Evaluation of the measurement accuracy of Higgs boson coupling constants via $e^+e^- \to ZH(jj)$ processes at the International Linear Collider

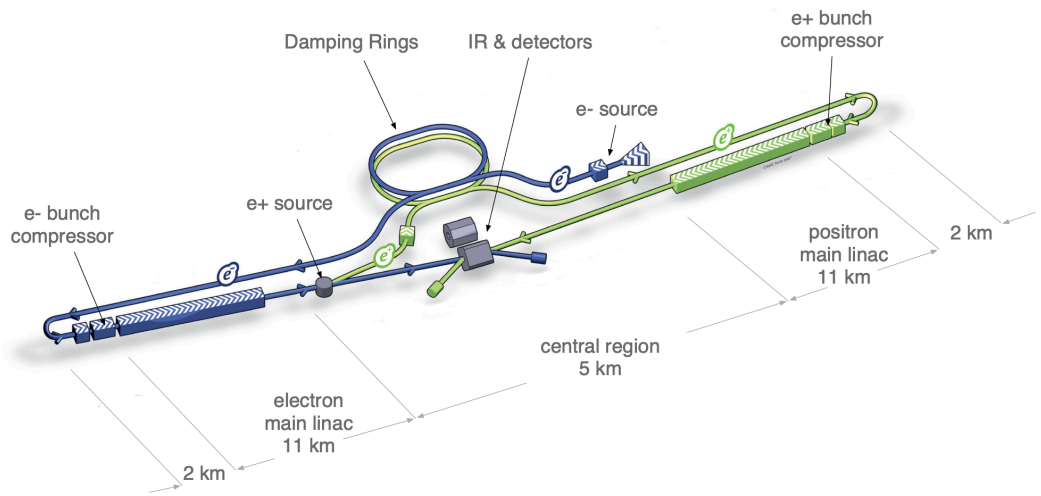
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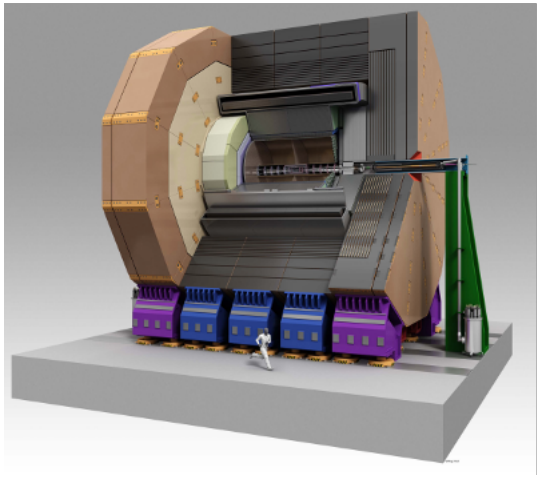
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ILC (Higgs Factory)





International Linear Collider (ILC)

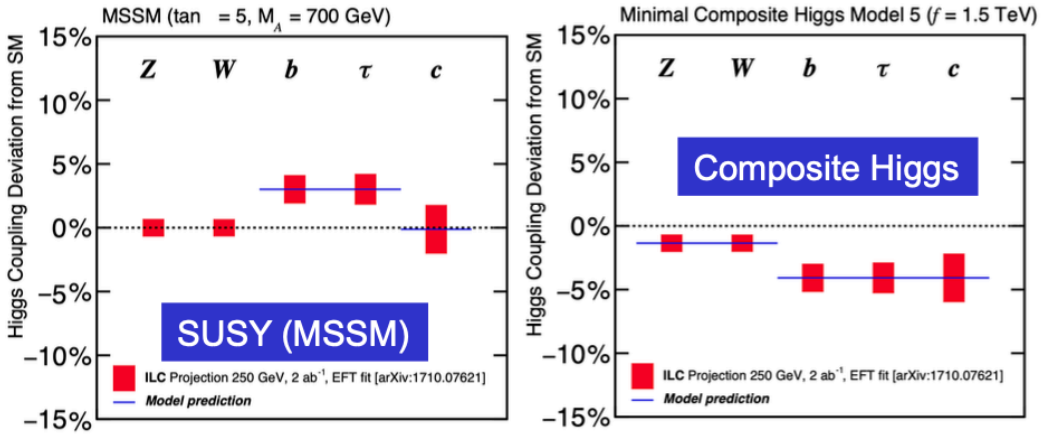
- electron/positron linear collider
  - with polarisation $\pm 80\%(\pm 30\%)$ for $e^-(e^+)$ beam
- Extendable Center-of-mass energy:
  - $250\ \mathrm{GeV}$ (precision measurement of Higgs)
  - $350\ \mathrm{GeV}$ ($t\bar{t}$ production threshold scan)
  - $500\ \mathrm{GeV}$ (Higgs self coupling)
  - > $1000\ \mathrm{GeV}$ (BSM direct search)

International Large Detector (ILD)

- Vertex Detector
  - impact parameter
- Tracker (Time Projection Chamber + Silicon Detector)
  - momentum and dE/dx for charged particles
- Calorimeter (ECAL, HCAL)
  - energy of photons and charged/neutral particles
  - TOF of charged particles
- Muon Detector

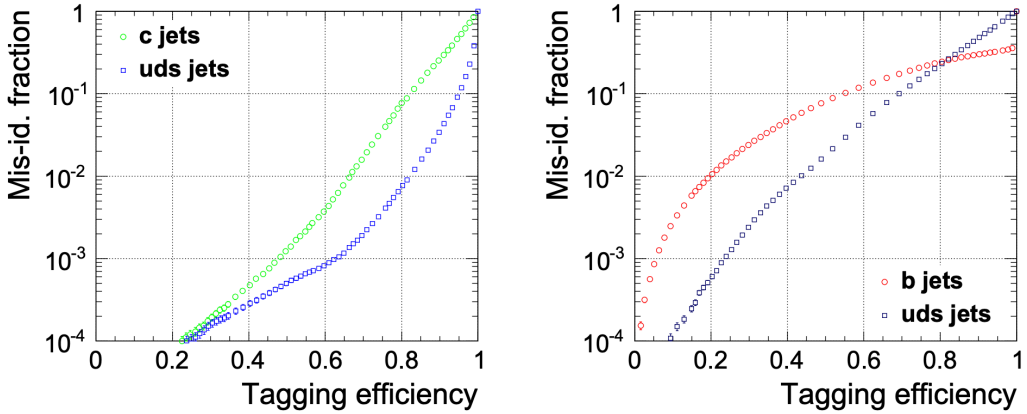
Motivation

- Measurement of Higgs boson couplings is one of the most important goals of the ILC
  - pattern of deviations can be used as probes of BSM models
  - separation of $H \to b\bar{b}/c\bar{c}/gg/s\bar{s}$ modes is critical
- Coupling to light quark (like c, s) is challenging due to its tiny Branching Ratio and large QCD background



LCFIPlus: old framework for flavor tagging

- arXiv:1506.08371
- Vertex finding → Jet clustering → Flavor tagging
  - GBDT for flavor tagging
  - separate jets into 3 categories: $b/c/\mathrm{light}$



(a) b tag (b) c tag

(framework before flavor tagging is also used for following analysis)

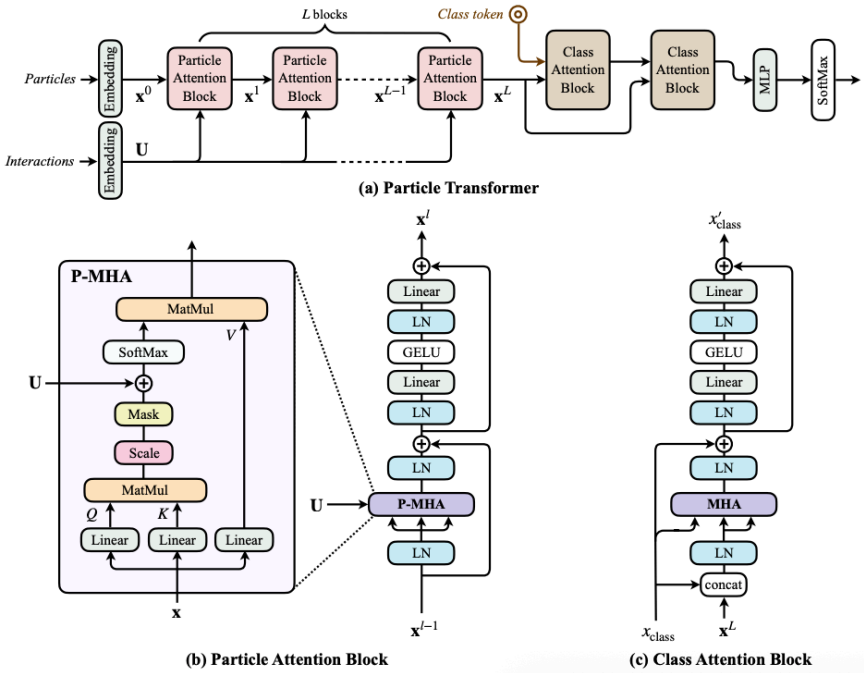
Flavor tagging with ParT + CPID

Introduction of Particle Transformer (ParT) with Comprehensive PID (CPID) enabled strange tagging

arXiv:2410.11322

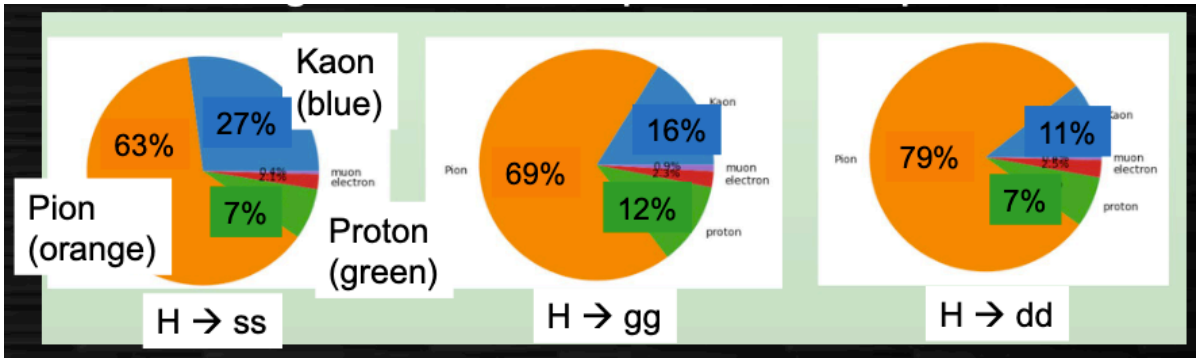
ParT

- Transformer-based architecture for Jet tagging
- Pair-wise variables (interaction, U) are added to plain Transformer encoder



CPID

- Computes hadron ID scores using dE/dx and Time-of-Flight
- Since strange jets have more strange hadrons, identifying Kaons made improvement in discrimination between strange jets and other light jets



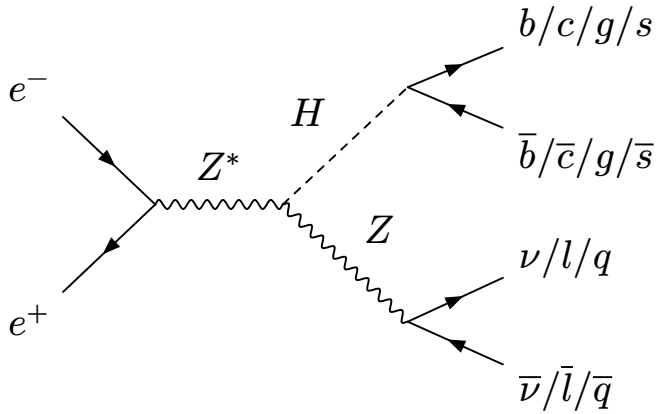
Aim:

- Evaluate measurement accuracy for Higgs couplings to b, c, g, s
  - in all 3 channels: $Z \to q\bar{q}/\nu\bar{\nu}/\ell^+\ell^-$
- Quantify improvements by the upgraded flavor tagging

Method

Basic configurations

- $P(e^-, e^+) = (-80\%, +30\%), (+80\%, -30\%)$ (eLpR, eRpL, respectively)
- Integrated luminosity $1.8\,\mathrm{ab}^{-1}$
  - $900\,\mathrm{fb}^{-1}$ for eLpR, eRpL
- Bkg: possible processes with 2/4 fermions in the final state
- Analysis channel is separated according to Z boson decay modes
  - mainly $Z \to q\bar{q}$ ch., then briefly $Z \to \nu\bar{\nu}/\ell^+\ell^-$ ch.



target process

Analysis flow

1. Reconstruction
- track/particle reco.
- CPID
- isolated lepton/photon tag
- jet clustering (Durham)
- flavor tagging
  - ParT w/ CPID → 11 categories ($u/\bar{u}/d/\bar{d}/c/\bar{c}/s/\bar{s}/b/\bar{b}/g$)

→ **2. Precut**
- kinematic cuts
- ParT score cut (only $Z \to q\bar{q}$)

→ **3. H/Z reco.**
- jet pairing (only $Z \to q\bar{q}$)

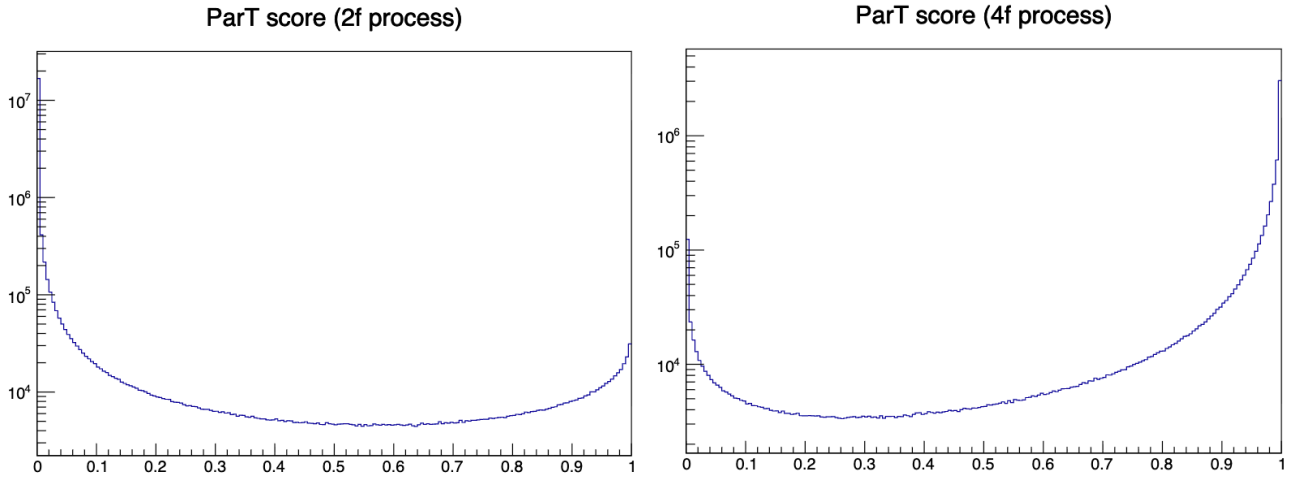
→ **4. Analysis**
- multi-class DNN
  - bkg suppression
- Template fit
  - 4D fit + toy MC

2-fermion veto by ParT (only for $Z \to q\bar{q}$)

Done after event reconstruction and kinematic cuts

- ParT training for 4f/2f event separation
  - 2f bkg largely survives the y-value cut
- Train with 4-momentum and CPID score of all particles
  (CPID scores only available for charged particles with energy > 1 GeV)

# used samples	train	val	test
Higgs process	0	0	3.5M
4f non-Higgs process	10M	50k	3.5M
2f process	10M	50k	30M



4f-likeness score by ParT

precut: score > 0.1
→ Decreased 2f events down to 5.2%

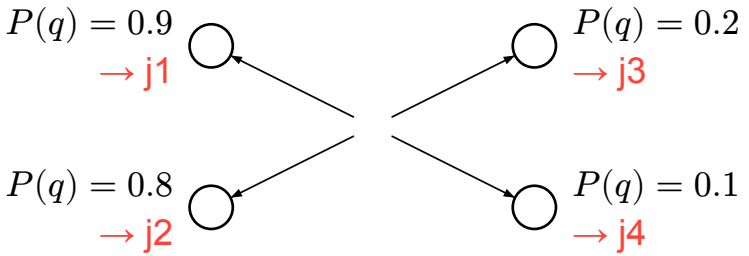
# events	full	after precut
4f processes	15.2M	15.1M
2f process	67.0M	3.5M

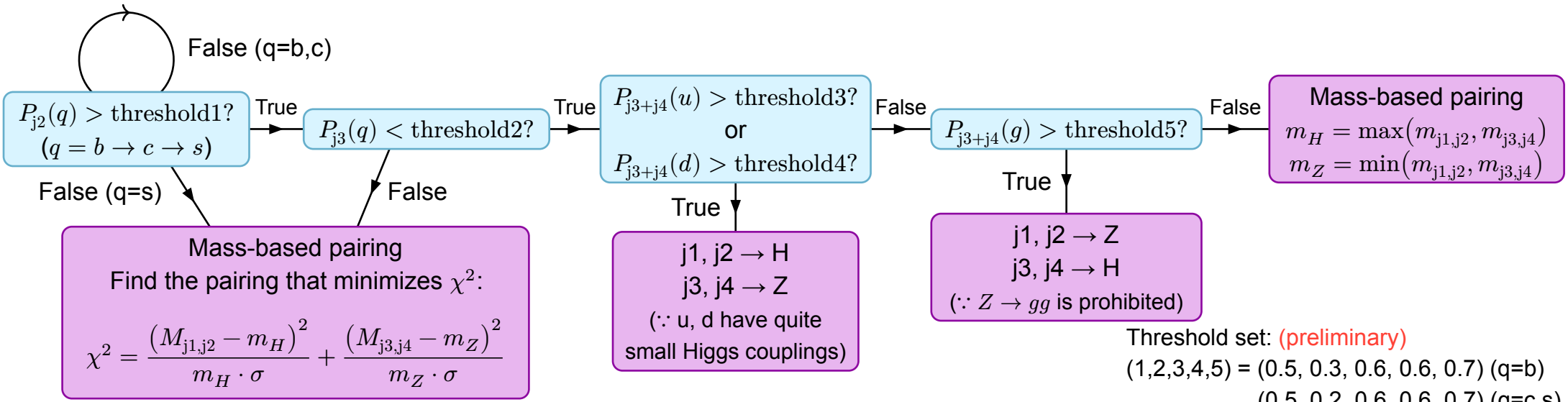
H/Z reconstruction (only for $Z \to q\bar{q}$)

- Reconstructed particles are clustered into 4 jets → Perform jet pairing
- Assign jets to H/Z, mainly using flavor tag scores
  1. check if 2 pairs (qq+q'q') can be formed
  2. if possible,
     - if the rest are u,d,g: Assign H/Z via flavor scores
     - otherwise: rely on mass-based pairing
  3. if not, go on to next flavor test
  4. when no pair was made, rely on mass-based method (minimizing χ^2)

Definition of $P(q)$: q-tag + $\bar{q}$-tag

→ Let "ji" be the jet with the i-th highest $P(q)$ value.





Threshold set: (preliminary)
(1,2,3,4,5) = (0.5, 0.3, 0.6, 0.6, 0.7) (q=b)
(0.5, 0.2, 0.6, 0.6, 0.7) (q=c,s)

DNN + Template fit

- DNN (TMVA, multi-class) to suppress SM bkg → events with Higgs score > 0.9 are used

channel	DNN classes	precut
$q\bar{q}$	Hqq / 4f SM / 2f SM	ParT 2f veto (> 0.1), $100 < m_H < 140$ GeV
$\nu\bar{\nu}$	H$\nu\nu$ / $Z/\gamma^* \to q\bar{q}$ / $WW \to qq\ell\nu$ / other	iso. lepton veto, $M_{\text{miss}} < 140$ GeV, $100 < M_{\text{jj}} < 200$ GeV, …
$\ell\ell$	Higgs / SM bkg	2 iso. leptons, same as previous study

Template Creation

- **f-likeness** ($f = b, c, g, s$) of the 2 Higgs jets:

$$L_f = \frac{f_1 f_2}{f_1 f_2 + (1-f_1)(1-f_2)} \quad \left(\text{w/} \sum_f L_f = 1 \right)$$

- 4D histogram (b, c, s-likeness + DNN score)
  - b: {0, 0.2, 0.6, 0.9, 1}, c: {0, 0.2, 0.99, 0.995, 0.998, 1}
  - s: {0, 0.2, 0.6, 0.9, 1}, DNN: {0.9, 0.95, 0.99, 0.995, 1}

Sensitivity Evaluation

- **Toy MC**: 10^6 pseudo-experiments (Poisson fluctuation per bin)
- **Binned likelihood fit** on signal strengths r_s:

$$f = \sum_s r_s N^s_{ijkl} + N^{\text{bkg}}_{ijkl}$$

(bkg / other Higgs decays normalisation fixed)

- $\sigma = \text{RMS}/\text{Mean}$ of fitted r_s
- $1/\sigma^2_{\text{L+R}} = 1/\sigma^2_L + 1/\sigma^2_R$

$Z \to q\bar{q}$: results

acc. [%]	this work			previous work	
	eLpR	eRpL	L+R	ILC	FCC
$H \to b\bar{b}$	0.64	0.76	0.49	1.5	0.3
$H \to c\bar{c}$	14.4	12.1	9.3	10.2	3.5
$H \to gg$	7.3	5.7	4.5	13.1	3.1
$H \to s\bar{s}$	3583	2657	2134		410

- ILC: H. Ono and A. Miyamoto, (2013), eLpR only, $250\,\mathrm{fb}^{-1}$
- FCC: A. Del Vecchio et al., (2025), no polarisation, $10.8\,\mathrm{ab}^{-1}$

- Good improvement for $H \to b\bar{b}/gg$
- The accuracy for $H \to c\bar{c}$ is particularly poor
  - only limited improvement over the previous study
- Large discrepancy in $H \to s\bar{s}$:
  - the sensitivity is only about half that of a dedicated $H \to s\bar{s}$ analysis
  - the gap to FCC is possibly due to differences in simulation conditions (e.g. luminosity, polarisation, fast/full simulation, etc.)

Background breakdown in the $H \to c\bar{c}$ peak bin
($b < 0.2$, $c > 0.998$, $s < 0.2$, $0.95 < \mathrm{DNN} < 0.99$)

process	eLpR		eRpL	
	yield	frac.	yield	frac.
$H \to c\bar{c}$ (signal)	367	2.4 %	227	7.9 %
2f ($Z/\gamma^* \to q\bar{q}$)	3246	20.8 %	1131	39.2 %
4f mixed hadronic	5509	35.4 %	425	14.7 %
WW hadronic	4547	29.2 %	350	12.1 %
ZZ hadronic	1455	9.3 %	553	19.2 %
single-W (semi-lep.)	121	0.8 %	0.8	0.0 %
other Higgs decays	331	2.1 %	198	6.9 %
total	15 576		2885	

- 2f: almost all $Z/\gamma^* \to c\bar{c}$ (+ hard gluon, 4-jet like)
- 4f: $WW \to csud$, $c\bar{c}s\bar{s}$

$Z \to \nu\bar{\nu}/\ell^+\ell^-$ channels

$Z \to \nu\bar{\nu}$

- 4-class DNN: H$\nu\nu$ / $Z/\gamma^* \to q\bar{q}$ / $WW \to qq\ell\nu$ / other
- Main bkg: $WW \to qq\ell\nu$, $Z/\gamma^* \to q\bar{q}$
  - surviving $Z/\gamma^* \to q\bar{q}$: double ISR + b/c semi-leptonic decay
- $H \to s\bar{s}$: worse than previous BDT-only analysis (511 %)
  - template fit may be counterproductive for a very small signal?

acc. [%]	eLpR	eRpL	L+R	FCC
$H \to b\bar{b}$	0.80	0.97	0.62	0.35
$H \to c\bar{c}$	8.8	7.6	5.7	2.06
$H \to gg$	4.3	4.2	3.0	1.01
$H \to s\bar{s}$	1274	1028	800	100

$Z \to \ell^+\ell^-$

- 2-class DNN: Higgs / SM bkg
- Remaining bkg: almost only irreducible $\ell\ell qq$ ($ZZ/Z\gamma^*$)
  - ~ 6–15 % of the signal yield

acc. [%]	$Z \to e^+e^-$			$Z \to \mu^+\mu^-$			$\ell\ell$	FCC
	eLpR	eRpL	L+R	eLpR	eRpL	L+R	comb.	
$H \to b\bar{b}$	2.2	2.7	1.71	2.1	2.3	1.55	1.14	0.60
$H \to c\bar{c}$	18.3	19.7	13.4	16.3	16.4	11.6	8.8	3.47
$H \to gg$	8.2	9.6	6.2	7.4	8.4	5.6	4.1	1.93
$H \to s\bar{s}$	3938	3517	2623	3259	2909	2170	1672	220

Summary and Prospects

Summary

- Evaluated $H \to b\bar{b}/c\bar{c}/gg/s\bar{s}$ measurement accuracy at ILC 250 GeV ($1.8\,\mathrm{ab}^{-1}$) with ParT + CPID flavor tagging
- DNN + template fit applied to all of $Z \to q\bar{q}/\nu\bar{\nu}/\ell^+\ell^-$ channels
- obtained results shown in table

$\sigma_{\mathrm{L+R}}$ [%]	$Z \to q\bar{q}$	$Z \to \nu\bar{\nu}$	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$	combined	FCC
$H \to b\bar{b}$	0.49	0.62	1.71	1.55	0.36	0.21
$H \to c\bar{c}$	9.3	5.7	13.4	11.6	4.3	1.56
$H \to gg$	4.5	3.0	6.2	5.6	2.1	0.85
$H \to s\bar{s}$	2134	800	2623	2170	683	89

combined: 4 channels treated as independent, $1/\sigma^2 = \sum_{\mathrm{ch}} 1/\sigma^2_{\mathrm{ch}}$

Prospects

- $Z \to q\bar{q}$: check whether the surviving 2f bkg is due to the pile-up rejection
  - analysis with the overlay removed using MC truth is in progress
- DNN + template fit may not be the best approach → consider other methods

back up

Comprehensive Particle IDentification (CPID)

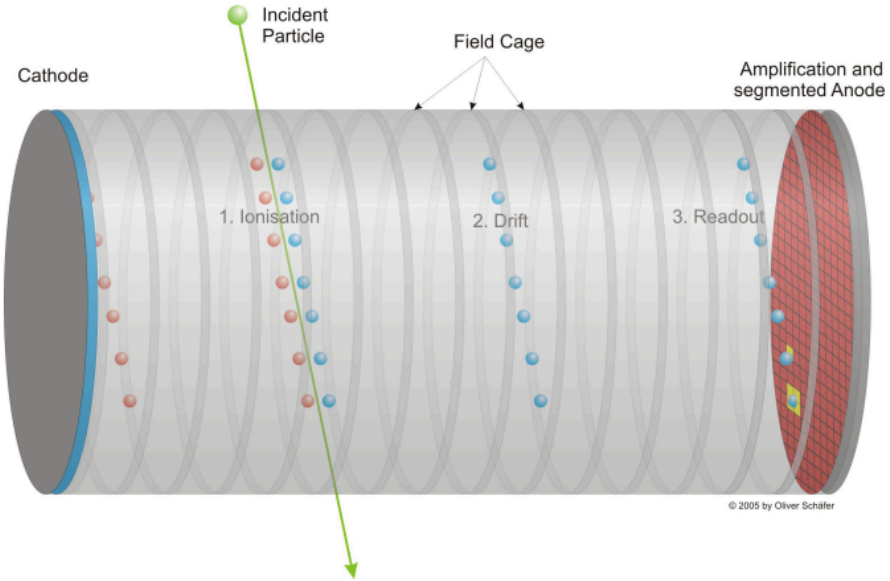
- computes hadron ID scores using dE/dx and Time-of-Flight
- 5 class separation: (e^-, μ, π, K, p)

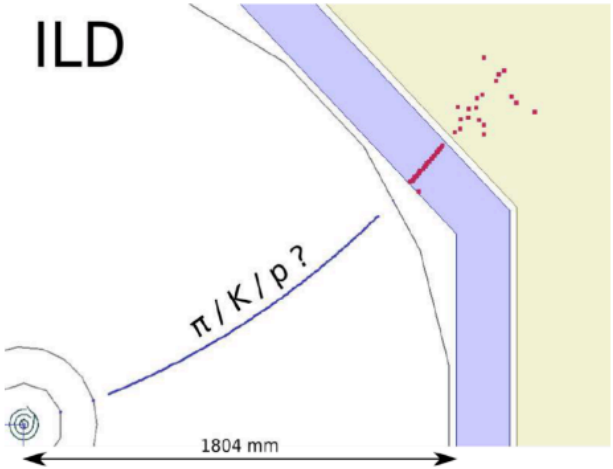
dE/dx

- useful to determine the particle species via Bethe's equation
- measure $\mathcal{O}(100)$ times per track in TPC

TOF

- used to compute particle mass along with reconstructed track length
- measure hit timing in ECAL with time resolution $100\,\mathrm{ps}$.

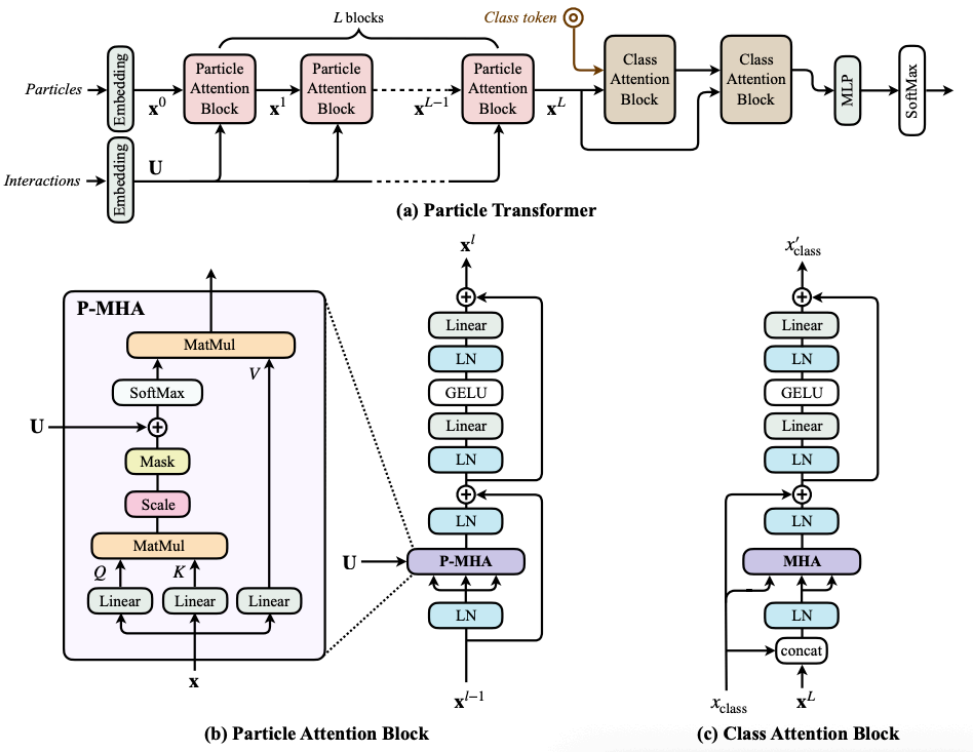




Particle Transformer

- Transformer based architecture
- uses Interaction(U)
  - mass, angle, etc..(table)
  - → relationships btw. particles can be used for training

interaction	definition
$\log(\Delta R)$	logarithm of $\sqrt{(\eta_i-\eta_j)^2+((\varphi_i-\varphi_j+\pi) \bmod 2\pi-\pi)^2}$
$\log(kt)$	logarithm of $\sin\theta_{ij} * p_{\min}$ $(p_{\min}=\min(p_i,p_j))$
$\log z$	logarithm of $p^{\mathrm{T}}_{\min}/(p^{\mathrm{T}}_i+p^{\mathrm{T}}_j)$ $(p^{\mathrm{T}}_{\min}=\min(p^{\mathrm{T}}_i,p^{\mathrm{T}}_j))$
$\log m$	logarithm of invariant mass



architecture of ParT

LCFIPlus is previous method using BDT

~9 times better performance than LCFIPlus

	b-tag 80% eff.		c-tag 50% eff.	
background	c jets	uds jets	b jets	uds jets
LCFIPlus (BDT)	6.3%	0.79%	7.4%	1.2%
ParT (initial)	1.3%	0.25%	1.0%	0.43%
ParT (improved)	0.48%	0.14%	0.86%	0.34%

ParT for 2f veto: configuration

# used samples	train	val	test
Higgs process	0	0	3.5M
4f non-Higgs process	10M	50k	3.5M
2f process	10M	50k	30M

precut: score > 0.1

→ Decreased 2f events down to 5.2%

# events	full	after precut
4f processes	15.2M	15.1M
2f process	67.0M	3.5M

configuration of ParT

layout	head	8
	layer	4
	particle embedding dim.	128
	interaction embedding dim.	64
	activation func.	GELU
	MLP layer	2
strategy	framework	weaver
	optimizer	Ranger
	loss func.	cross entropy error
hyperparameter	training epoch	20
	batch size	768
	initial LR	1×10^{-4}

$Z \to \nu\bar{\nu}$: comparison of analysis methods

$\sigma_{\mathrm{L+R}}$ [%]	bkg	$b\bar{b}$	$c\bar{c}$	gg	$s\bar{s}$
JPS: 6-class DNN + cut (R. Sugawara)	w/o `2f_Z_had`	0.54	4.77	2.02	–
2-class DNN + template fit	w/o `2f_Z_had`	0.52	5.3	2.65	845
2-class DNN + template fit	+`2f_Z_had`, `4f_Z_sl`	0.60	7.6	3.6	1025
4-class DNN + template fit	+`2f_Z_had`, `4f_Z_sl`	0.61	5.7	3.0	774
4-class, `2f_Z_had` MC stat. × 8–12	+`2f_Z_had`, `4f_Z_sl`	**0.62**	**5.7**	**3.0**	**800**

- JPS: 6-class DNN + cut-and-count (R. Sugawara)
- $Z/\gamma^* \to q\bar{q}$ and $(e^+e^- \to) Ze^+e^- \to e^+e^-q\bar{q}$ added to bkg
- 2-class DNN was pulled by the large $Z/\gamma^* \to q\bar{q}$ weight → $WW \to qq\ell\nu$ rejection got worse → 4-class DNN
- Increased $Z/\gamma^* \to q\bar{q}$ MC stat. (2 % → 16 / 24 % of full sample): no change

$Z \to \nu\bar{\nu}/\ell^+\ell^-$: remaining background

Breakdown in the $H \to c\bar{c}$ peak bin

process	$Z \to \nu\bar{\nu}$		$Z \to e^+e^-$		$Z \to \mu^+\mu^-$	
	eLpR	eRpL	eLpR	eRpL	eLpR	eRpL
$H \to c\bar{c}$ (signal)	275.4	138.2	15.6	11.4	16.6	15.1
4f WW semi-lep.	404.8	24.6				
4f $ZZ/Z\gamma^*$ ($\nu\nu qq$ / $\ell\ell qq$)	161.1	32.4	7.1	8.6	12.0	4.2
2f $Z \to q\bar{q}$	71.5	14.8				
other SM	22.1	1.0				
other Higgs decays	30.2	17.8	2.1	1.2	2.1	1.4
$\left(S/\sqrt{S+B}\right)^{-1}$ [%]	11.3	10.9	31.8	40.2	33.4	30.0

- $Z \to \nu\bar{\nu}$: $WW \to qq\ell\nu$ dominates in eLpR;
- $Z \to \ell^+\ell^-$: SM bkg is only the irreducible $\ell\ell qq$ final state ($ZZ/Z\gamma^* \to \ell\ell qq$; for ee also $(e^+e^- \to)Ze^+e^- \to e^+e^-q\bar{q}$)
  - DNN overtraining (val. loss minimum at epoch 2–3, small raw bkg stat.); Bhabha / 2f, 4f hadronic not yet included