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Measuring the Electron Yukawa Coupling at CEPC

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17 August 2026

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Physics Motivation

- Higgs production mediated by first-generation fermion Yukawa couplings （u、d、e^-、υ_e) remains experimentally unverified.
- The exceedingly small electron Yukawa coupling leads to a dramatically low resonant Higgs production cross section, making its measurement extremely challenging.
- Hadron colliders cannot effectively measure the electron Yukawa coupling, as the signal is overwhelmed by an enormous background. A new experimental approach is therefore required.
- CEPC's clean collision environment and precisely controlled initial state provide an ideal experimental platform for precision electroweak measurements.

Physics Motivation

- This study probes Higgs production mediated by first-generation fundamental fermion Yukawa couplings.
- It provides a rigorous test of the electron Yukawa coupling — **the first such investigation at CEPC**.
- It explores electron-associated scalar physics beyond the Standard Model, with sensitivity to energy scales of approximately 100 TeV and beyond.
- It searches for the potential existence of new particles nearly degenerate in mass with the Higgs boson.

Research Status

FCC–ee [link]	CMS [link]	ATLAS [link]	HL–LHC [link]	FCC–hh [link]
$y_e \le 1.6 y_e^{SM}$	$y_e \le 240 y_e^{SM}$	$y_e \le 260 y_e^{SM}$	$y_e \le 200 y_e^{SM}$	$y_e \le 50 y_e^{SM}$

Table 6 Individual significances (in std. deviations σ) expected per decay channel for s-channel Higgs boson production in e^+e^- collisions at FCC-ee for $\mathcal{L}_{int} = 10\,ab^{-1}$ and $\delta_{\sqrt{s}} = 4.1$ MeV. The last column quotes the combined significance

$H \to gg$	$H \to WW^* \to$ $\ell\nu\ 2j;\ 2\ell\ 2\nu;\ 4j$	$H \to ZZ^* \to$ $2j\ 2\nu;\ 2\ell\ 2j;\ 2\ell\ 2\nu$	$H \to b\bar{b}$	$H \to \tau_{had}\tau_{had};$ $c\bar{c};\ \gamma\gamma$	Combined
1.1σ	$(0.53 \otimes 0.34 \otimes 0.13)\sigma$	$(0.32 \otimes 0.18 \otimes 0.05)\sigma$	0.13σ	$< 0.02\sigma$	1.3σ

Main Content

- Measure the s-channel resonant Higgs production cross section at the CEPC, and extract y_e via $\sigma \propto y_e^2$.

- Focus on the most promising signal channel, $e^+e^- \to H \to gg$, and its corresponding background, $e^+e^- \to q\bar{q}$.

- Since FCC-ee only relies on simple event pre-selection and BDTs to improve the S/B, we can build upon their approach by employing more advanced methods to further enhance the significance:
  - Exploit beam polarization to enhance the signal cross section.
  - Employ machine learning (Particle Transformer) for event selection optimization, combined with a simultaneous fit to further enhance the signal sensitivity.

Polarization Study

Assess the feasibility of enhancing the S/B via polarization:

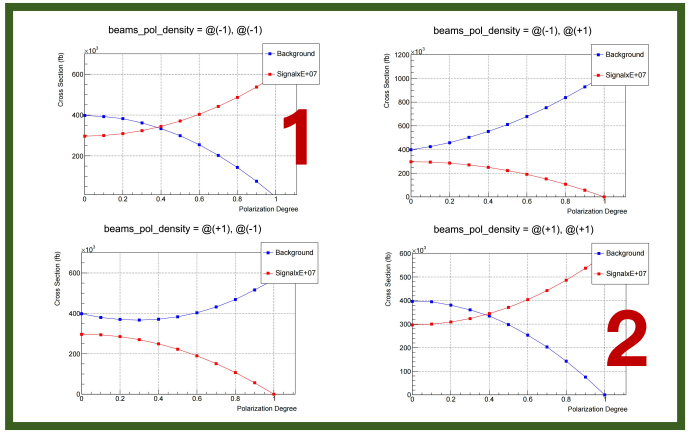
1. **Monte Carlo simulation — longitudinal polarization:**

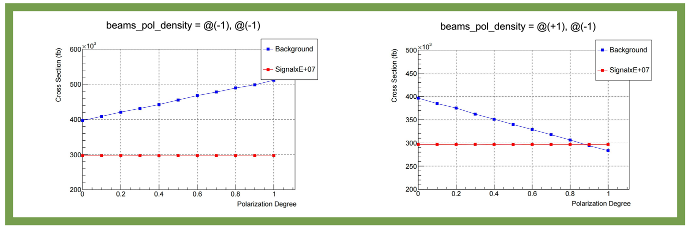
- Keep the degree of polarization the same
  - electron —— left–handed polarization, positron —— left–handed ~
  - electron —— left–handed polarization, positron —— right–handed ~
  - electron —— right–handed polarization, positron —— left–handed ~
  - electron —— right–handed polarization, positron —— right–handed ~

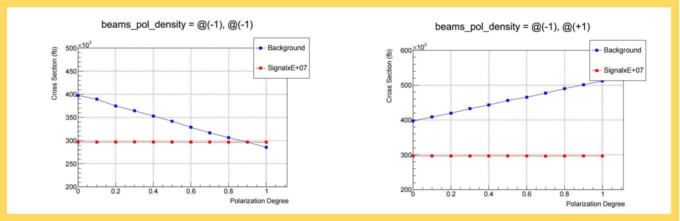
  Only change the electron's degree of polarization, keep $P_{e^+} = 0$.
  - electron —— left–handed polarization
  - electron —— right–handed polarization

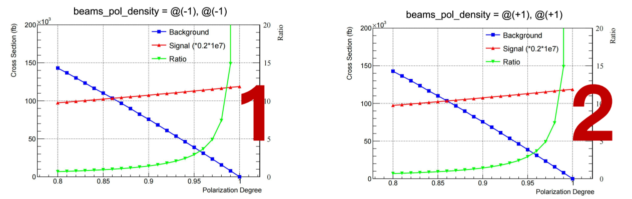
  Only change the positron's degree of polarization, keep $P_{e^-} = 0$.
  - positron —— left–handed polarization
  - positron —— right–handed polarization

- The scan results show that longitudinal polarization requires an excessively high polarization degree to reach the desired S/B. This approach is therefore **discarded**.









Polarization Study

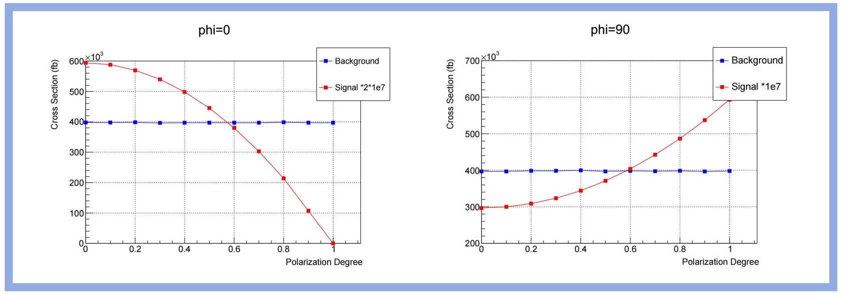
2. Monte Carlo simulation — transverse polarization

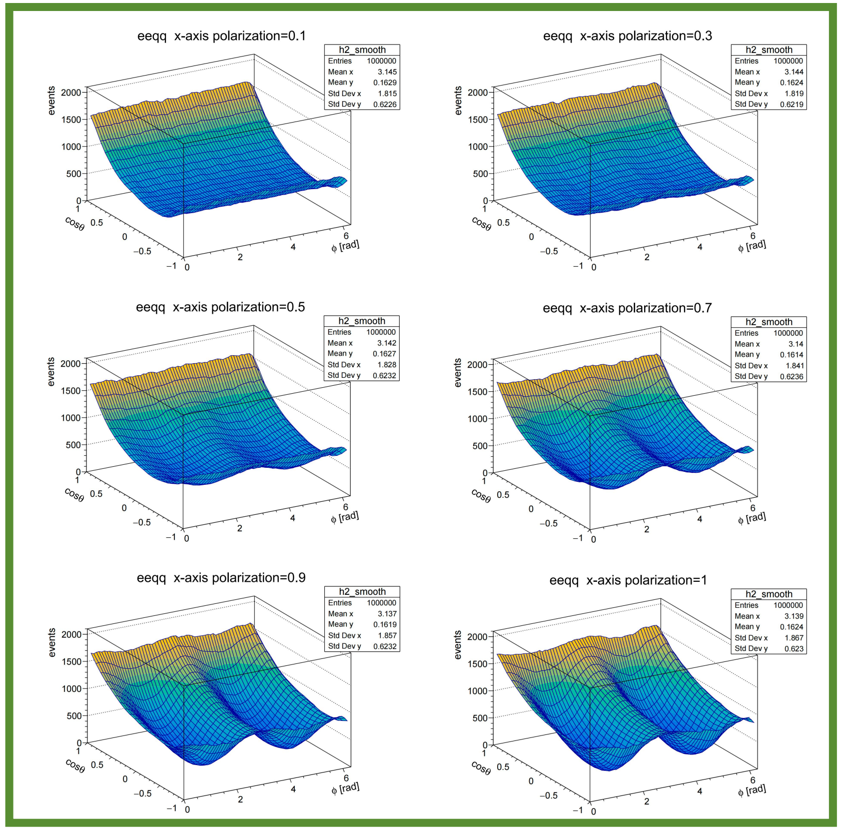
- The polarization direction serves as the primary discriminant: the signal cross section varies with it, whereas the background remains constant. Maximal signal enhancement is achieved with electron polarization along +x and positron polarization along −x.

Transverse polarization introduces two additional discriminants beyond the longitudinal case:

- ϕ: Signal and background distributions are examined at different polarization degrees. Higher polarization → better separation.
- $\cos\theta$: Signal and background are well separated regardless of polarization degree. (Signal remains uniform in both ϕ and cos θ; only background plots are shown.)

These variables can be fed into ParT or a simultaneous fit to further boost the S/B ratio.



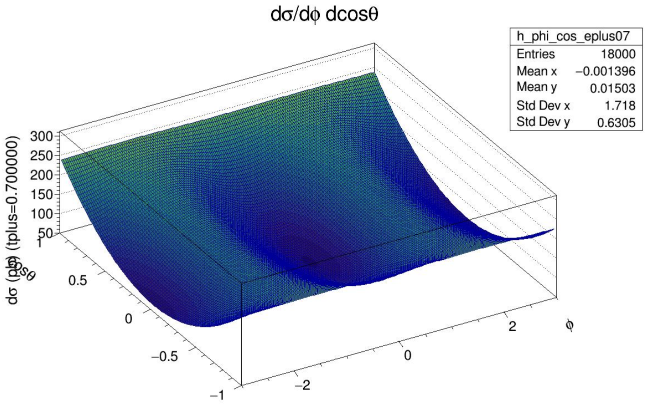


Polarization Study

3. Mathematical formula verification and fitting:

- **Formula verification:** The differential cross section formula for $e^+e^- \to q\overline{q}$ under transverse polarization was derived (**link**) based on the relevant literature. Evaluated at $s = (91.1880\ GeV)^2$, the calculated total cross section is 39.69 nb, in good agreement with the existing experimental result of 41.48 nb (**link**).

$$\frac{d\sigma}{d\Omega} = \frac{3\alpha^2}{4s}\Bigg[\left(1 + \frac{2v_e v_q}{\sin^2\theta_W \cos^2\theta_W} \cdot \frac{s(s-M_Z^2)}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2} + \frac{(v_e^2+a_e^2)(v_q^2+a_q^2)}{\sin^4\theta_W \cos^4\theta_W} \cdot \frac{s^2}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2}\right)(1+\cos^2\theta)$$
$$+ \left(\frac{4a_e a_q}{\sin^2\theta_W \cos^2\theta_W} \cdot \frac{s(s-M_Z^2)}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2} + \frac{8v_e a_e v_q a_q}{\sin^4\theta_W \cos^4\theta_W} \cdot \frac{s^2}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2}\right)\cos\theta$$
$$- P^2\left(1 + \frac{2v_e v_q}{\sin^2\theta_W \cos^2\theta_W} \cdot \frac{s(s-M_Z^2)}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2} + \frac{(v_e^2-a_e^2)(v_q^2-a_q^2)}{\sin^4\theta_W \cos^4\theta_W} \cdot \frac{s^2}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2}\right)\sin^2\theta\cos 2\phi$$
$$+ P^2 \cdot \frac{2a_e v_q}{\sin^2\theta_W \cos^2\theta_W} \cdot \frac{sM_Z\Gamma_Z}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2} \cdot \sin^2\theta \sin 2\phi\Bigg]$$



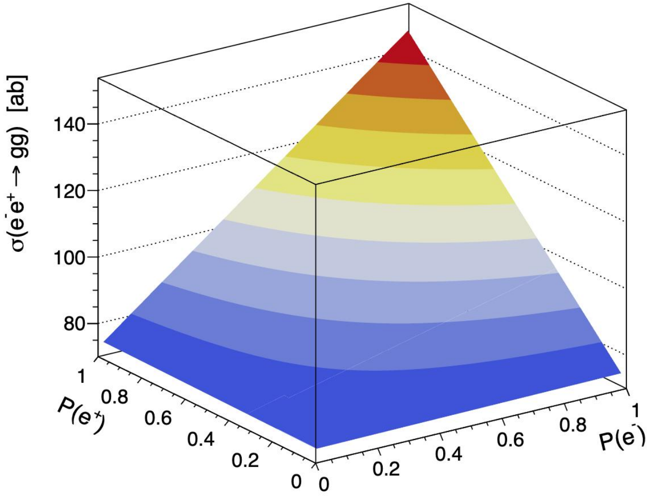
- **Fitting and plotting with the theoretical formula:** The resulting images are consistent with those obtained from Monte Carlo simulation, providing a cross-validation that the polarization-based S/B enhancement method is viable.

Analysis Framework/Sample Generation

Signal: $e^+e^- \to H \to gg$ **Background:** $e^+e^- \to q\bar{q}$ **Tool:** Whizard3

Variation of signal cross- section under different polarization conditions (ISR is turned off here to more intuitively observe the impact of polarization on cross-section):

P_{e^+}/P_{e^-}	0	60%	70%	80%	90%	100%
0	73.8	73.8	73.8	73.8	73.8	73.8
40%	73.8	91.6	94.5	97.5	100.4	103.4
70%	73.8	104.8	110.0	115.2	120.4	125.5
100%	73.8	118.1	125.5	132.9	140.3	147.7



Condition Settings:

- Set the collision energy to 125.0 GeV and enable ISR. (For the impacts of ISR and beam energy spread on the signal cross-section, see the appendix A for details.)
- Set both electrons and positrons to be transversely polarized with P=70%, where electrons are polarized along the positive x-axis and positrons along the negative x-axis.

Analysis Framework/Detector Simulation and Object Reconstruction

Signal: $e^+e^- \to H \to gg$ **Background:** $e^+e^- \to q\bar{q}$ **Tool:** Delphes

We use Delphes to simulate the CEPC detector response and reconstruct leptons, photons, and jets from final-state particles.

		b jets (CEPC)	c jets (CEPC)	Gluon jets (CEPC)	Gluon jets (FCC-ee)
Reco/tagging efficiency		92.3%	80.3%	65.0%	70%
Mistagging rates	b jets	/	4.1%	2.7%	0.001%
	c jets	2.8%	/	6.6%	0.01%
	u jets	0.3%	3.0%	18.4%	1%
	d jets	0.3%	3.0%	18.4%	1%
	s jets	0.3%	4.0%	16.1%	1%
	Gluon jets	2.5%	5.2%	/	/

- The CEPC performance, based on full simulation, is provided by Zhang Kaili.
- The FCC-ee performance is based on idealized assumptions of a perfect detector.

Analysis Framework/Event Preselection

	CEPC	FCC–ee
$\sigma_{ee\to H\to gg}$	34.3 ab (with polarization)	23 ab (without polarization)
$\sigma_{ee\to qq}$	396.3 pb (with isr)	61 pb (without isr)
L	$10\ ab^{-1}/year$	$10\ ab^{-1}/year$
cut	2 gluon – tagged jets	2 gluon – tagged jets
	0 isolated $l^{\pm}$	0 isolated $l^{\pm}$
	visible mass > 114GeV	
S/B (before cut)	8.6×10^{-8} (with isr)	3.8×10^{-7} (without isr)
S/B (after cut)	4.3×10^{-6}	1.8×10^{-3}
Signal efficiency	24.91%	50%
Background efficiency	0.51%	0.006%

- CEPC preselection is performed programmatically via ROOT tree branches.
- FCC-ee relies on direct numerical calculation to obtain the idealized result.

Analysis Framework/Particle Transformer

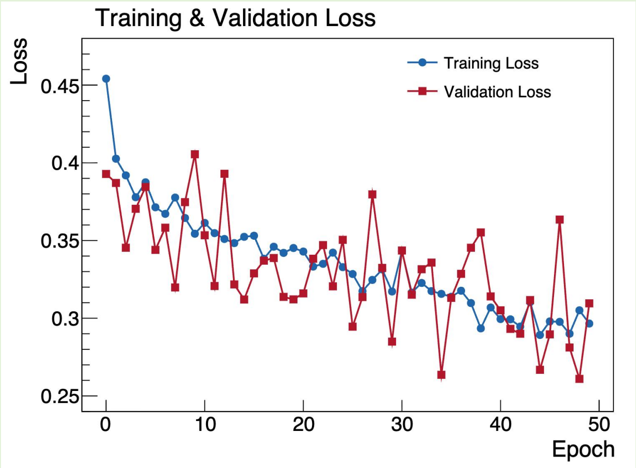
Input Features (see the appendix B for plots)

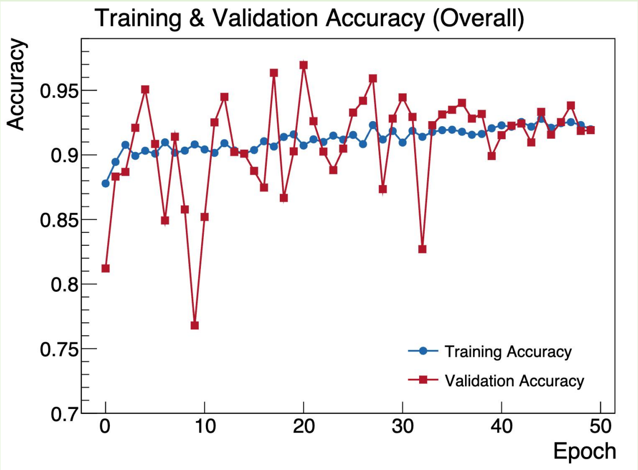
- Particle-level Features：

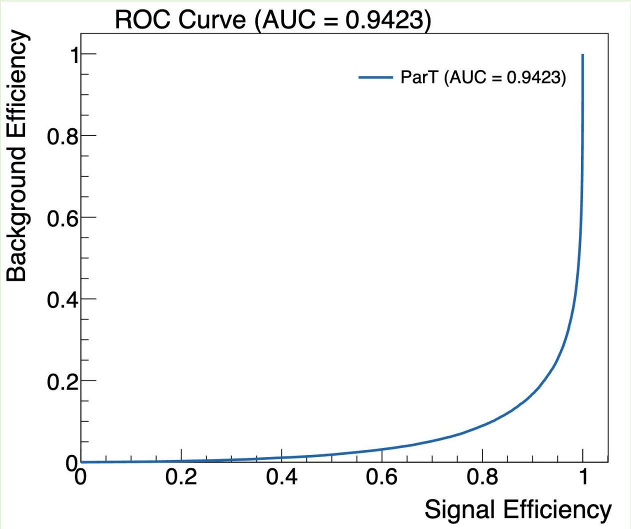
  1. Kinematics： part_pt_log, part_e_log， part_logptrel, part_logerel， part_deltaR, part_deta, part_dphi
  2. Particle Identification： part_charge， part_isChargedHadron， part_isNeutralHadron, part_isPhoton， part_isElectron， part_isMuon
  3. Tracking： part_d0， part_d0err， part_dz， part_dzerr
  4. Calorimeter： part_em_fraction， part_had_fraction
  5. dE/dx PID Probabilities： part_prob_pi, part_prob_k, part_prob_p

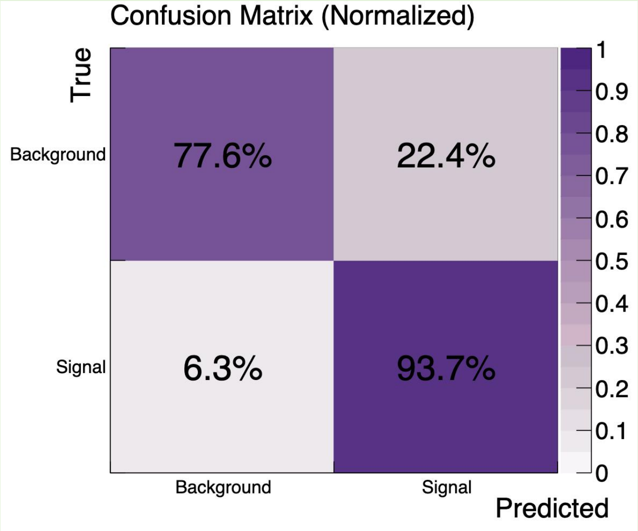
- Lorentz Vectors： part_px, part_py, part_pz, part_energy

Analysis Framework/Particle Transformer



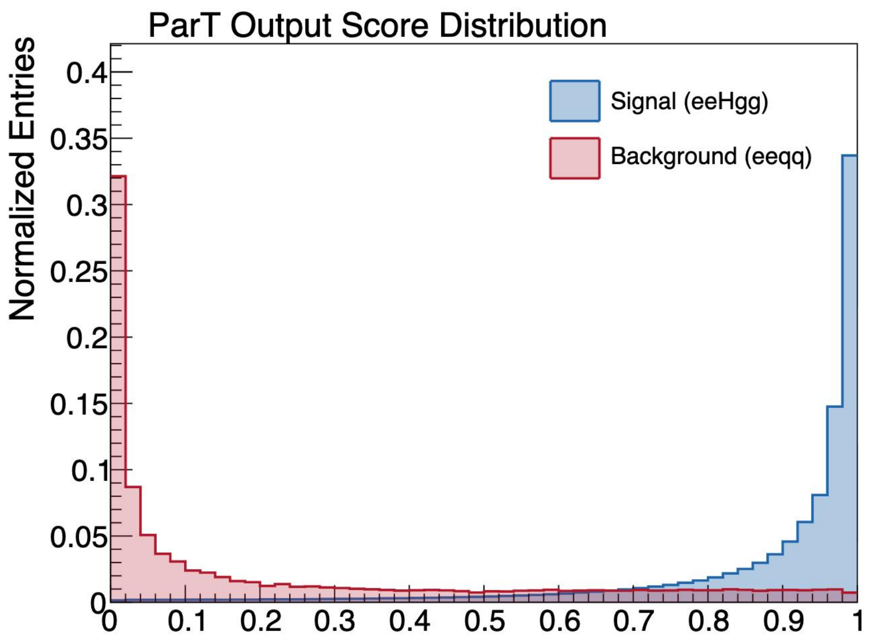


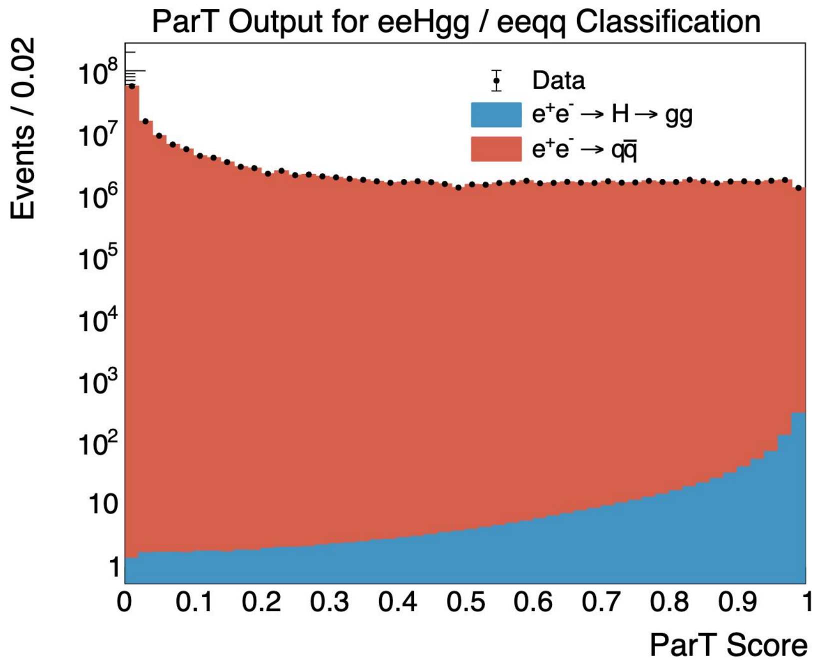




- **Loss:** Training loss decreases steadily from 0.454 to ~0.29, with no rise in validation loss — no overfitting. Best epoch: 44.
- **Accuracy:** Validation Balanced Accuracy fluctuates within a narrow range of 0.075, indicating stable training. Best value: 0.881.
- **ROC curve:** AUC = 0.94, demonstrating excellent signal–background score separation.
- **Confusion matrix:** Signal efficiency 93.7%, background efficiency 77.6%, Balanced Accuracy = 0.856.

Analysis Framework/Particle Transformer

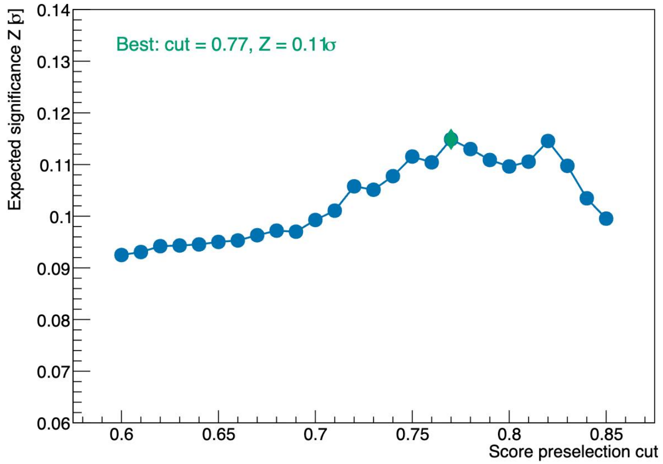


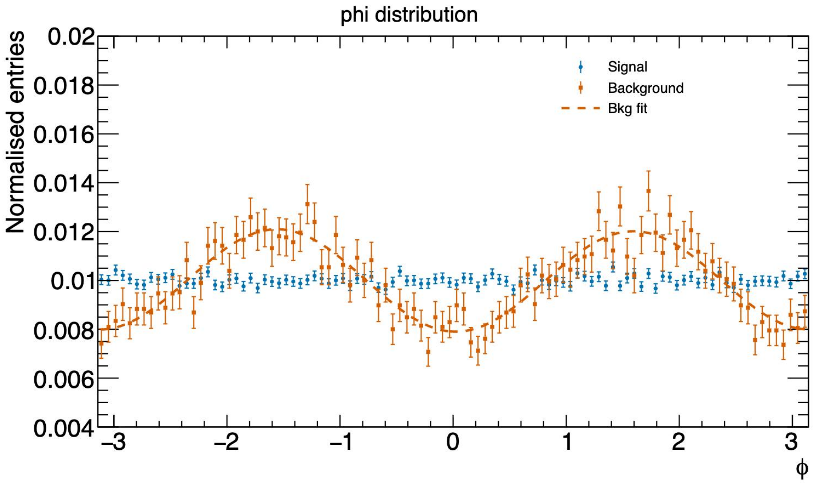


- **Score distribution:** Signal peaks near 1 and background near 0, with clear separation — the model achieves strong discriminative power.
- **Cross-section weighted score distribution:** After applying the true cross sections at an integrated luminosity of 10 ab^{-1}/year, the background outnumbers the signal by ~7 orders of magnitude. Nevertheless, a stringent high-score cut can suppress the background dramatically while retaining most of the signal.

Analysis Framework/Simultaneous Fit

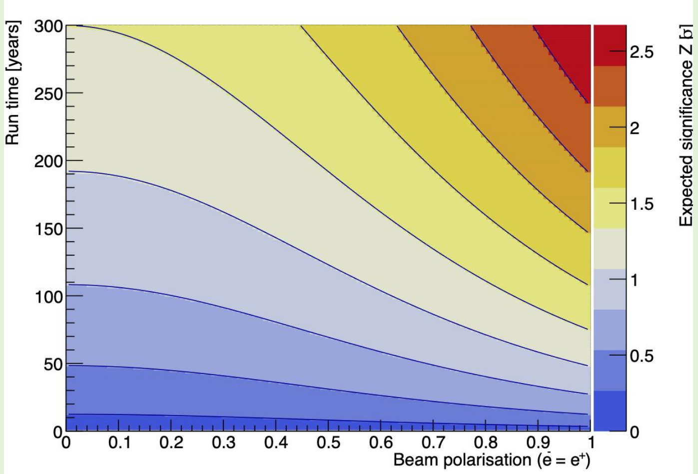
- Unlike hard cuts that discard events, the simultaneous fit uses all data — high-S/B regions are naturally weighted more, while information from the rest is retained rather than thrown away.
- Before the fit, a score preselection is applied (score > 0.77), with the optimal threshold determined by a significance scan.
- A simultaneous binned likelihood fit is performed in the 2D (ParT score, φ) plane.

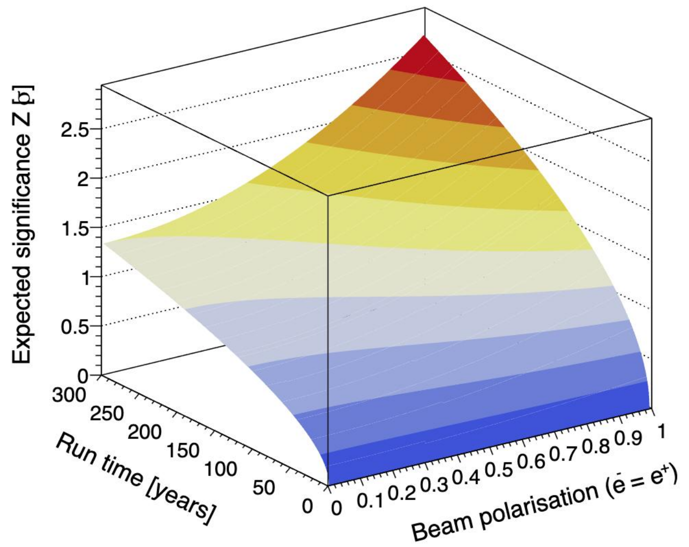


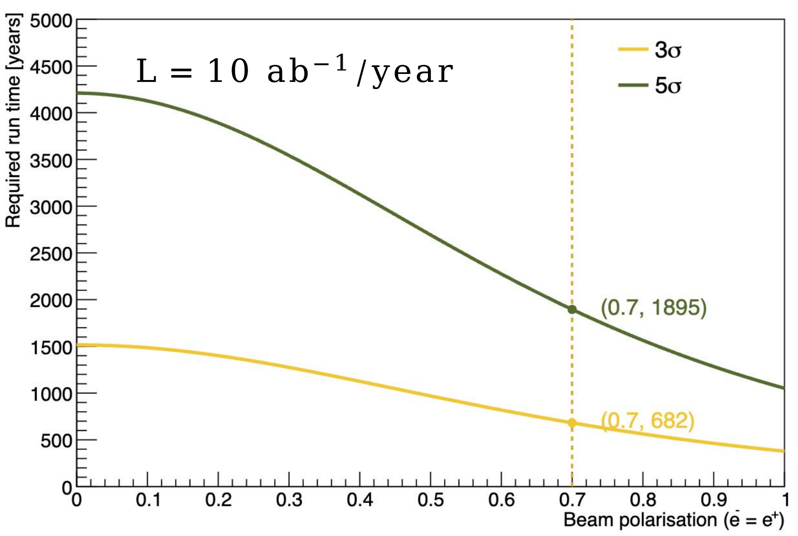


Method	Significance
Hard cut (score>0.98)	0.08σ
2D simultaneous fit	0.11σ

Analysis Framework/Simultaneous Fit







	P = 0	P = 70%	P = 90%	P = 100%
3σ	1516 year	682 year	462 year	379 year
5σ	4212 year	1895 year	1284 year	1052 year

Comparison with FCC-ee Results

	CEPC	FCC–ee	Combined
Polarization	70%	0	70%
Gluon tagging/mis–tagging rates	CEPC version	FCC–ee version	FCC–ee version
Event Preselection	2 gluon – tagged jets 0 isolated $l^{\pm}$ visible mass > 114GeV	2 gluon – tagged jets 0 isolated $l^{\pm}$	2 gluon – tagged jets 0 isolated $l^{\pm}$ visible mass > 114GeV
Event Selection Optimization	ParT Simultaneous Fit	BDT	ParT Simultaneous Fit
Significance	0.1σ	1.1σ	4.5σ

Summary and Next Steps

Summary:

Feasibility study of measuring the electron Yukawa coupling at the CEPC:

- Completed the background survey and defined the research direction: enhancing the signal-to-background ratio via beam polarization and machine learning.
- Verified the feasibility of this approach through Monte Carlo simulation and analytical cross-section calculations.
- Generated signal and background samples with Whizard3, and performed detector simulation and object reconstruction with Delphes.
- Implemented event preselection, yielding a preliminary improvement in the S/B ratio.
- Performed event selection optimization using the Particle Transformer and a simultaneous fit, achieving an expected significance of 0.1σ.
- Compared with the FCC-ee result, and evaluated the maximum achievable significance when adopting the FCC-ee gluon-tagging approach, yielding 4.5σ.

Outlook:

- Estimate systematic uncertainties using toy Monte Carlo.
- Write and publish the paper.

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Appendices

Appendix A

$$\sigma_{ee\to H} = \frac{4\pi\Gamma(H\to e^+e^-)}{\left(s - m_H^2\right)^2 + m_H^2\Gamma_H}$$

$$s = (125\ GeV)^2$$

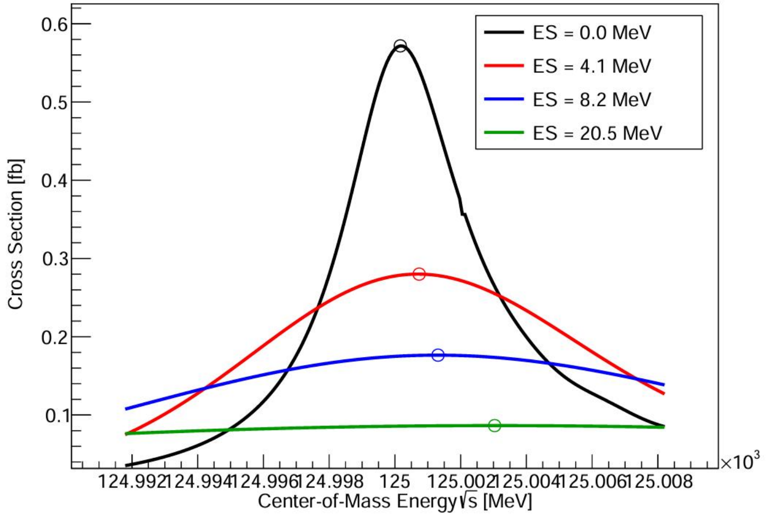
$$\sigma_{ee\to H} = \frac{4\pi\Gamma(H\to e^+e^-)}{m_H^2\Gamma_H} = 1.64\ fb$$

ISR

$$\sigma_{res}(s) = \int_0^{1-s_m/s} dx\,\sigma(s(1-x))F(x,s) = 0.57\ \text{fb}$$

Beam Energy Spread

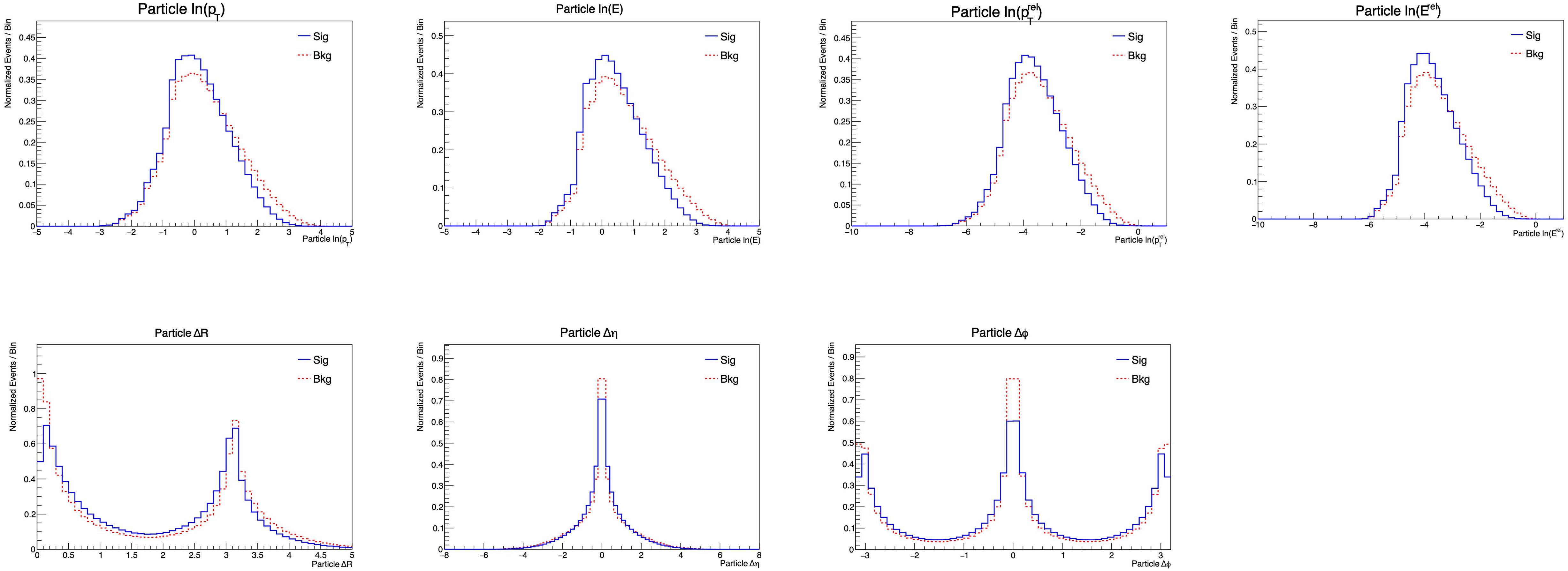
$$\sigma_{obs}(s) = \frac{R}{s} + \int_0^{\infty} G(s,s')\sigma_{res}(s')\,ds' = 0.28\ \text{fb}$$



ES(MeV)	σ_{max}(fb)
0	0.57
4.1	0.28
8.2	0.18
20.5	0.09

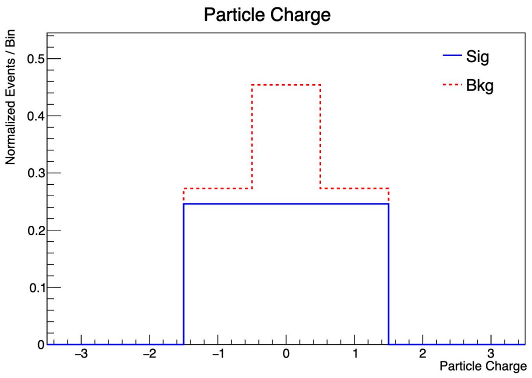
Appendix B

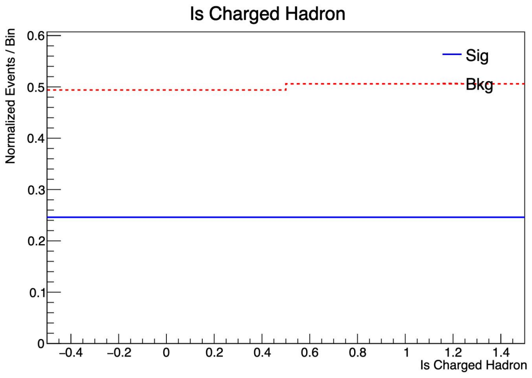
Kinematics:

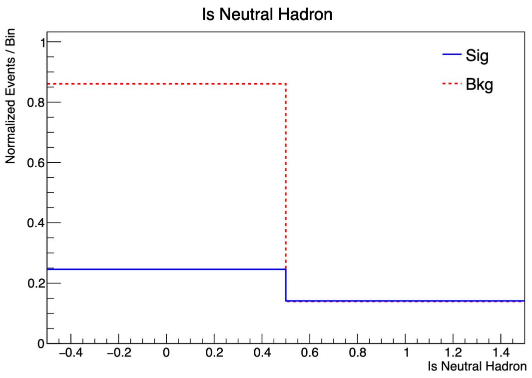


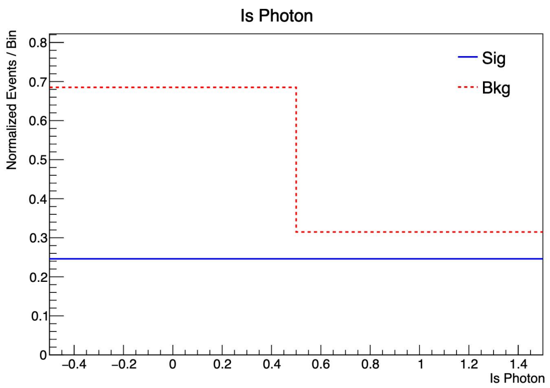
Appendix B

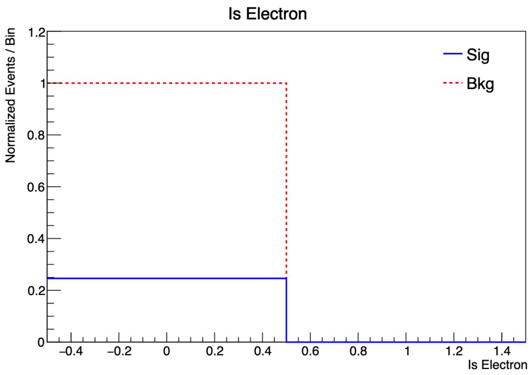
Particle Identification：

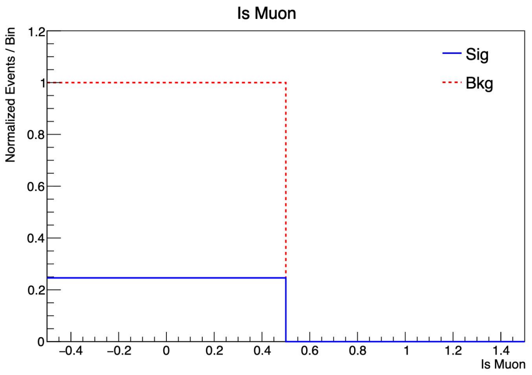






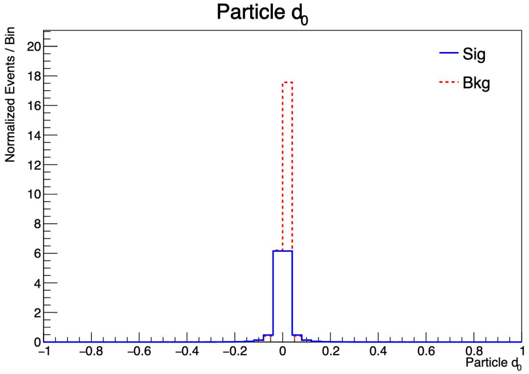


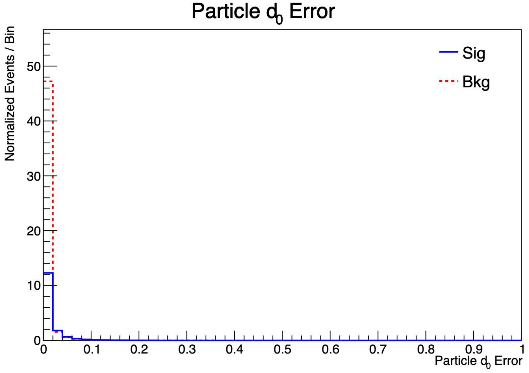


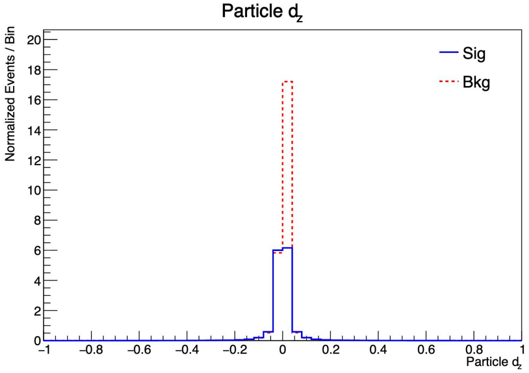


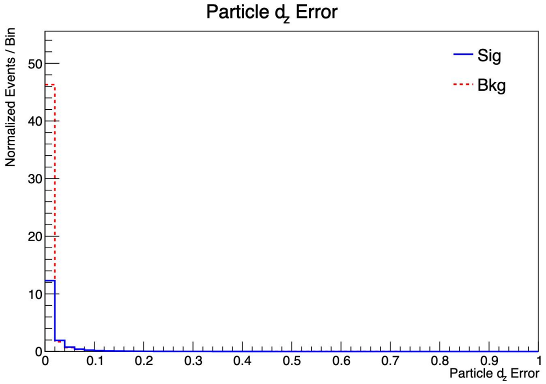
Appendix B

Tracking:









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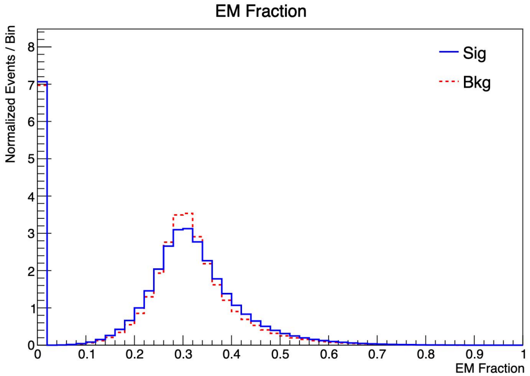
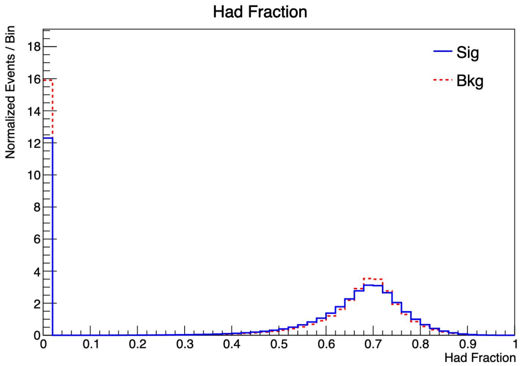
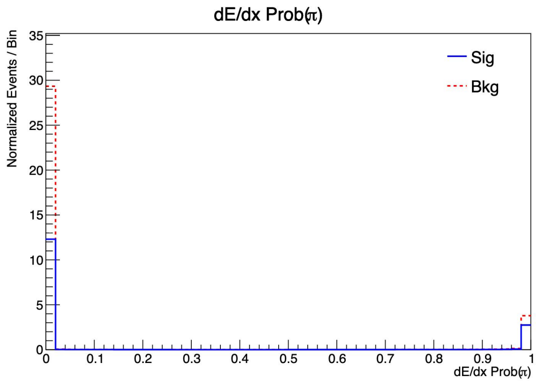
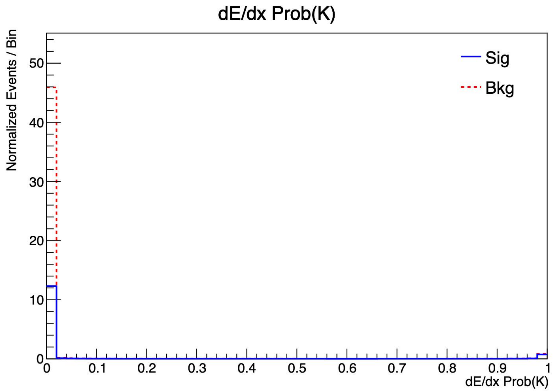


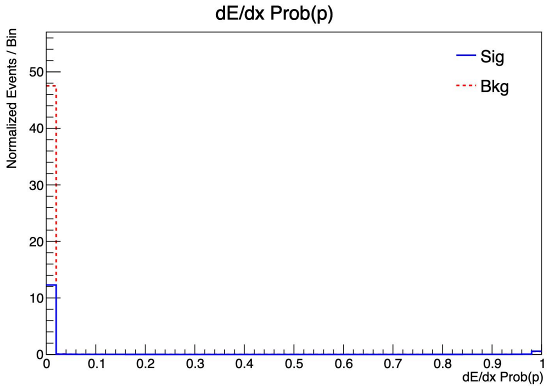


Appendix B

dE/dx PID Probabilities：







Lorentz Vectors：