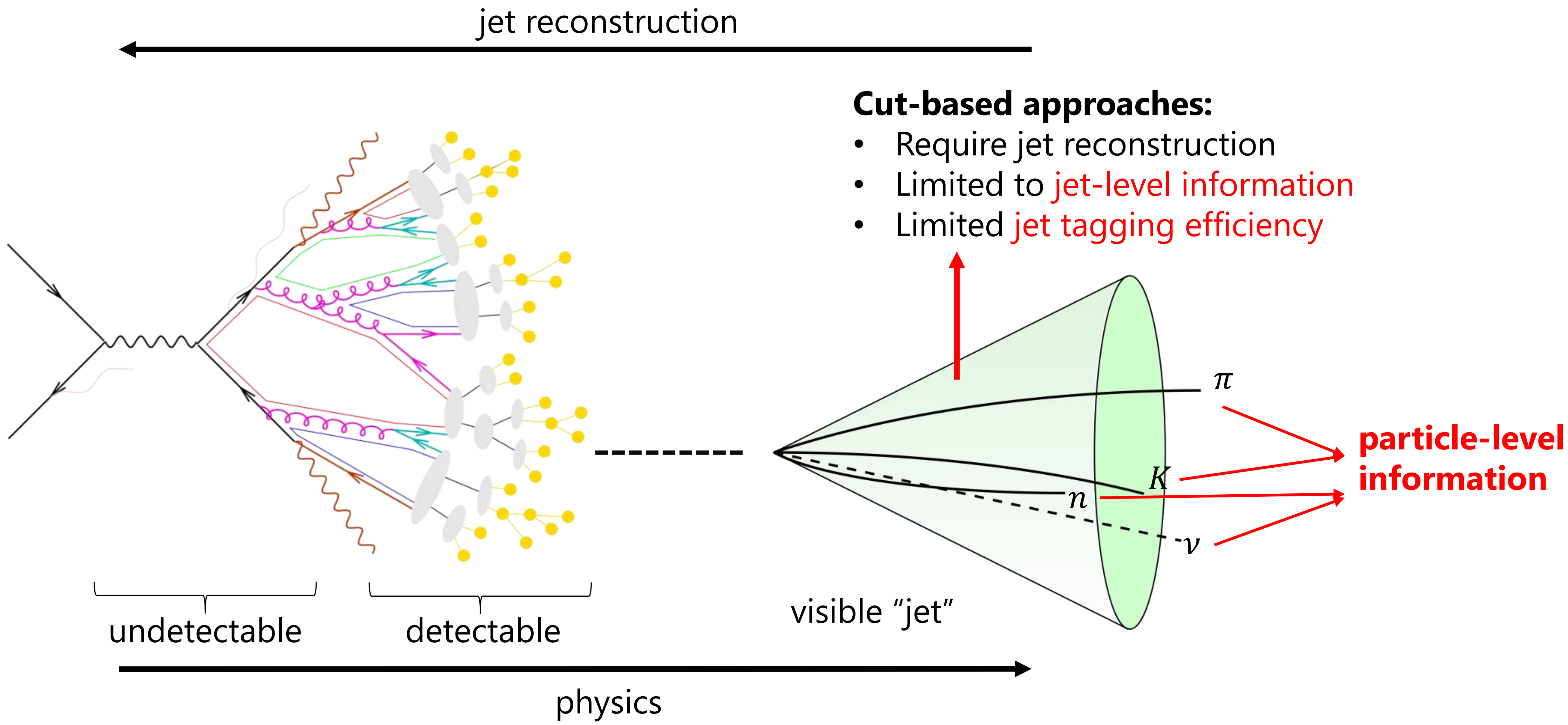
b. 95.4 GeV dipohoton channel 2.9σ
CMS 2024.arXiv: 2407.07546.

Two physics targets & The shared challenge

- **The shared challenge: particle-level information bottleneck**

Cut-based approaches:

- Require jet reconstruction
- Limited to jet-level information
- Limited jet tagging efficiency



A Short Evolution of Jet Tagging

CNN on Jet Images (2015-2016)

RNN on Sequences (2016-2017)

Point Clouds: ParticleNet (2018-2019)

Transformer: ParT (2021-2022)

Enhanced Transformer: MIParT (2024-)

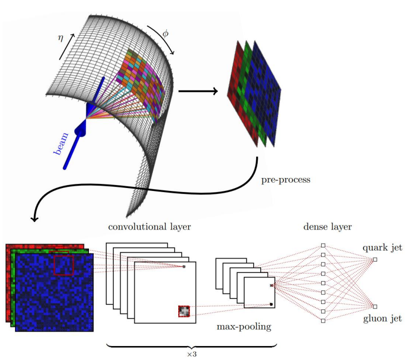


Fig from 1612.01551

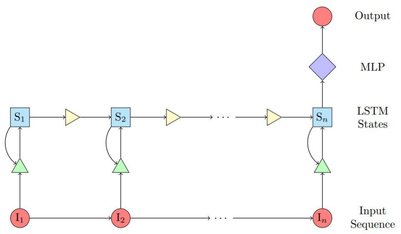


Fig from 1607.08633

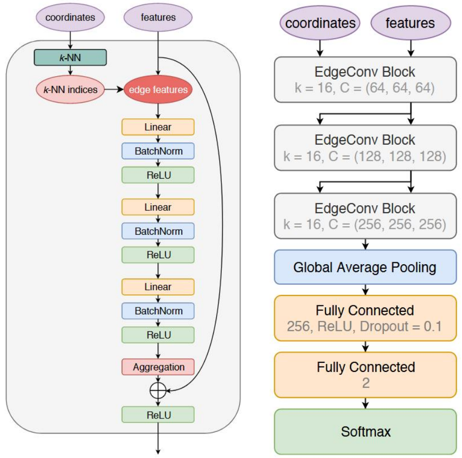


Fig from 1902.08570

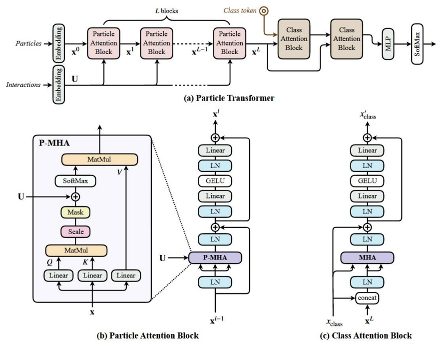


Fig from 2202.03772

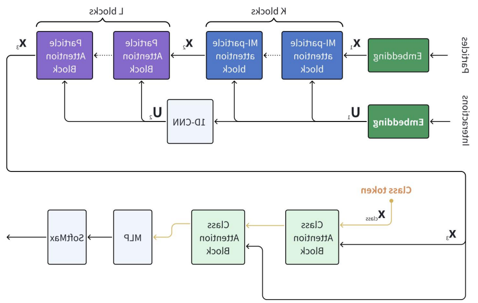


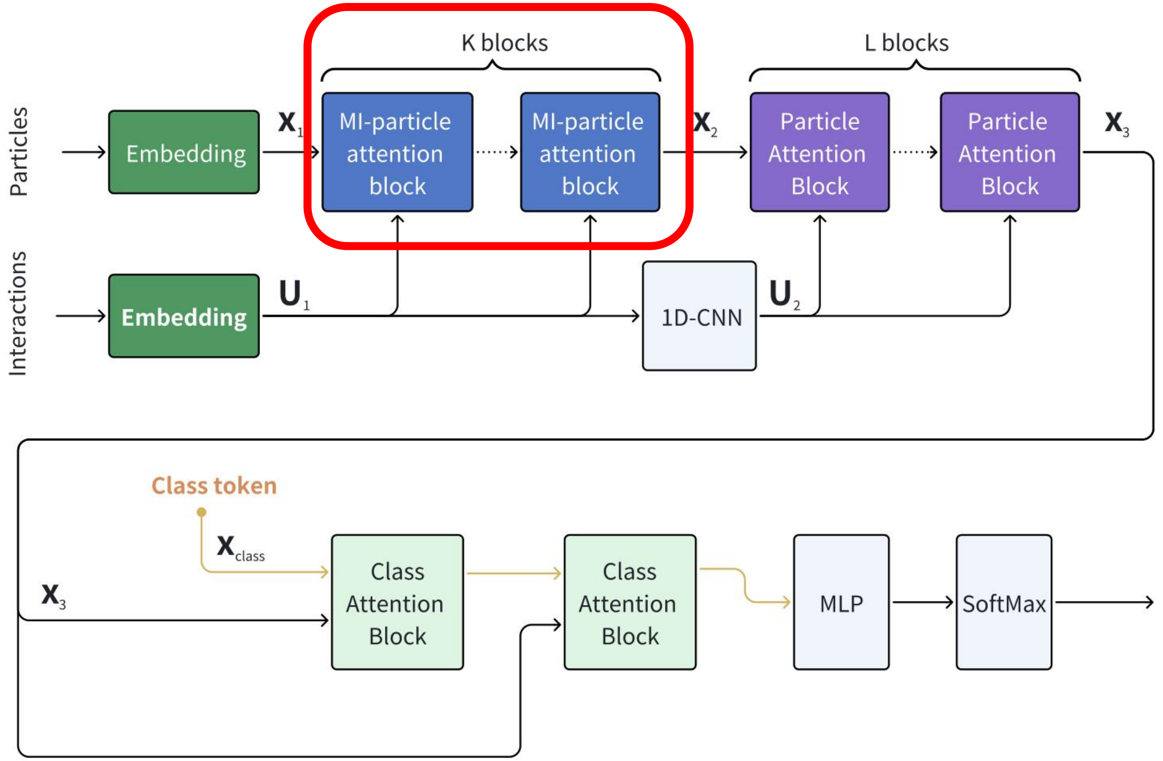
Fig from 2407.08682

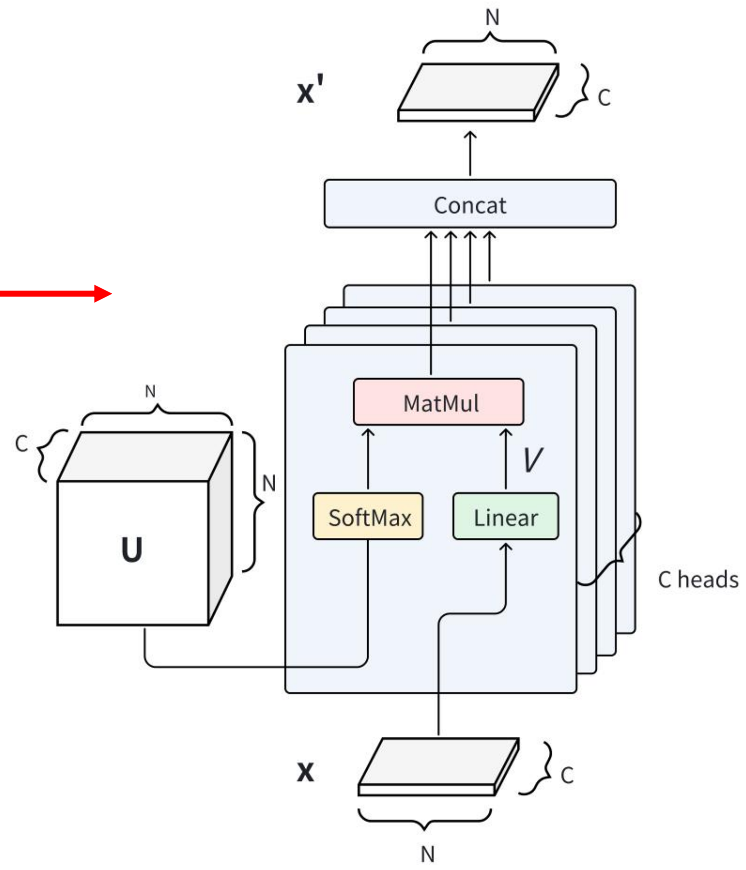
Our Innovation: MIParT

More-Interaction Attention (MIA)

- **More-Interaction Particle Transformer (MIParT)**
  - Inspired by the success of pairwise attention in jet tagging

MI-Particle Attention Block





$$\mathrm{MIA}(\mathbf{U}, V) = \mathrm{SoftMax}(\mathbf{U})V,$$

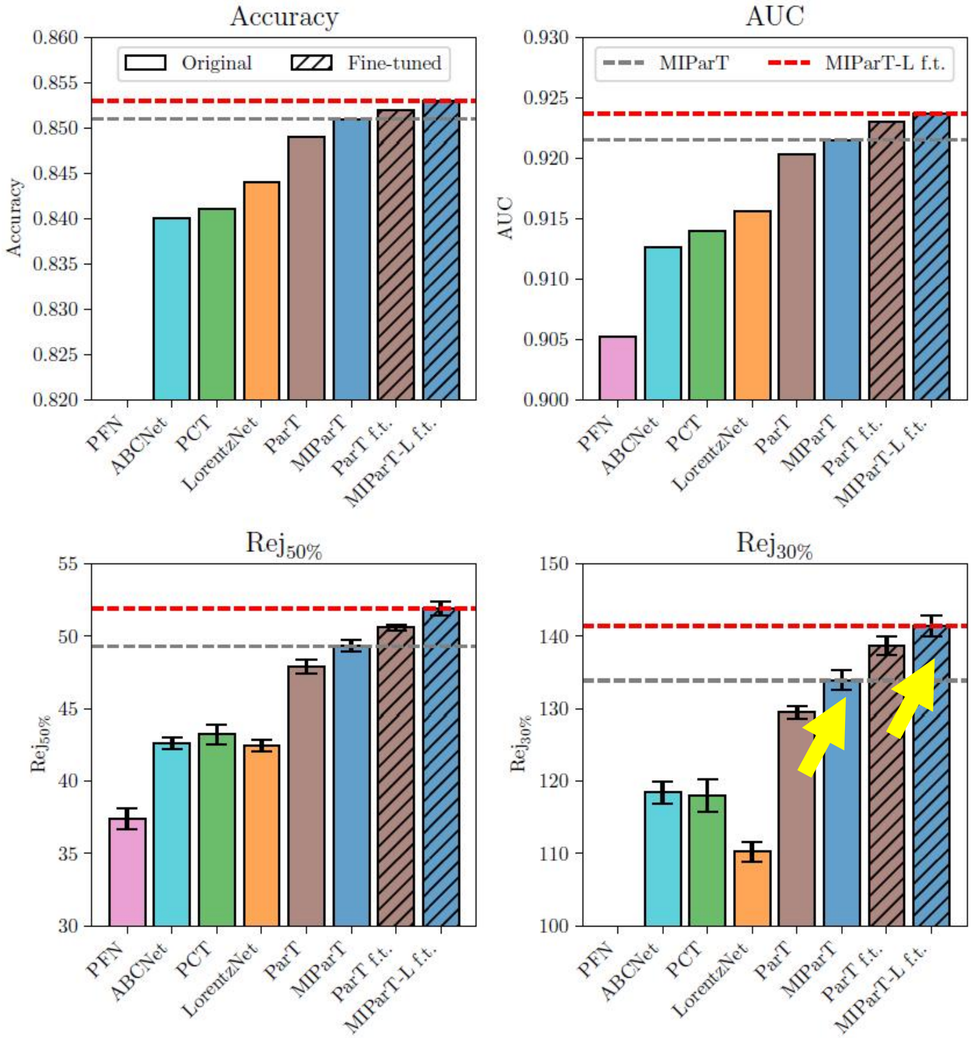
Code: https://github.com/USST-HEP/MIParT

arXiv: 2407.08682

Fig from 2407.08682

MIParT Benchmark Validation

On the Quark-gluon Dataset

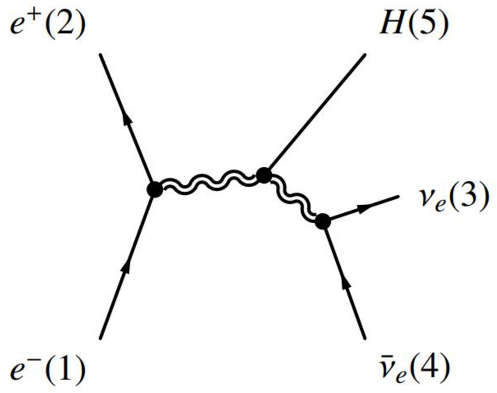


	TOP	QG	Params	FLOPs
PFN	—		86.1k	4.62M
P-CNN	0.930	—	354k	15.5M
ParticleNet	0.940	—	370k	540M
ParT	0.940	0.849	2.14M	340M
MIParT (ours)	**0.942**	**0.851**	720.9k	180M
MIParT-L f.t. (ours)	**0.944**	**0.853**	2.38M	368M

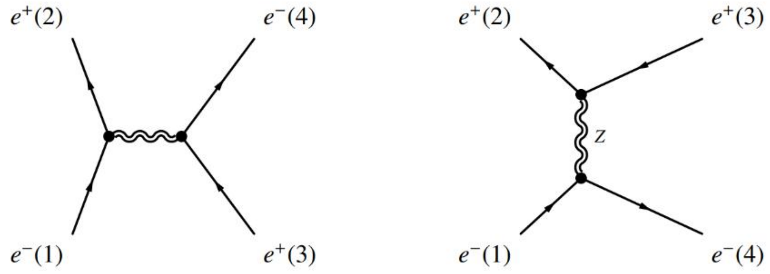
- MIParT improving background rejection by 3% compared to ParT.
- MIParT-L (pre-trained on 100M JetClass) improving background rejection by 6% compared to fine-tuned ParT.
- MIParT requires only 30% of the parameters and 53% of the complexity needed by ParT.

Application 1: Precision Hadronic Higgs Measurements

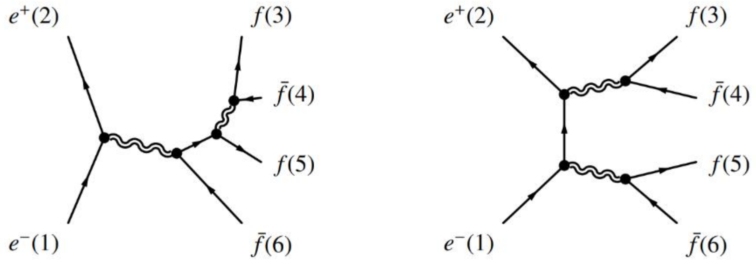
- **Signal**: ee→ZH, Z→$\nu\ \nu$, H→qq/gg @ 240GeV 20ab^{-1}



- **Backgrounds**: Dominated by H→ZZ, 2 fermions and 4 fermions



2 fermions



4 fermions

Two-Stage Analysis Strategy

- Jet tagging: particle-level deep neural networks (PN, ParT and MIParT)
- Event-level classification : a gradient-boosted decision-tree method (XGBoost)

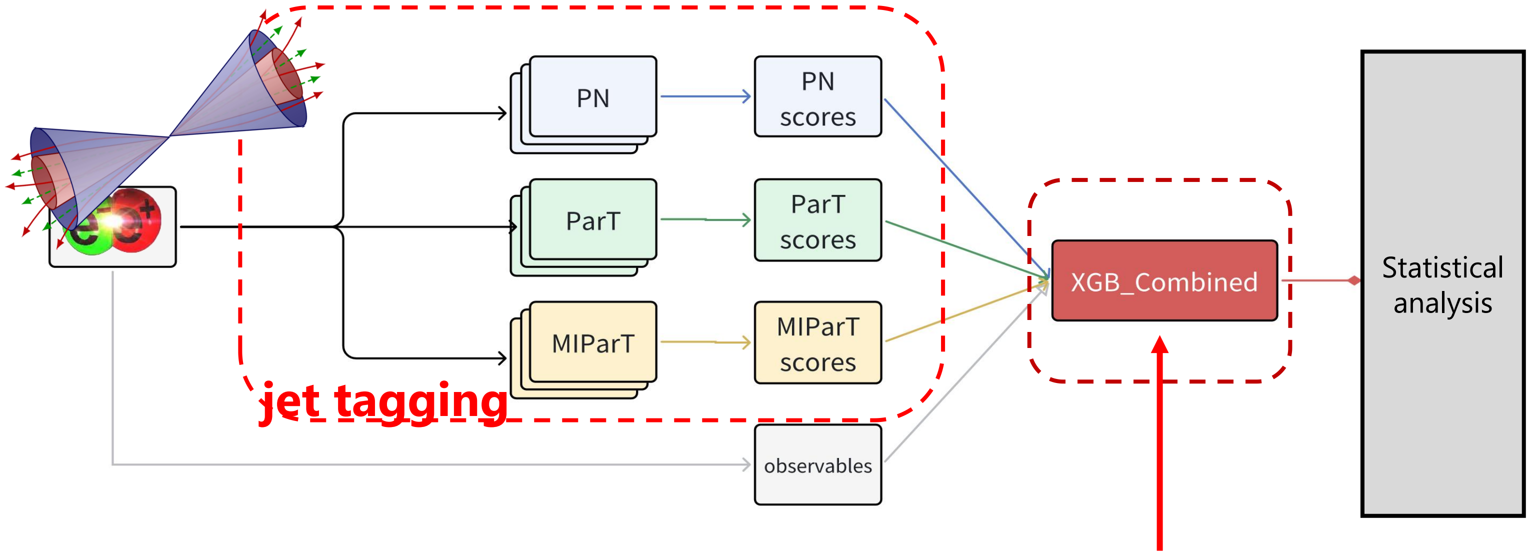


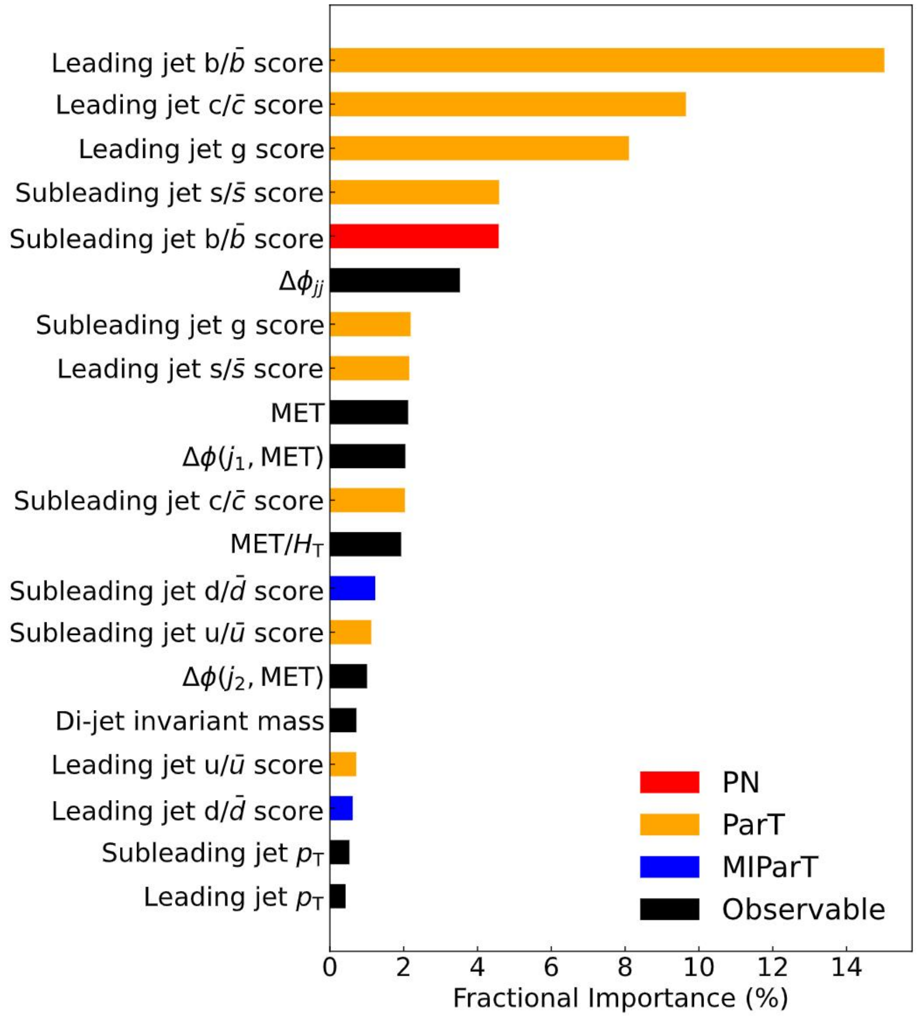
Table 3. Inputs for XGBoost classification.

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, MEZ, η_{ME}, θ_{ME}, ϕ_{ME}, MET$/H_T$
Jet–MET correlations	$\Delta\eta$, $\Delta\phi$, $\Delta\theta$ between each jet and MET
Jet flavor tagging scores	outputs from ParticleNet, ParT, and MIParT

arXiv: 2512.21558

Event-Level Interpretation

- **Feature Importance Analysis**



- **b and c Scores Dominate bb/cc Separation**
- **MET and MET/HT Reject 2f Backgrounds**

arXiv: 2512.21558

Precision Results at Higgs Factories (20 ab^{-1}, Z → νν 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%**	—

XGB_Topfeatures
0.18%
1.10%
0.54%
73%

arXiv: 2512.21558

Top 26 input-features

physically interpretable

- **H → bb Precision 15% improvement** vs CEPC benchmark
- **H → cc Precision 43% improvement**
- **H → gg Precision 29% improvement**
- **H → ss Precision 68% ≈ 1.5σ sensitivity** (νν channel only)

Signal significance $Z = \frac{S}{\sqrt{S+B}}$

Measurement precision $\Delta = \frac{\sqrt{S+B}}{S}$

Application 2: Search for New Physics

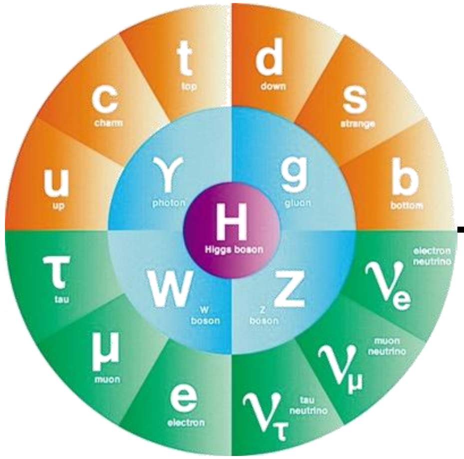
- **The puzzle of SM**

Dark matter

Neutrino mass

Baryon asymmetry

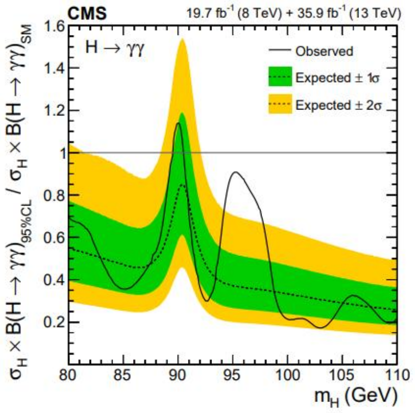
solve



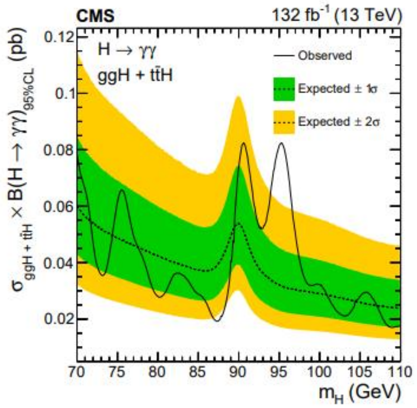
extend

Additional Higgs

- **Recent excesses**



arXiv: 1811.08459



arXiv: 2407.07546

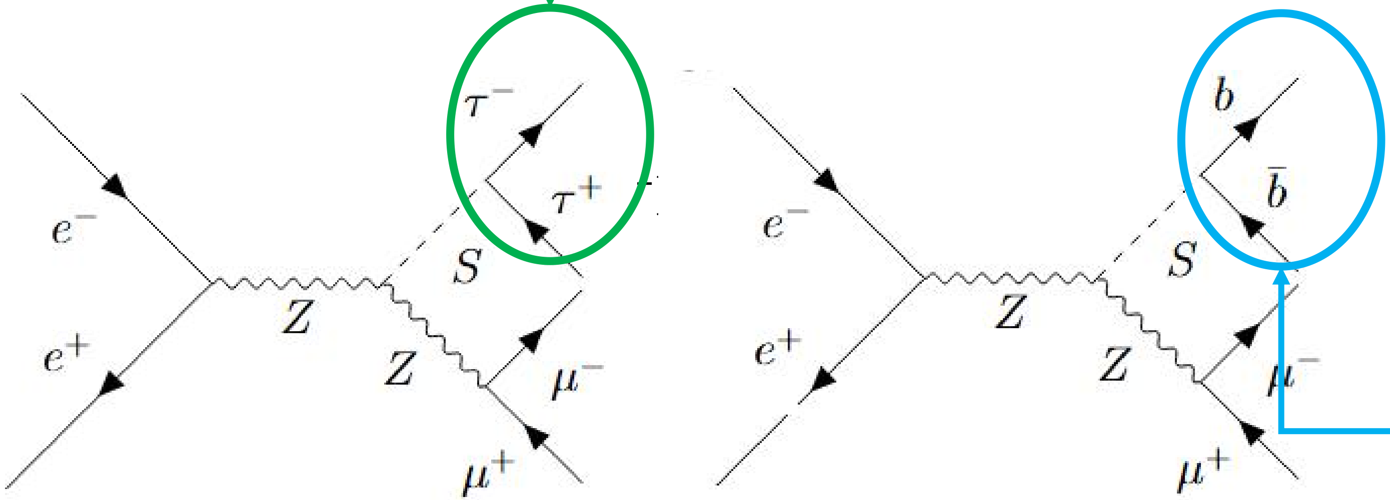
suggest

95 GeV Higgs

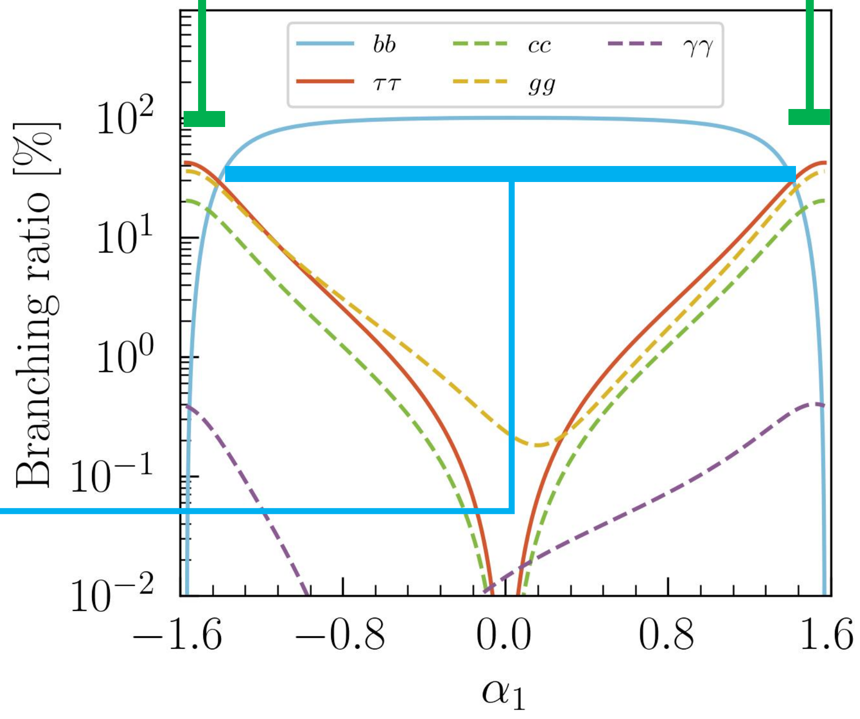
Application 2: Search for a 95 GeV Scalar

- **Signal and background**

Signal: ee→ZS, Z→ μμ, S→ ττ/bb @ 240GeV 20ab^{-1}



N2HDM dominant decay channels



$tan\beta = 2,\ cos\alpha_2 = \sqrt{2}/2$

Background: ee→ μμff, f= u/d/c/s/e/μ/τ/b

arXiv: 2510.24662

Cut based analysis

- **On $\tau\tau$ channel**

The cut flow with $L = 20\ \text{ab}^{-1}$

Cuts	Cross section [fb]		Measurement precision [%]
	Signal	Background	
Initail	0.218	84.250	29.8
Basic	0.177	72.202	34.1
$\boldsymbol{M_{\mu_1\mu_2} > 50\ \text{GeV}}$	0.165	58.617	32.9
N[τ-jet] $\geq$ 1	0.040	1.094	18.7
$\boldsymbol{\Delta M_{recoil} = 0.6\ \text{GeV}}$	0.026	0.026	6.2

- **On bb channel**

The cut flow with $L = 20\ \text{ab}^{-1}$

Cuts	Cross section [fb]		Measurement precision [%]
	Signal	Background	
Initail	2.099	84.250	3.13
Basic	1.700	72.244	3.58
$\boldsymbol{M_{\mu_1\mu_2} > 50\ \text{GeV}}$	1.633	58.552	3.36
$\boldsymbol{\Delta M_{recoil} = 0.6\ \text{GeV}}$	1.094	1.633	1.07

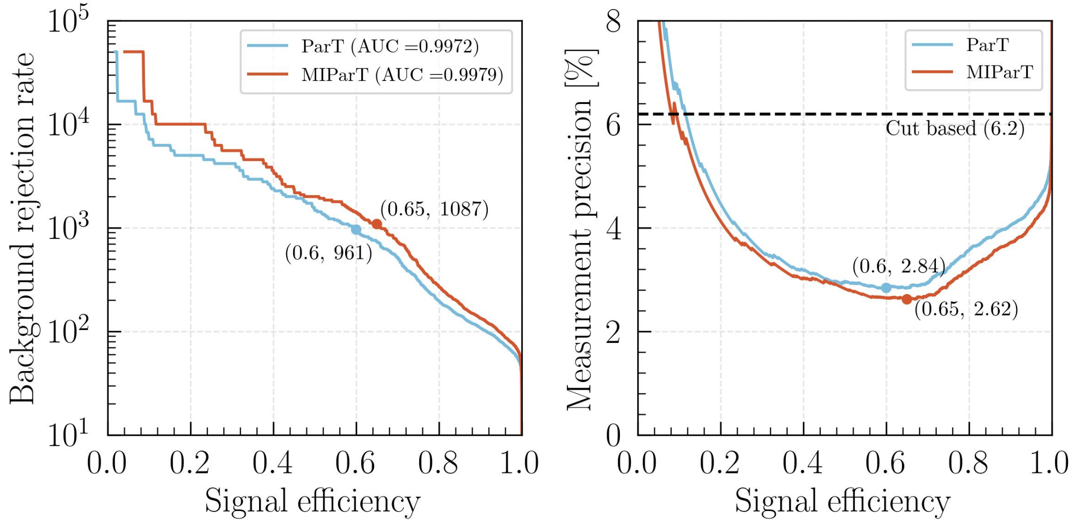
arXiv: 2510.24662

Measurement precision $\Delta = \dfrac{\sqrt{S+B}}{S}$

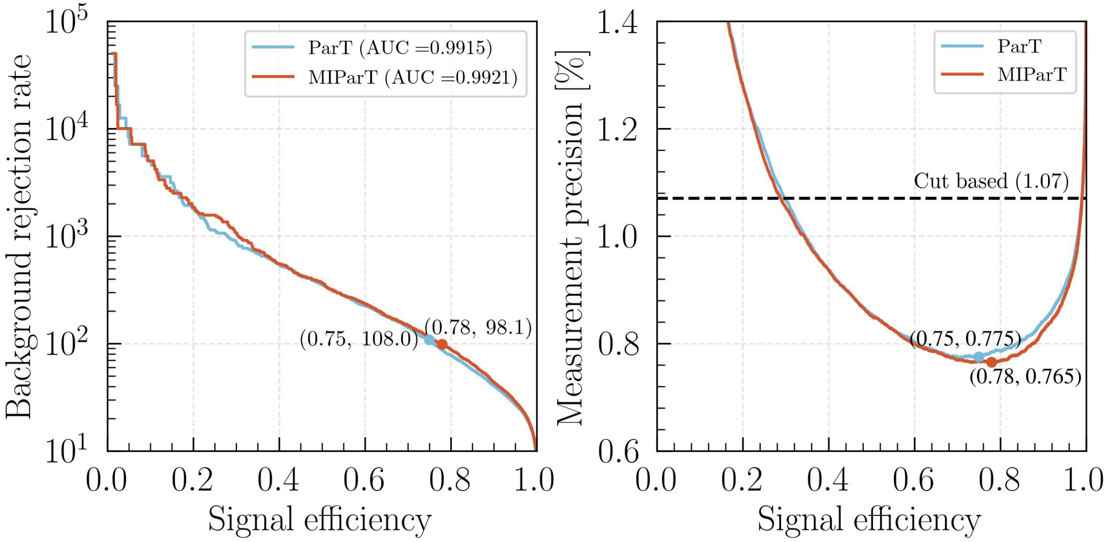
Signal significance $\mathcal{S} = \sqrt{2\left[(S+B)ln\left(1+\frac{S}{B}\right)-S\right]}$

Particle-level transformers for 95 GeV Higgs boson searches

ττ channel



bb channel



arXiv: 2510.24662

Method	Signal efficiency	background refection rate	Measurement precision [%]
Cut based	0.15	2777	6.2
ParT	0.60	916	2.8
MIParT	0.65	1087	2.6

↑ 58%

×2.4 times

Method	Signal efficiency	background refection rate	Measurement precision [%]
Cut based	0.64	43.3	1.07
ParT	0.75	108	0.78
MIParT	0.78	98.1	0.77

↑ 28%

×1.4 times

Summary & Outlook

- **Information Maximization:**
  - The principle drives our improvements: **maximizing the use of recorded information**.

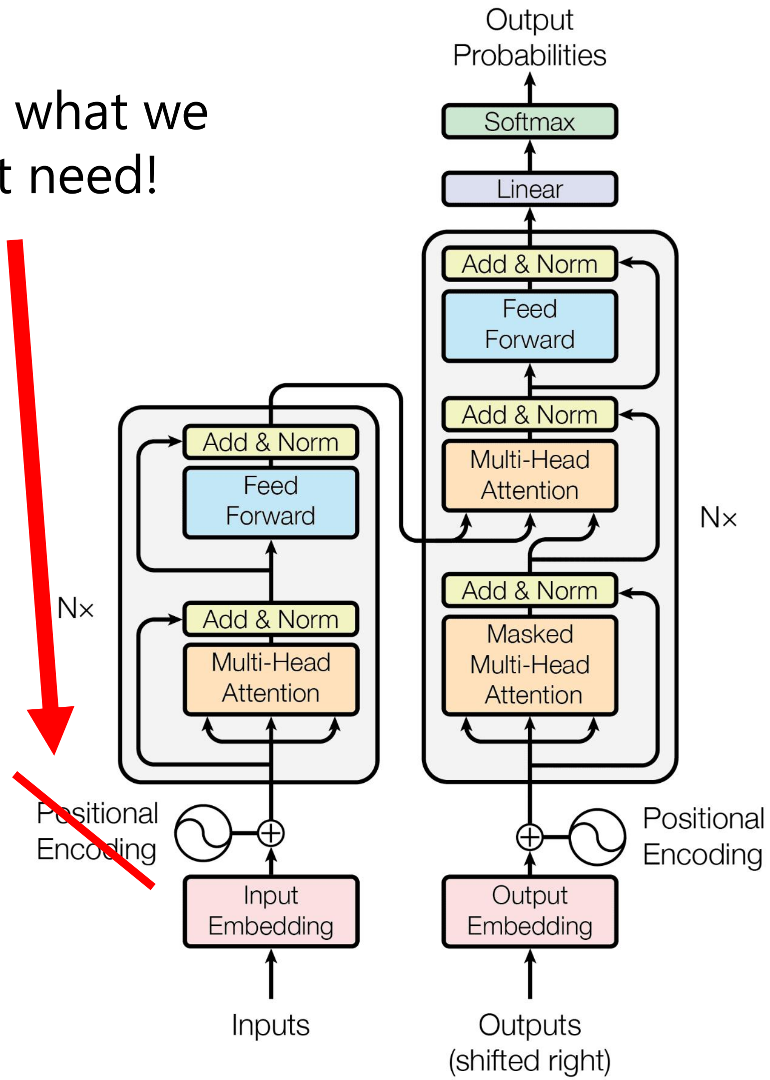
- **Physics Impact at Future Higgs Factories**
  - **Precision Measurements:**
    - H→bb precision: 0.17% (15% improvement over benchmark)
    - H→cc precision: 1.06% (43% improvement over benchmark)
    - H→gg precision: 0.50% (29% improvement)
    - H→ss precision: 68%: (~1.5σ sensitivity in Z→νν channel)
  - **Searches for New Physics:**
    - 95 GeV scalar in $\tau\tau$: ×2.4 statistical precision gain vs cut-based methods
    - 95 GeV scalar in *bb*: ×1.4 statistical precision gain

- **Next steps:**
  - combine Z→*ll* and Z→*qq* channels
  - foundation-model

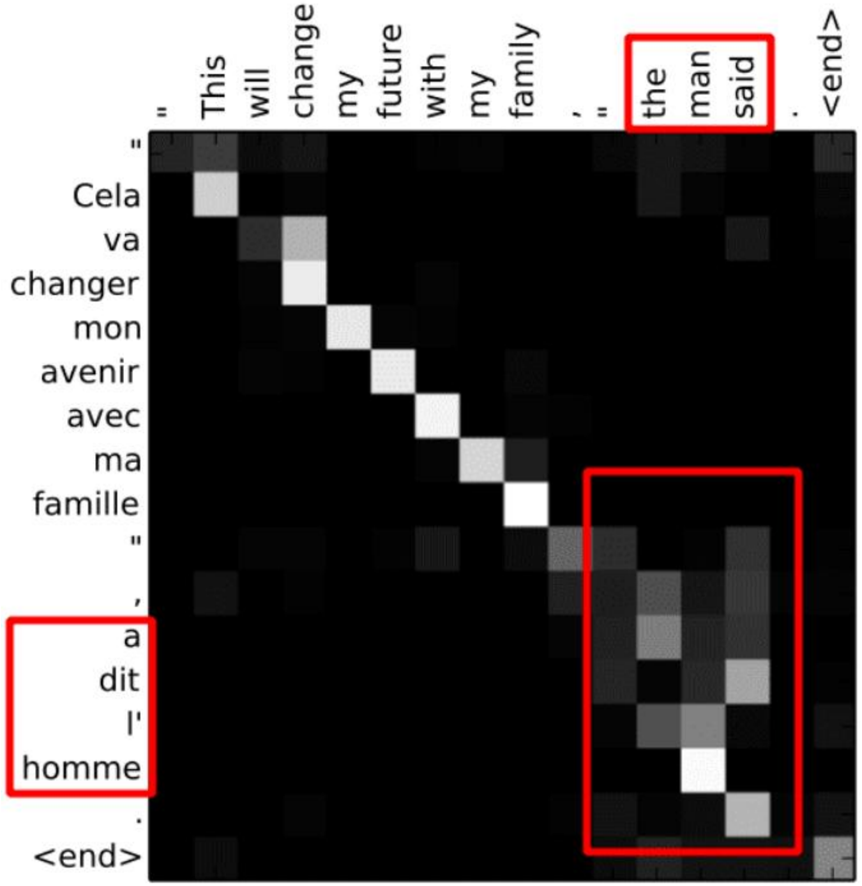
Thank you!

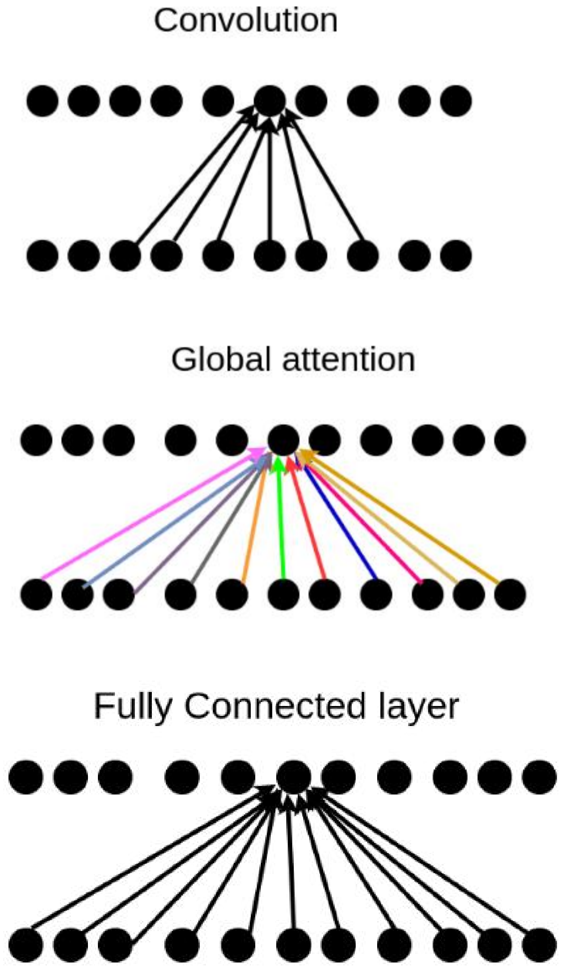
Attention Mechanism

This is what we do not need!



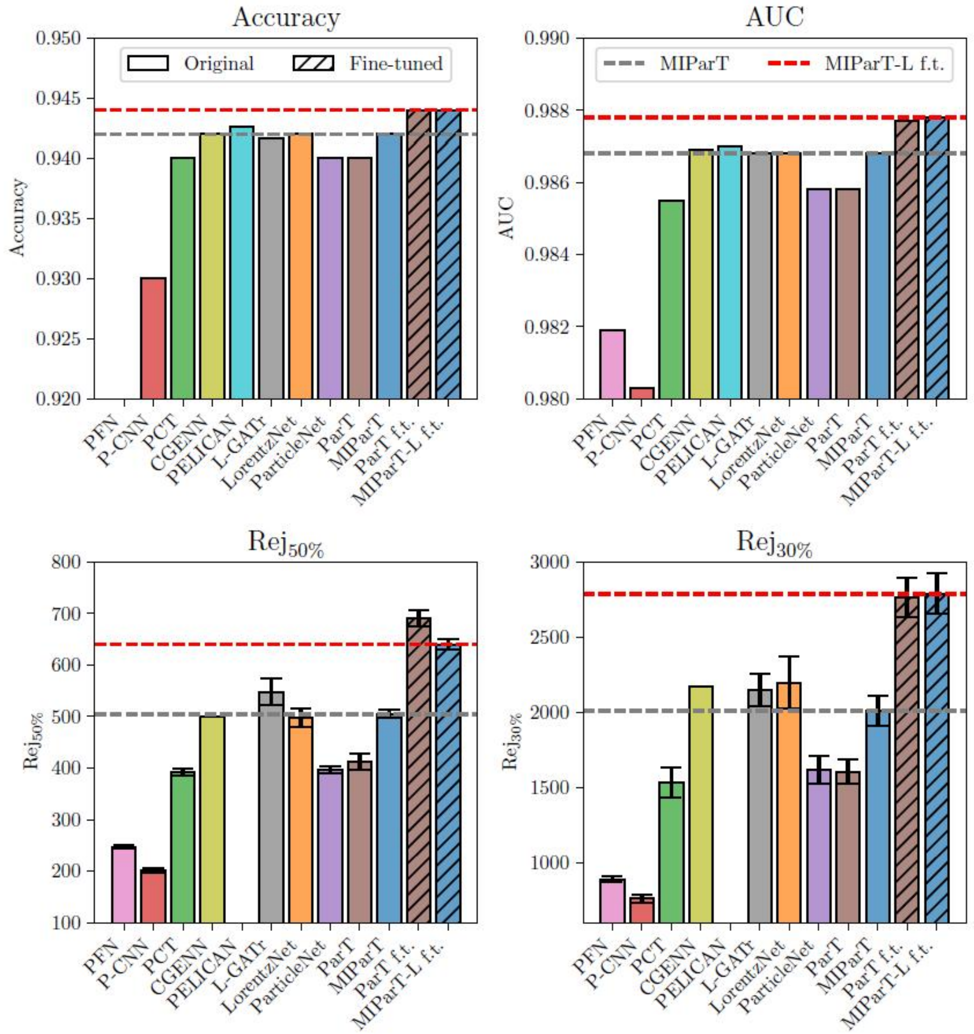
Transformer



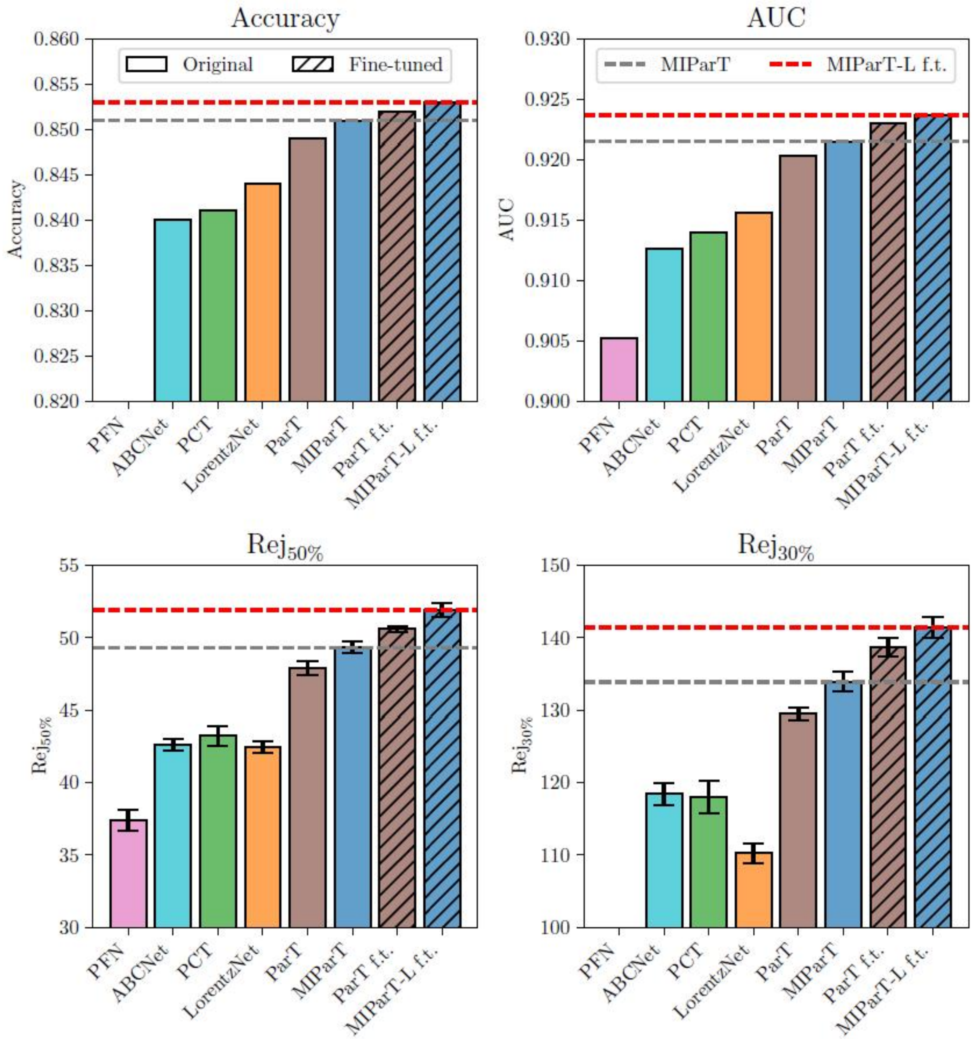


Attention Mechanism

MIParT Benchmark Validation



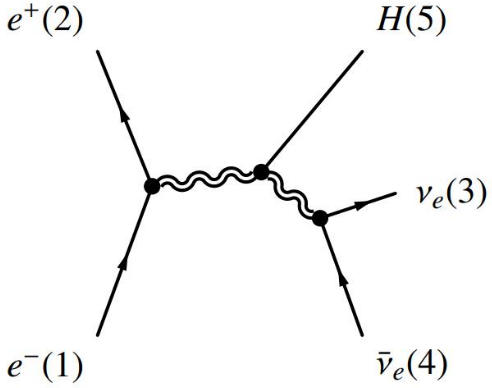
On the Top Tagging Dataset



On the Quark-gluon Dataset

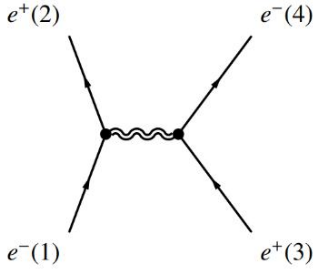
Application 1: Precision Hadronic Higgs Measurements

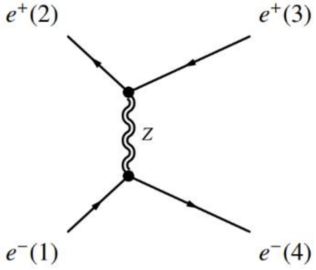
- **Signal**: ee→ZH, Z→$\nu\nu$, H→qq/gg
- @ 240GeV 20ab^{-1}



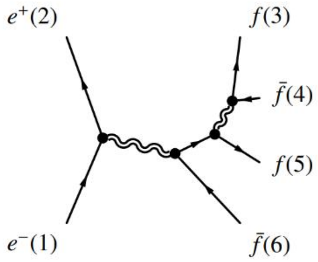
- **Backgrounds**: Dominated by H→ZZ, 2 fermions and 4 fermions

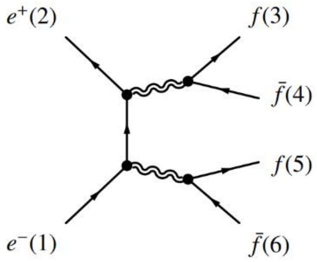
Category	Channel	Cross Section [fb]	Expected Events [M]	Simulated Events [M]
Signal	ZH, Z→νν, H->bb	26.71	0.5342	10
	ZH, Z→νν, H->cc	1.35	0.027	10
	ZH, Z→νν, H->ss	0.01	0.0002	10
	ZH, Z→νν, H->gg	3.97	0.0794	10
Background	ZH, Z→νν, H->ZZ; Z->νν, Z->qq	0.34	0.0068	10
	4f	369.71	7.3942	44
	2f	54106.86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





2 fermions





4 fermions