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Institute of High Energy Physics Chinese Academy of Sciences

CMS

Measuring the Electron Yukawa Coupling at CEPC

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2026.4.20

Outline

1 Physics Motivation

1. It will explore the (so far hypothetical) Higgs mass generation mechanism for elementary particles of the first family of fermions that form the stable matter of the visible universe.
2. It will scrutinize the electron's Yukawa coupling that, through its impact on the electron mass, sets the size of atoms and their energy levels (the Bohr radius is proportional to $1/m_e$).
3. It can access BSM scalar physics connected to the electron above the ~100 TeV scale.
4. It can directly probe the potential presence of any new particle that is quasi–degenerate (at the MeV level) with the Higgs boson mass.

2 Research Status

FCC-ee	CMS	ATLAS	HL-LHC	FCC-hh
$y_e \leq 1.6 y_e^{SM}$	$y_e \leq 240 y_e^{SM}$	$y_e \leq 260 y_e^{SM}$	$y_e \leq 200 y_e^{SM}$	$y_e \leq 50 y_e^{SM}$

FCC-ee	https://link.springer.com/article/10.1140/epjp/s13360-021-02204-2
CMS	https://www.sciencedirect.com/science/article/pii/S037026932300117X?via%3Dihub
ATLAS	https://www.sciencedirect.com/science/article/pii/S0370269319308706?via%3Dihub
HL-LHC	https://arxiv.org/abs/1906.02693
FCC-hh	https://link.springer.com/article/10.1140/epjst/e2019-900087-0

2 Research Status

It can be seen that the current research results from FCC-ee are the best. Therefore, we aim to reproduce this research at CEPC and make further improvements.

Our Plan
Accelerator polarization
Beam monochromatization
Machine learning and 2D fitting

High requirements on the accelerator (Accelerator polarization; Beam monochromatization)

Improve S/B and maximize the utilization of data information. (Accelerator polarization; Beam monochromatization; Machine learning and 2D fitting)

3 Verify the Feasibility of the Research Direction

We intend to use simple Monte Carlo simulations to verify whether polarization can improve the S/B.

- **Longitudinal polarization**

It means particle spins are aligned along the momentum direction (z). Helicity eigenstates are right/left (helicity $=\pm 1$).

- **Transverse polarization**

It means particle spins lie in the plane perpendicular to momentum (x–y). It is described by transverse vector with direction ϕ.

- **Polarization degree P**

It means polarized particle ratio. $\mathrm{P}=1$ means fully polarized, $\mathrm{P}=0$ means unpolarized.

3.1 Longitudinal Polarization Study

Signal: $e^+e^- \to H \to gg$ **Background:** $e^+e^- \to q\bar{q}$ **Tool:** Whizard 3

Plan: 1. Keep the degree of polarization the same.

- electron —— left–handed polarization, positron —— left–handed polarization
- electron —— left–handed polarization, positron —— right–handed polarization
- electron —— right–handed polarization, positron —— left–handed polarization
- electron —— right–handed polarization, positron —— right–handed polarization

2. Only change the electron's degree of polarization, keep $P_{e^+} = 0$.

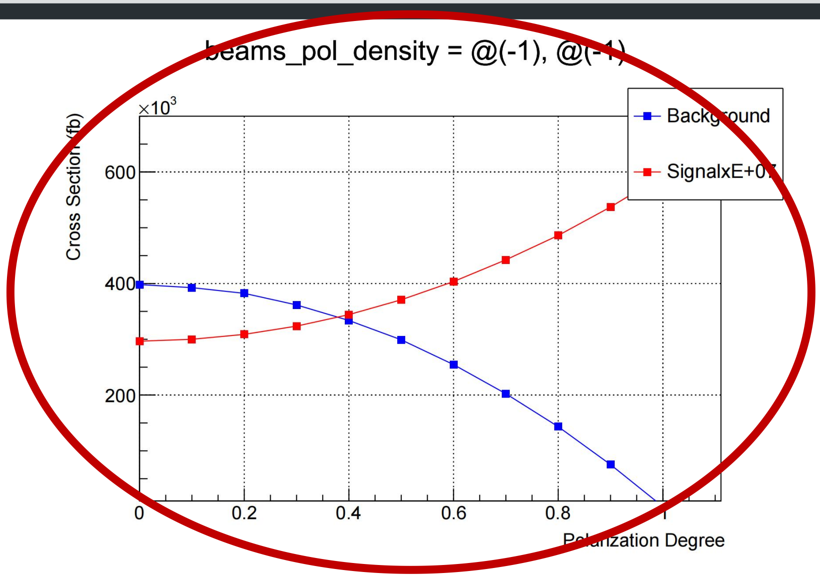
- electron —— left–handed polarization
- electron —— right–handed polarization

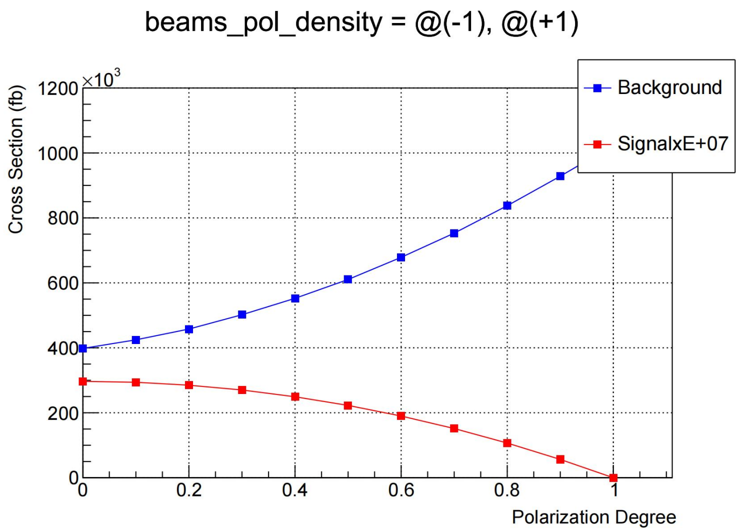
3. Only change the positron's degree of polarization, keep $P_{e^-} = 0$.

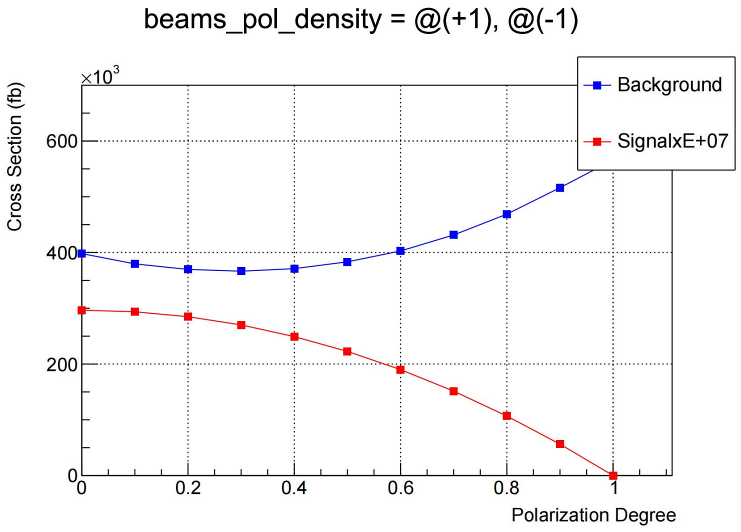
- positron —— left–handed polarization
- positron —— right–handed polarization

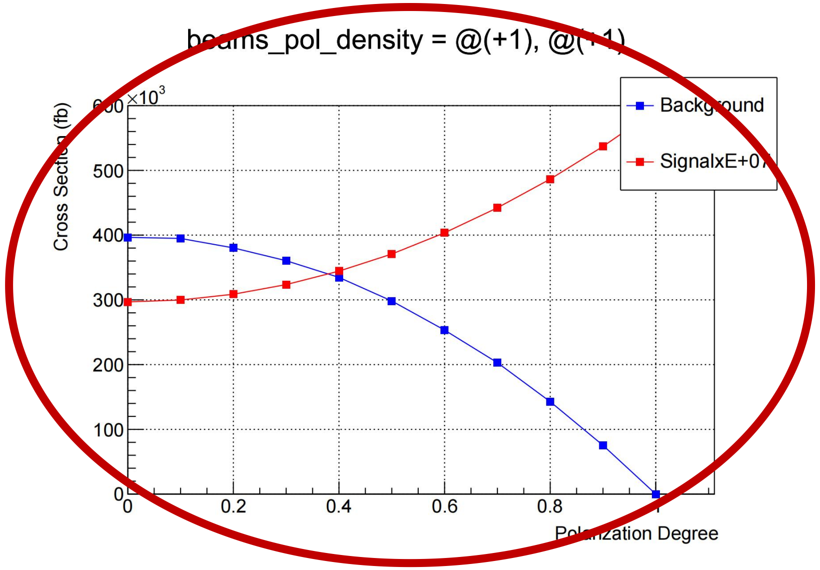
3.1 Longitudinal Polarization Study

Situation 1:
Keep the degree of polarization the same.



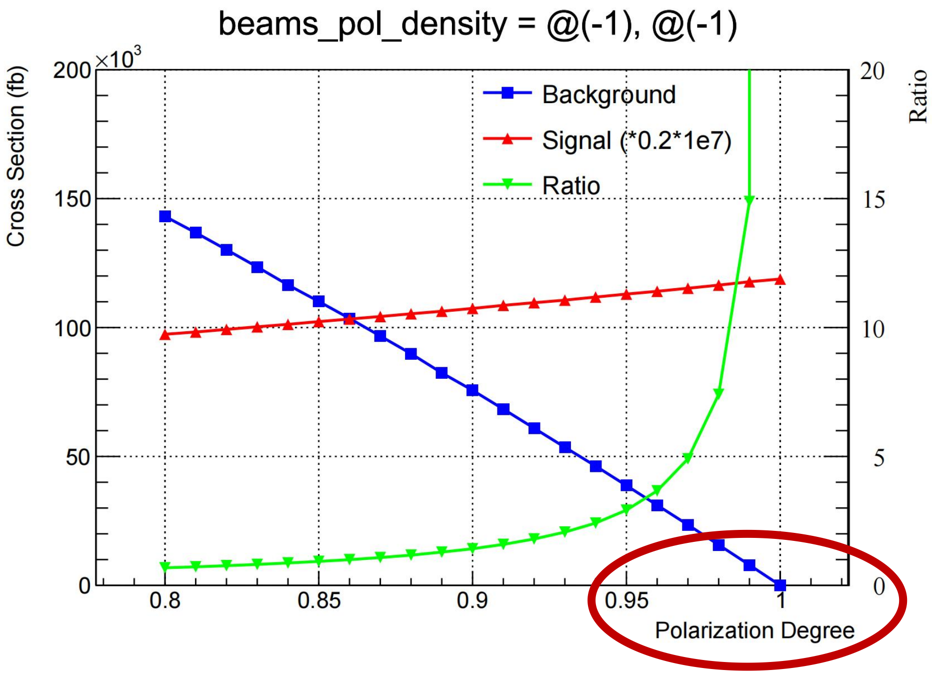


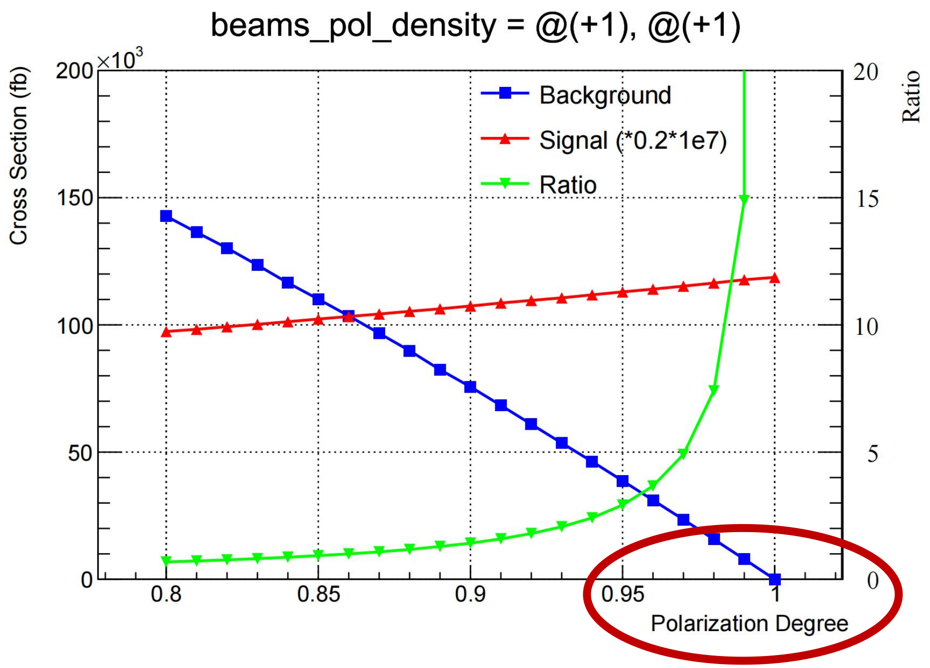




3.1 Longitudinal Polarization Study

Situation 1:
Keep the degree of polarization the same.

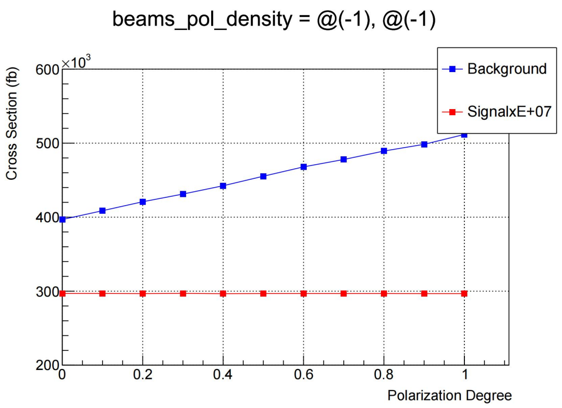


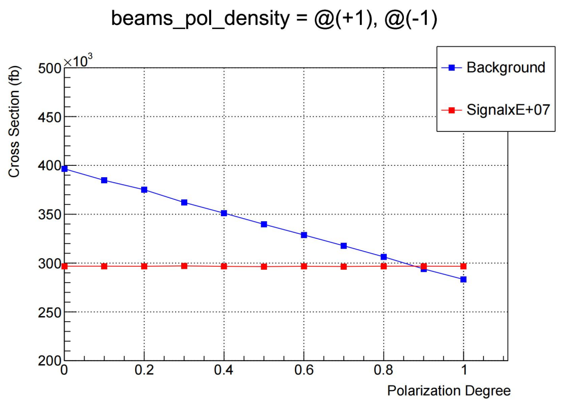


The S/B exhibits an exponential growth. At high ratios, the requirement for the degree of polarization is extremely high, demanding it to be above 0.95—which is unattainable with our accelerator, thus we abandoned it.

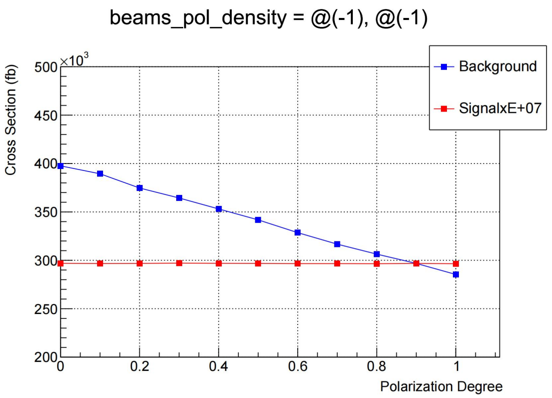
3.1 Longitudinal Polarization Study

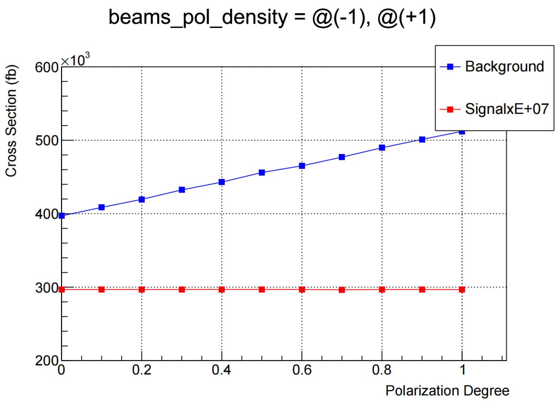
Situation 2: Only change the electron's degree of polarization, keep $P_{e^+} = 0$.





Situation 3: Only change the positron's degree of polarization, keep $P_{e^-} = 0$.





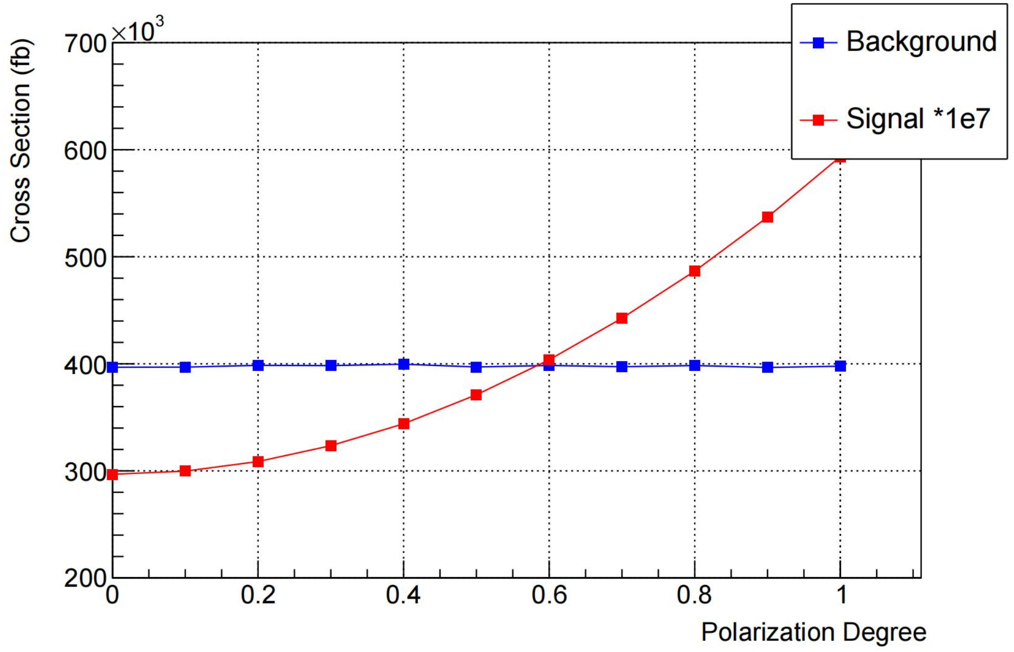
The results of Situation 2、3 were not satisfactory, thus we abandoned it.

3.2 Transverse Polarization Study

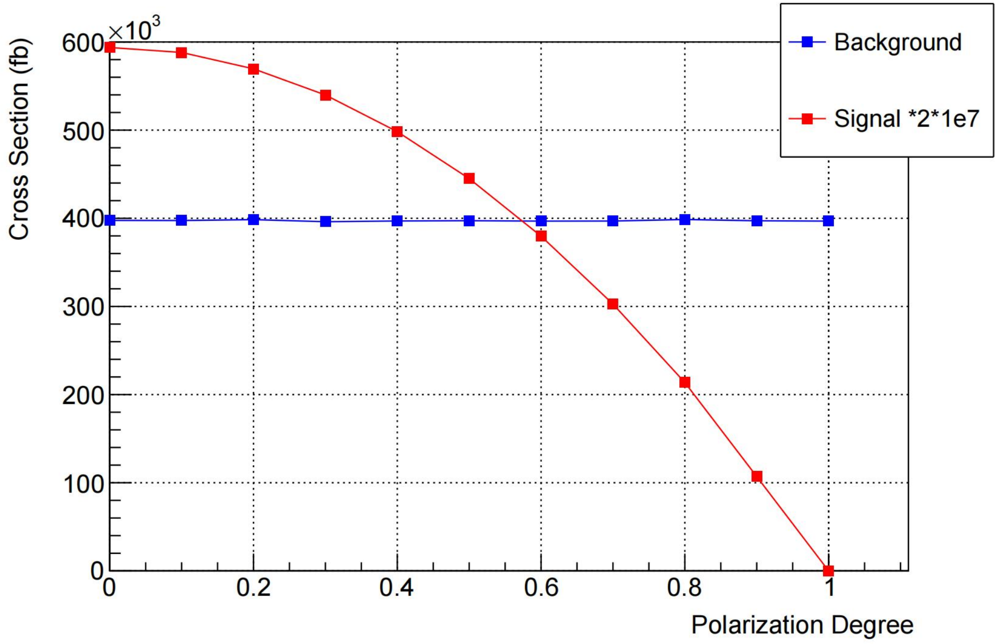
We examined two representative transverse polarization orientations in the x–y plane as illustrative cases to study their impact on the cross section, without performing an exhaustive angular scan.

Transverse polarization induces azimuthal (ϕ) and polar ($\cos\theta$) dependencies, and signal and background typically respond differently in these angular variables; hence ϕ and $\cos\theta$ carry additional discriminating power.

Electron ––– positive x-axis, Positron --- positive y-axis



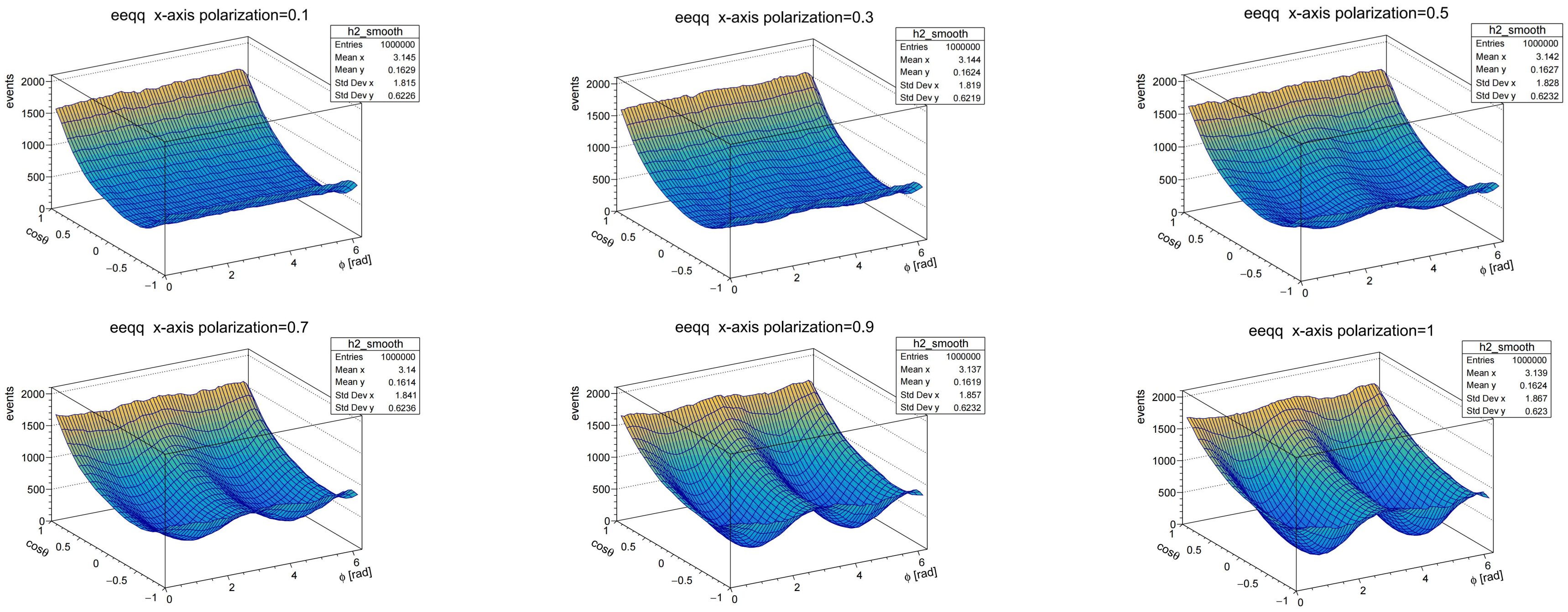
Electron ––– positive y-axis, Positron --- positive x-axis



3.2 Transverse Polarization Study

The following shows the distribution changes of ϕ and $\cos\theta$ with varying polarization degrees. (Since the 3D plot of the signal is just a flat plane, only the 3D plot of the background is presented here.)

Background



Obviously, this is exactly what we expected: the signal and background exhibit different distributions with respect to ϕ and $\cos\theta$, allowing us to set cut conditions to improve the S/B.

3.3 Theory Calculation and Code Validation

To make our conclusions more reliable and to facilitate subsequent fitting, we sought theoretical basis.
Transverse-polarization effects in e^+e^- collisions: The role of chiral symmetry
https://doi.org/10.1103/PhysRevD.33.3203

$e^+e^- \rightarrow \mu^+\mu^-$

$$
\begin{aligned}
\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\Bigg[& \left[1+\frac{2v_e v_\mu}{\sin^2\theta_W\cos^2\theta_W}\frac{s(s-M_Z{}^2)}{(s-M_Z{}^2)^2+M_Z{}^2\Gamma_Z{}^2}+\frac{(v_e{}^2+a_e{}^2)(v_\mu{}^2+a_\mu{}^2)}{\sin^4\theta_W\cos^4\theta_W}\frac{s^2}{(s-M_Z{}^2)^2+M_Z{}^2\Gamma_Z{}^2}\right](1+\cos^2\theta) \\
& +\left[\frac{4a_e a_\mu}{\sin^2\theta_W\cos^2\theta_W}\frac{s(s-M_Z{}^2)}{(s-M_Z{}^2)^2+M_Z{}^2\Gamma_Z{}^2}+\frac{8v_e a_e v_\mu a_\mu}{\sin^4\theta_W\cos^4\theta_W}\frac{s^2}{(s-M_Z{}^2)^2+M_Z{}^2\Gamma_Z{}^2}\right]\cos\theta \\
& -P^2\left[1+\frac{2v_e v_\mu}{\sin^2\theta_W\cos^2\theta_W}\frac{s(s-M_Z{}^2)}{(s-M_Z{}^2)^2+M_Z{}^2\Gamma_Z{}^2}+\frac{(v_e{}^2-a_e{}^2)(v_\mu{}^2-a_\mu{}^2)}{\sin^4\theta_W\cos^4\theta_W}\frac{s^2}{(s-M_Z{}^2)^2+M_Z{}^2\Gamma_Z{}^2}\right]\sin^2\theta\cos2\phi \\
& +P^2\frac{2a_e v_\mu}{\sin^2\theta_W\cos^2\theta_W}\frac{sM_Z\Gamma_Z}{(s-M_Z{}^2)^2+M_Z{}^2\Gamma_Z{}^2}\sin^2\theta\,\sin2\phi\Bigg]\,. \qquad \text{(C6)}
\end{aligned}
$$

This paper presents the formula for the angular distribution of the differential cross-section of transversely polarized beams in the $e^+e^- \rightarrow \mu^+\mu^-$ process, considering both photon and Z boson exchange, with the masses of electrons and muons neglected.

3.3 Theory Calculation and Code Validation

Background: $e^+e^- \to q\bar{q}$

3 denotes the color factor

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

$$\sigma = \frac{3\alpha^2}{4s}\frac{16\pi}{3}\bullet\left(1 + \frac{(v_e^2+a_e^2)(v_q^2+a_q^2)}{\sin^4\theta_W\cos^4\theta_W}\cdot\frac{s}{\Gamma_Z^2}\right)$$

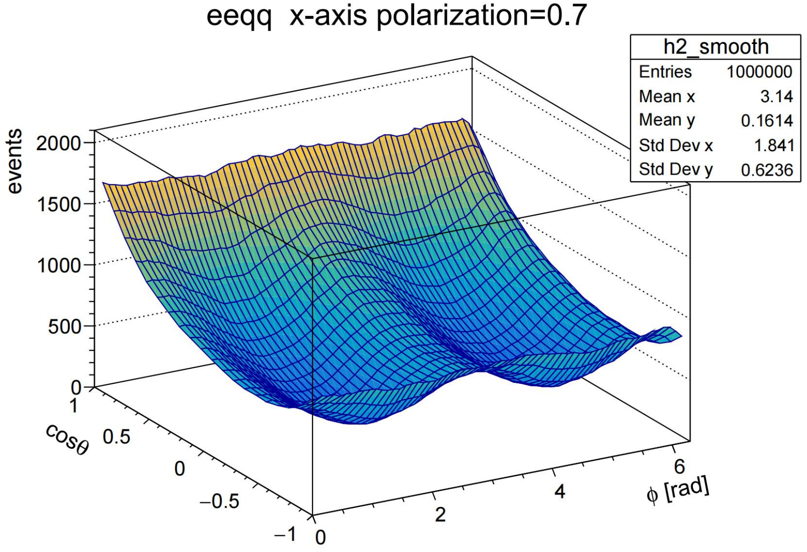
$$\sigma_q = 2\bullet\sigma_u + 3\bullet\sigma_d = 39.69\ nb$$

This result is basically consistent with the current experimental result of 41.48 nb.
https://pdg.lbl.gov/2024/listings/rpp2024-list-z-boson.pdf

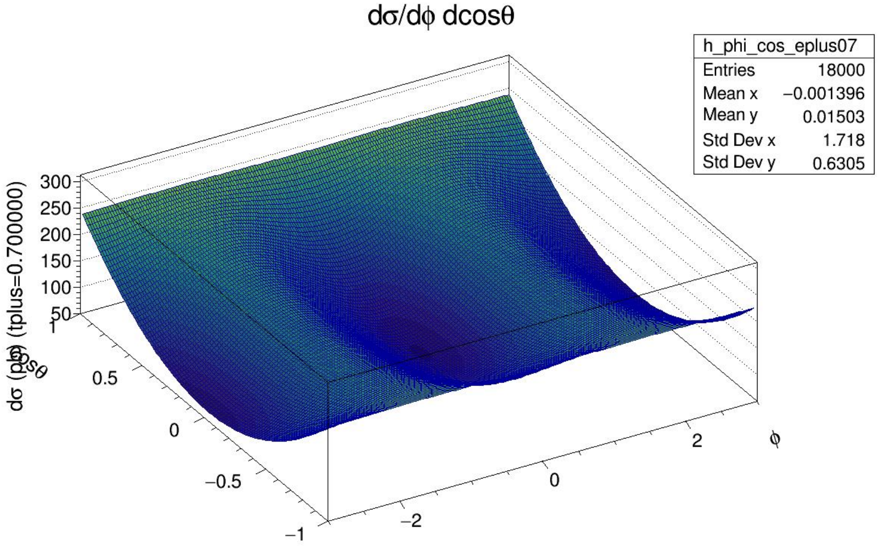
3.3 Theory Calculation and Code Validation

Meanwhile, I directly evaluated the analytical function point by point on a regular grid and output a smooth mathematical surface.

This surface plot is consistent with the graph we previously generated using MC sampling.



$P_{e^-} = P_{e^+} = 0.7$



$P_{e^-} = P_{e^+} = 0.7$

4 Sample Generation

Condition Settings

- Keep the electrons transversely polarized along the positive x–axis, and the positrons transversely polarized along the negative y–axis.
- Keep the polarization degree of both electrons and positrons at 70%.
- Set the number of events to 1000,000.

Tool: Whizard 3

Process
$e^+e^- \to H \to gg$
$e^+e^- \to qq$

- Difficulties have been encountered in the production of other samples, along with poor sensitivity, so they are temporarily excluded from consideration.

5 Detector Simulation and Object Reconstruction

- Use Delphes to fit the CEPC detector response, and then reconstruct leptons, photons, and jets from the final–state particle.

	b jets	*c* jets	Gluon jets
Reco/tagging efficiency (ε_i)	92.3%	80.3%	65.0%
Mistagging rates ($\varepsilon_{j \to i}^{\text{mistag}}$)	2.8% (for c)	4.1% (for b)	2.7% (for b)
			6.6% (for c)
	0.3% (for uds)	4.0% (for s)	16.1% (for s)
		3.0% (for ud)	18.4% (for ud)
	2.5% (for g)	5.2% (for g)	

The data is contributed by Kai Li.

6.1 Normalize to the laboratory luminosity

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

$s = (125\ GeV)^2$

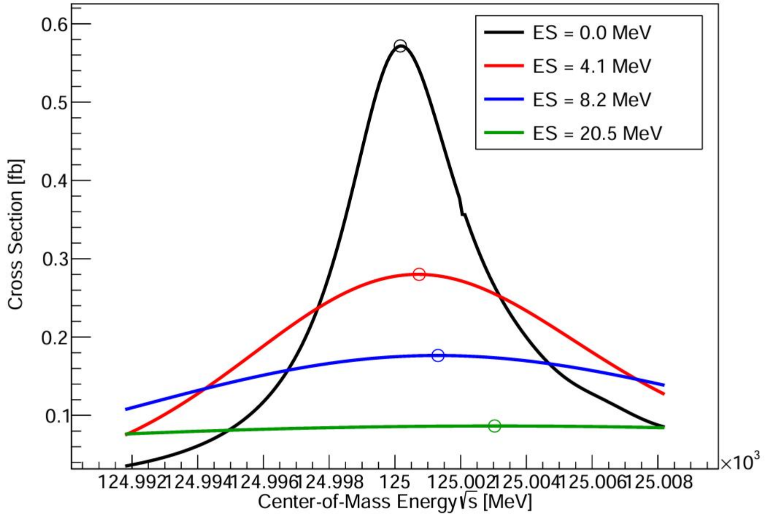
$$\sigma_{ee\to H} = \frac{4\pi\Gamma(H\to e^+e^-)}{m_H^2\Gamma_H} = 1.64\ fb$$

ISR

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

Beam energy spread

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



ES(MeV)	σ max(fb)
0	0.57
4.1	0.28
8.2	0.18
20.5	0.09

6.1 Normalize to the laboratory luminosity

$\sigma_{obs}(s) = 0.28$ fb → Polarization →

$\sigma_{ee\to H} = \sigma_{obs}(s) \times 1.49 = 0.42$ fb

$\sigma_{ee\to H\to gg} = \sigma_{ee\to H} \times 8.2\%$ (BR) $= 34.2$ ab

	CEPC
$\sigma_{ee\to H\to gg}$	34.2 ab
$\sigma_{ee\to qq}$	99.1 pb
$\sigma_{ee\to H\to gg}/\sigma_{ee\to qq}$	3.6×10^{-7}
S/B (before any analysis cuts)	$\mathcal{O}(10^{-6})$
$L\ /10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	10
$\delta_{\sqrt{s}}$	4.1 MeV
$\sqrt{s}$	125 GeV

6.2 Event Preselection

Cuts : 2 (excl.) gluon – tagged jets, 0 isolated $l^{\pm}$

	CEPC
Signal Efficiency	57.08 %
Background Efficiency	17.53 %
S/B (before cuts)	3.6×10^{-7}
S/B (after cuts)	1.2×10^{-6}
L $/10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	10
$\delta_{\sqrt{s}}$	4.1 MeV
$\sqrt{s}$	125 GeV

7 Summary and Next Steps

Summary

- Completed background research and confirmed the research direction.
- Analyzed longitudinal/transverse polarization characteristics, confirming transverse polarization can distinguish signals from backgrounds.
- Validated theoretical calculations and code with effective MC sampling results.
- Conducted sample generation, Detector Simulation and Object Reconstruction.
- Perform event preselection.

Next Steps

- Use Particle Transformer to optimize event selection.
- Use toy-MC to estimate the statistical error.