

Summary of the ILD physics activities

in recent years

Aleksander Filip Żarnecki



A detector for the next CERN flagship project

ILD meeting at CERN

September 15, 2026

Physics Working Group summary

Main Physics WG goals are to

- make compelling physics case for ILC
convince decision makers that ILC is worth the investment
- and for the e^+e^- Higgs Factory in general
contribute to the ECFA Higgs/EW/Top factory study in particular
- optimize the ILD detector design for ILC
to make full use of the ILC physics potential
- present ILD as a compelling option for other colliders
defined last year as one of our priorities
- and explore novel design options, based on new technologies
to remain both “mature” and “modern” design
- develop new analysis tools and concepts
make full use of recent ML and AI developments

ECFA Focus topics

- ① **HtoSS** – $e^+e^- \rightarrow Zh: h \rightarrow ss$ ($\sqrt{s} = 240/250$ GeV)
- ② **ZHang** – Zh angular distributions and CP studies
- ③ **Hself** – Determination of the Higgs self-coupling
- ④ **Wmass** – Mass and width of the W boson ...
- ⑤ **WWdiff** – Full studies of WW and $e\nu W$
- ⑥ **TTthres** – Top threshold: Detector-level simulation study of $e^+e^- \rightarrow t\bar{t}$...
- ⑦ **LUMI** – Precision of the luminosity measurement
- ⑧ **EXscalar** – New exotic scalars
- ⑨ **LLPs** – Long-lived particles
- ⑩ **EXtt** – Exotic top decays
- ⑪ **CKMWW** – CKM matrix elements from W decays
- ⑫ **BKtautau** – $B^0 \rightarrow K^{0*} \tau^+ \tau^-$
- ⑬ **TwoF** – EW precision: 2-fermion final states ($\sqrt{s} = M_Z$ and beyond)
- ⑭ **BCfrag** and **Gsplit** – Heavy quark fragmentation and hadronisation, gluon splitting...

Few numbers from ILD PSB indico pages

12 contributions from physics studies (19 total) at LCWS'2024

<https://agenda.linearcollider.org/event/10372/>

18 contribution to the 3rd ECFA workshop (9-11 October 2024)

<https://agenda.linearcollider.org/event/10420/>

21 contributions submitted to the final ECFA study report

<https://agenda.linearcollider.org/event/10484/>

11 contributions from physics studies (17 total) at LCWS'2025

<https://agenda.linearcollider.org/event/10786/>

and many more results presented just at our Software and Analysis meetings...

I had to make a selection, I focused on the studies concluded (published) in 2024-2026...

Apologies for all omissions and mistakes!



Probing gauge-Higgs unification models at the ILC with quark–antiquark forward–backward asymmetry at center-of-mass energies above the Z mass

A. Irles^{1,a} , J. P. Márquez¹, R. Pöschl², F. Richard², A. Saibel¹, H. Yamamoto¹, N. Yamatsu^{3,4}

¹ IFIC, Universitat de València and CSIC, C./ Catedrático José Beltrán 2, 46980 Paterna, Spain

² Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

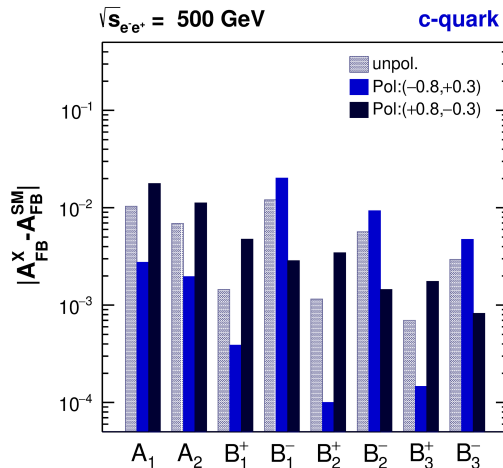
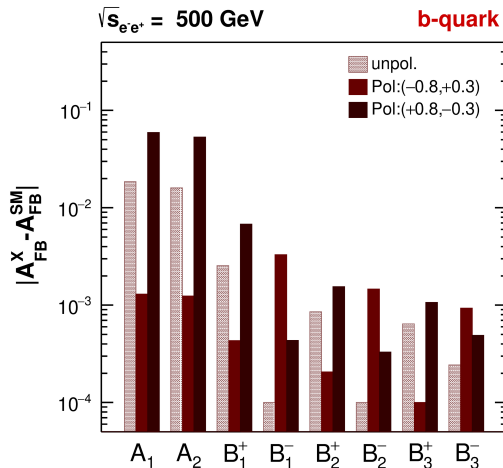
³ Department of Physics, National Taiwan University, Taipei 10617, Taiwan, ROC

⁴ Yukawa Institute for Theoretical Physics, Kyoto University, Kitashirakawa Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan

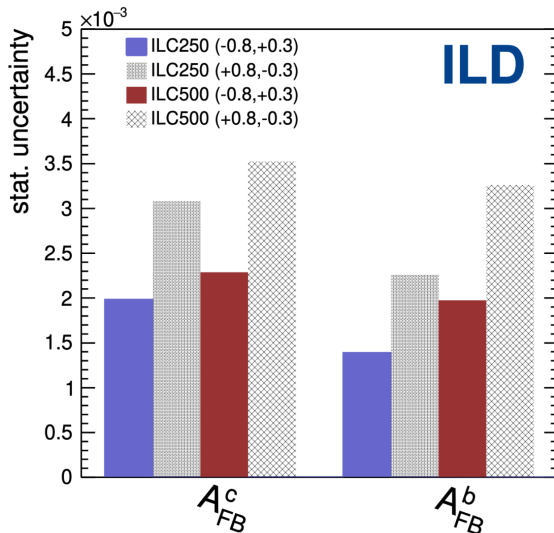
Received: 15 March 2024 / Accepted: 14 May 2024

© The Author(s) 2024

GHU vs SM (500 GeV)

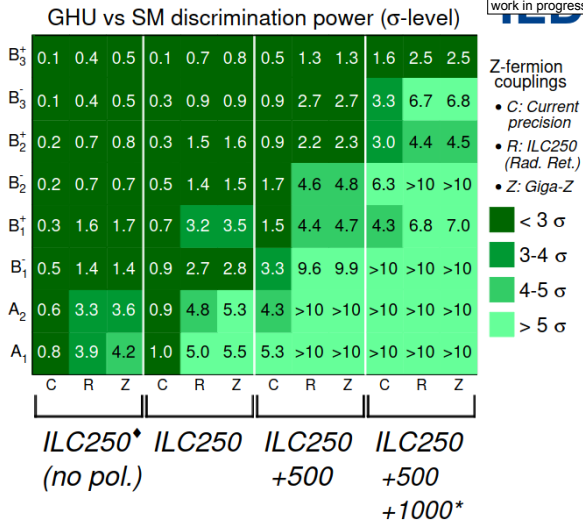


$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$



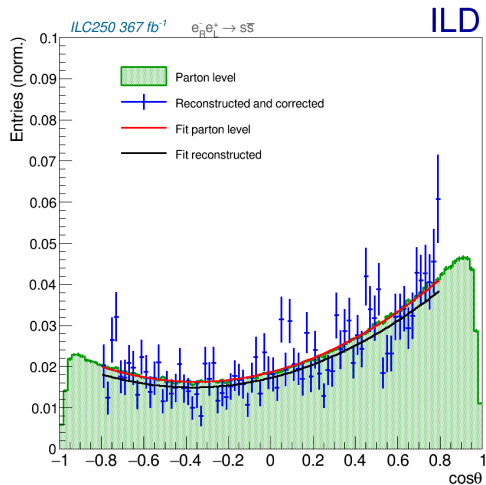
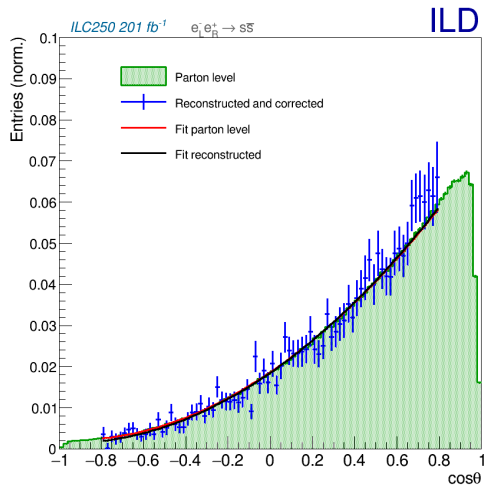
GHU vs SM: discrimination power plots

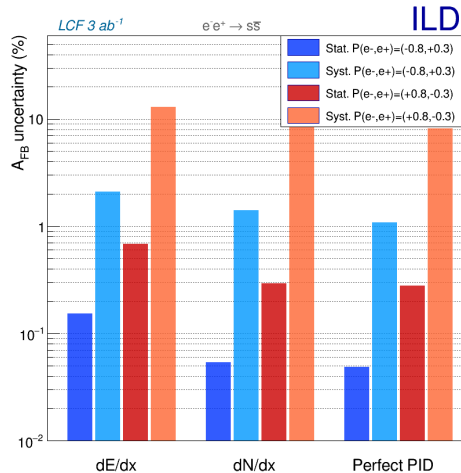
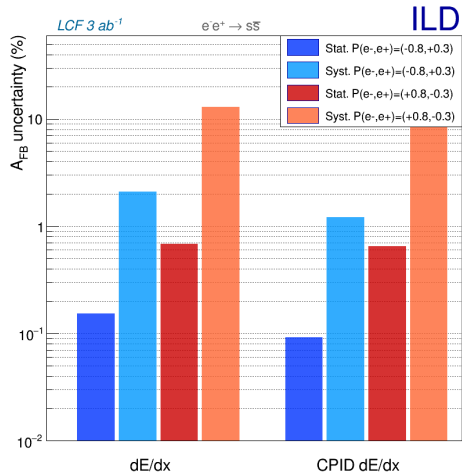
work in progress



Fit to reconstructed signal

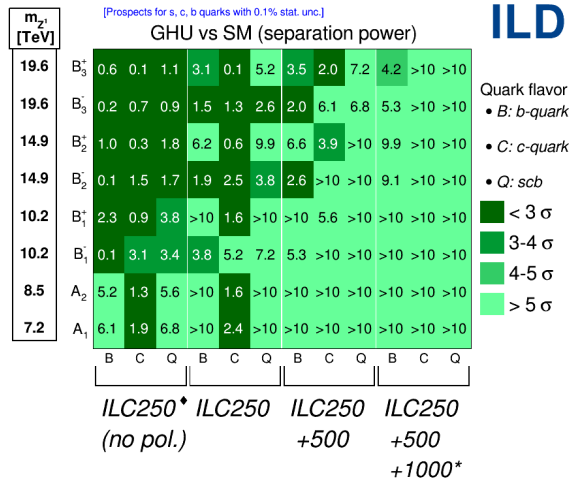
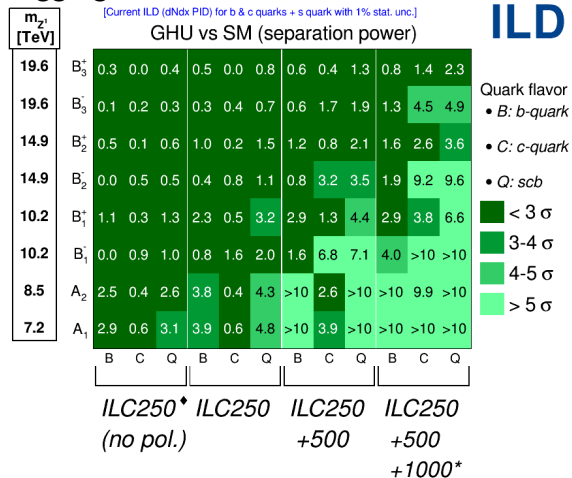
- Fit constrained to $|\cos\theta| < 0.8$ shows good agreement





Prospects for GHU phenomenology

► ILC with pixel TPC (dN/dx for PID) || ILC with prospects using ParT flavour tagging



Probing CPV mixing in the Higgs sector in vector boson fusion at a 1 TeV ILC

N. Vukašinović^{},^{*} I. Božović-Jelisavčić^{}, G. Kačarević^{}, I. Smiljanić^{}, and I. Vidaković

*“VINČA” Institute of Nuclear Sciences–National Institute of the Republic of Serbia,
University of Belgrade, 11001 Belgrade, Serbia*



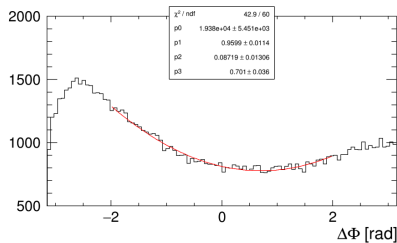
(Received 10 May 2024; accepted 11 July 2024; published 9 August 2024)

With the current precision of measurements by the ATLAS and CMS experiments, it cannot be excluded that a standard model (SM)-like Higgs boson is a CP violating mixture of CP -even and CP -odd states. We explore this possibility here, assuming Higgs boson production in ZZ -fusion, at 1 TeV ILC, with unpolarized beams. The full simulation of SM background and fast simulation of the signal is performed, simulating 8 ab^{-1} of data collected with the ILD detector. We demonstrate that the CP mixing angle Ψ_{CP} between scalar and pseudoscalar states can be measured with the statistical uncertainty of 3.8 mrad at 68% CL, corresponding to 1.44×10^{-5} for the CP parameter f_{CP} , for the pure scalar state. This is the first result on sensitivity of an e^+e^- collider to measure f_{CP} in the Higgs production vertex in vector boson fusion.

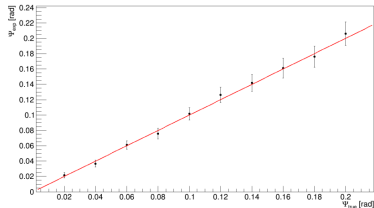
DOI: [10.1103/PhysRevD.110.032011](https://doi.org/10.1103/PhysRevD.110.032011)

2. Perform a local fit around the minimum b/a,
generator 10^5 events

$\Delta\Phi$ fit for $\Psi_{CP}=0.1$
(b/a)= 0.70 ± 0.4

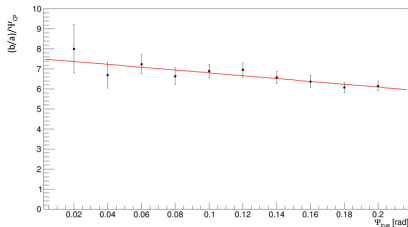


5. Retrieved vs. true values of Ψ_{CP} (generator) +
uncertainties from fit parameters

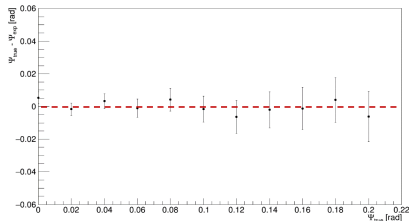


3, 4. Position of minimum (b/a)/ Ψ_{CP} is a linear
function of Ψ_{CP}

$$k = -7.9 \pm 1.9; m = 7.6 \pm 0.2$$



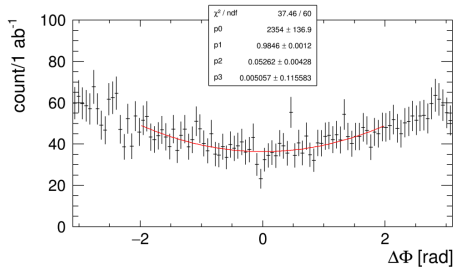
Dissipation of extracted Ψ_{CP} around true Ψ_{CP} values
 $\Delta \Psi_{CP} = 5 \text{ mrad}$ for $\Psi_{CP} = 0$



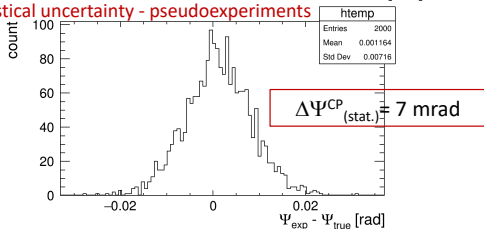
5. Ψ_{CP} FROM EXPERIMENTAL DATA, SCALAR

$\Delta\Phi$ reconstructed, corrected, local fit

$\Psi_{CP}=0.0009 \text{ rad}, |\Psi_{\text{true}}-\Psi_{CP}|=0.9 \text{ mrad}$

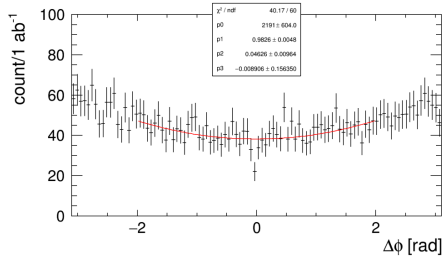


Statistical uncertainty - pseudoexperiments

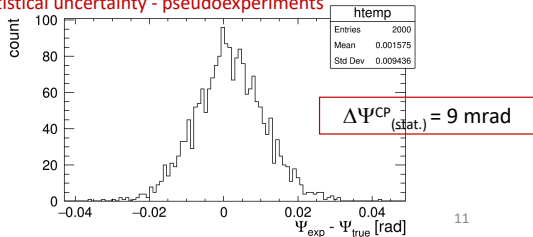


$\Delta\phi$ reconstructed, corrected, local fit

$\Psi_{CP}=0.0016 \text{ mrad}, |\Psi_{\text{true}}-\Psi_{CP}|=1.6 \text{ mrad}$



Statistical uncertainty - pseudoexperiments



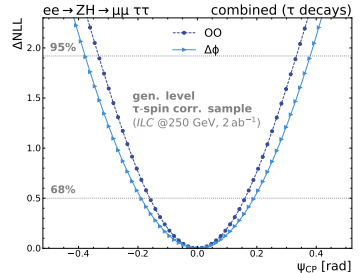
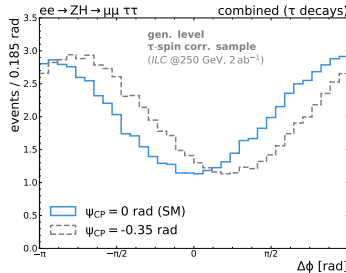
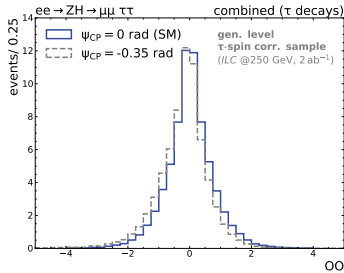
Estimating CP-Sensitivity of OO and $\Delta\phi$ NLL Scans

Lea Kuttler @ LCWS'2025

Figure of merit for estimating CP-sensitivity

- Length of central 68% confidence interval constructed from Negative Log Likelihood (NLL) scans
- Only considering shape of distributions:

$$\ln \mathcal{L}(\psi_{\text{CP}}) = \sum_i^{n_{\text{bins}}} n_i \ln \nu_i, \text{ with } \sum_i^{n_{\text{bins}}} n_i = \sum_i^{n_{\text{bins}}} \nu_i$$



*Note: comb. distributions shown here are just for illustrative purposes; comb. NLL scan uses the three tau decay modes and & their distributions

Summary & Outlook

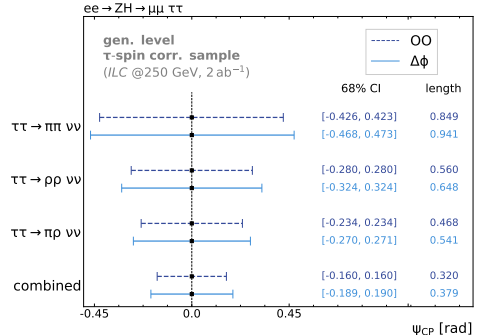
Lea Kuttler @ LCWS'2025

To summarize

- Clean e^+e^- events allow precise CP study of $H \rightarrow \tau\tau$ decays
- Matrix-element based reweighting allows CP-mixing studies without extra BSM samples
- Truth level, signal-only estimates of CP sensitivity:
OO exceeds $\Delta\phi$ in CP sensitivity by 16%

Next steps

- Transfer studies to official ILD samples
 - Include transverse tau spin correlations using *TauSpinner*
- Include backgrounds
- Transfer studies to reconstruction level
 - Implement tau ID & reco + decay mode ID



Many thanks to Jenny List, Daniel Jeans and Yann Stoll for their kind support, guidance and provision of resources!

RECEIVED: October 4, 2024

ACCEPTED: January 20, 2025

PUBLISHED: February 18, 2025

Searching for displaced vertices with a gaseous tracker for a future e^+e^- Higgs factory

Jan Klamka  and Aleksander Filip Żarnecki  on behalf of the ILD concept group

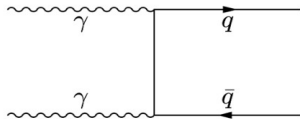
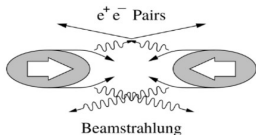
*Faculty of Physics, University of Warsaw,
Pasteura 5, 02-093 Warsaw, Poland*

E-mail: jan.klamka@fuw.edu.pl, filip.zarnecki@fuw.edu.pl

Overlay events background

At linear e^+e^- colliders beams are strongly focused and radiate photons, so $\gamma\gamma$ interactions also occur in detector

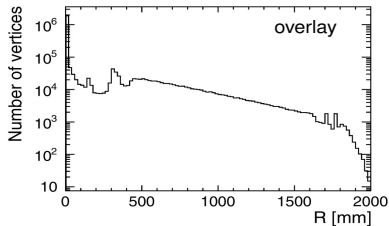
Incoherent e^+e^- pairs



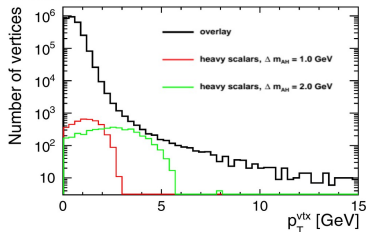
Low- p_T $\gamma\gamma \rightarrow$ hadrons

These events are soft, usually important because they **overlay** on physical events... But occur in each bunch crossing (BX) and with $\sim 10^{11}$ BXs/yr at ILC can also be a source of a standalone background

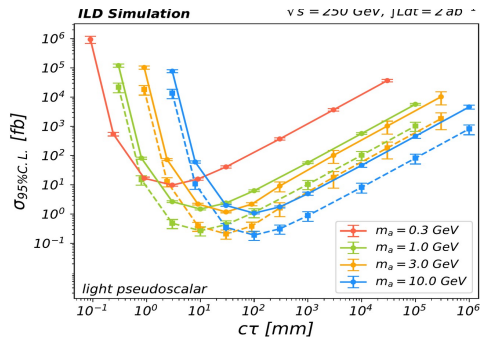
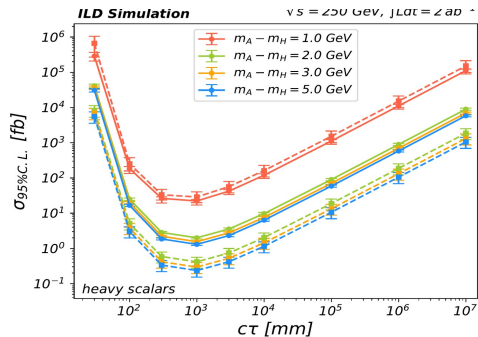
ILD Simulation



ILD Simulation

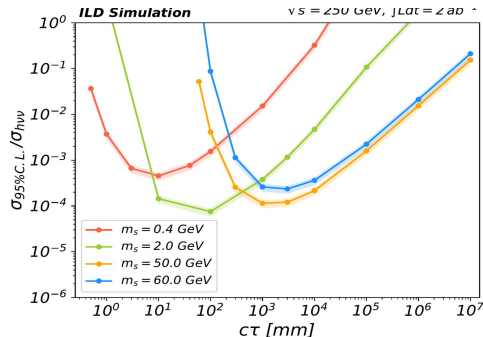
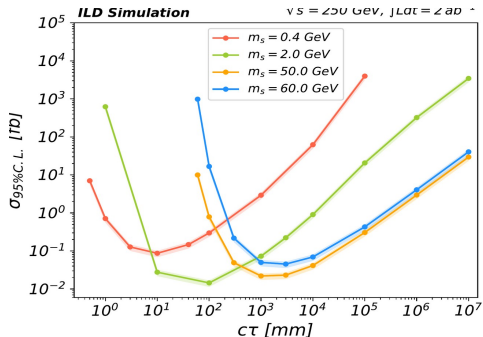


Cross section limits



- Tight selection: dashed line, standard selection: solid line
- A wide range of models with heavy scalars with small mass splittings, or light pseudo scalar particles, can be excluded down to 0.1 fb

Higgs decays to LLPs



- Current limits: down to 10^{-4} (low masses), down to 10^{-3} in $s \rightarrow b\bar{b}$ and 10^{-5} in $s \rightarrow \mu\mu$ (high masses)
- ILD can improve the current constraints and probe higher lifetimes already @ ILC250 thanks to higher TPC acceptance
- The limits could be further improved by dedicated searches using vertex detector and by more data at higher energy stages



ILD-PHYS-2026-001

DESY-26-039

15 April 2026

The SUSY reach of Higgs Factories in the most challenging scenario: scalar τ -leptons with lowest cross section and small mass differences

M.T. Núñez Pardo de Vera^{*}, M. Berggren^{*}, J. List^{*}

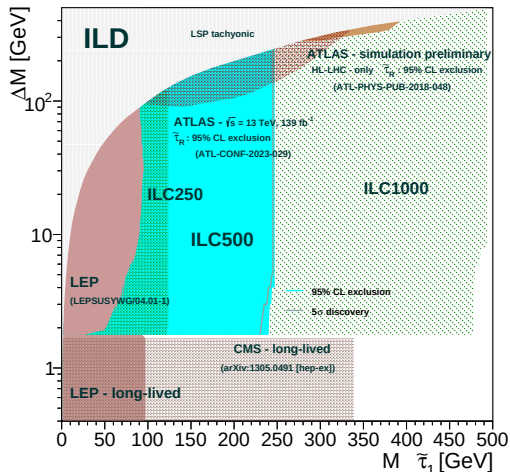
^{*} *Deutsches Elektronen-Synchrotron DESY,
Notkestr. 85, 22607 Hamburg, Germany*

14 Apr 2026

arXiv:2604.06103

ILC-500 to ILC-250 or ILC-1000 comparison

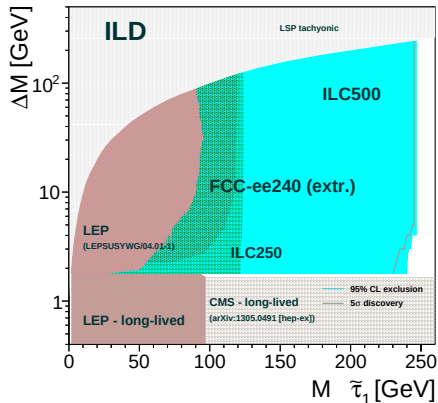
- Final result of our study for ILD at ILC500
- ... and with recasts to 250 GeV and 1 TeV



ILC-500 to FCCee-250 comparison

FCCee: Assume

- Hypothetical ILC-500, as before.
- Optimise ρ cut for FCCee hermeticity: optimal $S/\sqrt{B}$ would be for **B in the millions**.
- So, **systematics will dominate**, and to add insult to injury, the background is $\gamma\gamma$, with important theoretical uncertainties.
- We assumed 15 permil systematic uncertainty.



Article

Exploring Hidden Sectors with Two-Particle Angular Correlations at Future e^+e^- Colliders

Emanuela Musumeci ¹, Adrián Irles ^{1,*}, Redamy Pérez-Ramos ^{2,3}, Imanol Corredoira ⁴,
Edward Sarkisyan-Grinbaum ^{5,6}, Vasiliki A. Mitsou ¹ and Miguel Ángel Sanchis-Lozano ¹

¹ IFIC (Instituto de Física Corpuscular), Universitat de València and CSIC (Consejo Superior de Investigaciones Científicas), 46980 Paterna, Spain; emanuela.musumeci@ific.uv.es (E.M.); vasiliki.mitsou@ific.uv.es (V.A.M.); mas@ific.uv.es (M.Á.S.-L.)

² DRII-IPSA (Direction de la Recherche et de l'Innovation de l'Institut Polytechnique des Sciences Avancées), 94200 Ivry-sur-Seine, France; redamy.perez-ramos@ipsa.fr

³ Laboratoire de Physique Théorique et Hautes Energies (LPTHE), UMR 7589, Sorbonne Université et Centre National de la Recherche Scientifique (CNRS), 75252 Paris Cedex 05, France

⁴ Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain; imanol.corredoira.fernandez@cern.ch

⁵ Experimental Physics Department, CERN (European Organization for Nuclear Research), 1211 Geneva 23, Switzerland; edward.sarkisyan-grinbaum@cern.ch

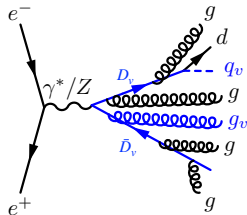
⁶ Department of Physics, The University of Texas at Arlington, Arlington, TX 76019, USA

* Correspondence: adrian.irles@ific.uv.es

$$\sqrt{s} = 250 \text{ GeV}$$

SIGNAL

$$e^+e^- \rightarrow \gamma^*/Z^0 \rightarrow D_v \bar{D}_v \rightarrow \text{hadrons}$$



$$m_{D_v} = 125 \text{ GeV}$$

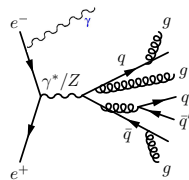
$$\alpha_v = 0.1$$

No polarised beam

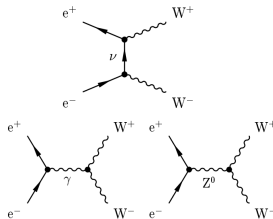
Process	σ_{PYTHIA8} [pb]	
$e^+e^- \rightarrow D_v \bar{D}_v$	m_{D_v}	
$m_{q_v} = 0.1 \text{ GeV}$	125 GeV	0.13
$m_{q_v} = 10 \text{ GeV}$	125 GeV	0.12
$m_{q_v} = 50 \text{ GeV}$	125 GeV	0.12
$m_{q_v} = 100 \text{ GeV}$	125 GeV	0.12
$m_{q_v} = 50 \text{ GeV}$	100 GeV	1.29
$m_{q_v} = 40 \text{ GeV}$	80 GeV	1.54
$e^+e^- \rightarrow q\bar{q}$ with ISR		48
$WW \rightarrow 4q$		7.4

BACKGROUND

i) $q\bar{q}$ production with ISR



ii) $WW \rightarrow 4q$



Yield

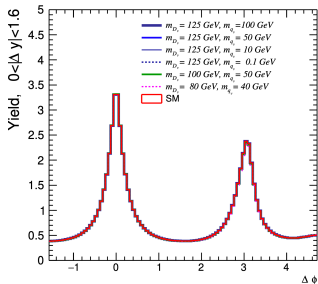
$$S^{SM}(\Delta y, \Delta\phi) = \frac{1}{N_{\text{pairs}}^{SM}} \frac{d^2 N_{\text{same}}^{SM}}{d\Delta y d\Delta\phi};$$

$$S^{SM+HV}(\Delta y, \Delta\phi) = \frac{1}{N_{\text{pairs}}^{SM} + N_{\text{pairs}}^{HV}} \left(\frac{d^2 N_{\text{same}}^{SM}}{d\Delta y d\Delta\phi} + \frac{d^2 N_{\text{same}}^{HV}}{d\Delta y d\Delta\phi} \right);$$

$$Y(\Delta\phi) = \frac{\int_{y_{\text{inf}} \leq |\Delta y| \leq y_{\text{sup}}} S(\Delta y, \Delta\phi) dy}{\int_{y_{\text{inf}} \leq |\Delta y| \leq y_{\text{sup}}} B(\Delta y, \Delta\phi) dy}$$

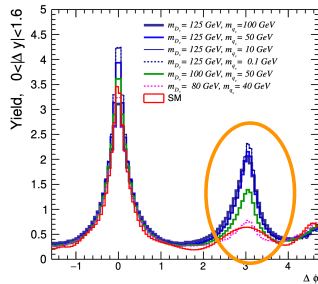
estimated from a SM back-to-back sample

NO CUTS



Pythia8+SGV (ILC detector)

CUTS

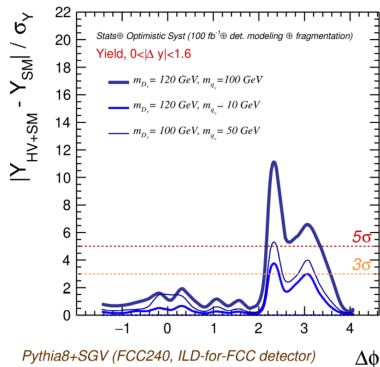


Pythia8+SGV (ILC detector)

WORK IN PROGRESS

Emanuela Musumeci @ ILD S&A meeting, Dec. 2024

Still, the angular correlation observables are very powerful



RECEIVED: April 30, 2025

REVISED: August 26, 2025

ACCEPTED: October 2, 2025

PUBLISHED: November 11, 2025

Determination of the first-generation quark couplings at the Z -pole

K. Mękała^{a,b,*} D. Jeans^c J. Reuter^b J. Tian^d and A.F. Żarnecki^a

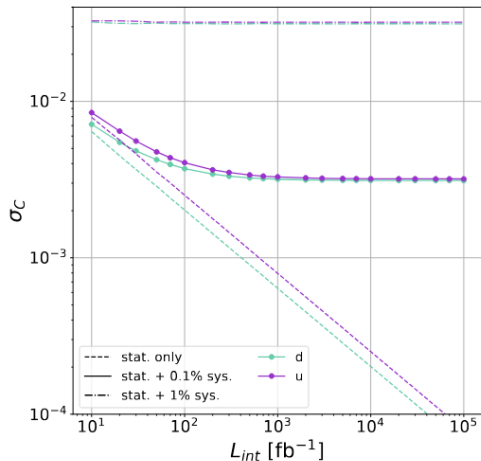
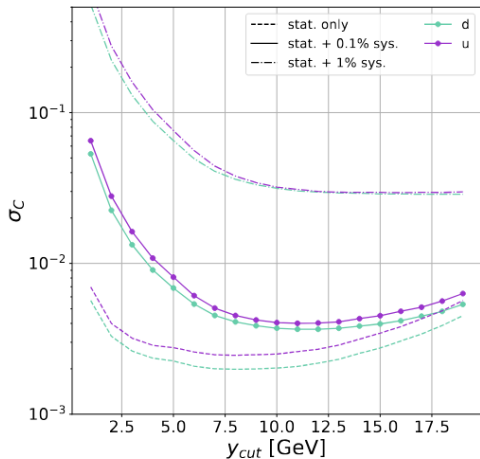
^a*Faculty of Physics, University of Warsaw,
Pasteura 5, 02-093 Warsaw, Poland*

^b*Deutsches Elektronen-Synchrotron DESY,
Notkestr. 85, 22607 Hamburg, Germany*

^c*KEK,
1-1 Oho Tsukuba, Ibaraki 305-0801, Japan*

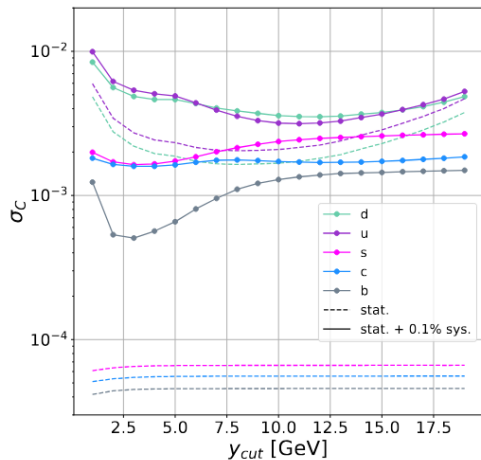
^d*International Center for Elementary Particle Physics ICEPP, University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*

Results – 2 flavours

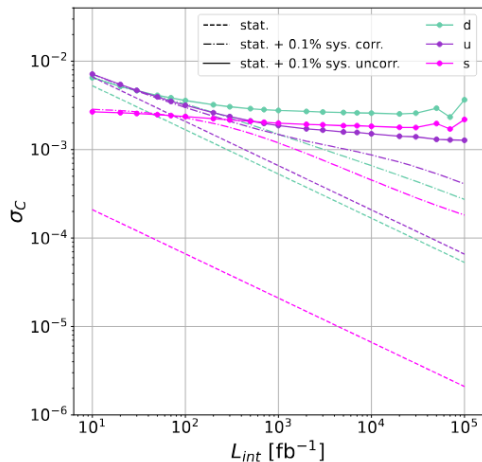


assuming int. lumi of 100 fb^{-1}

Results – 5 flavours



assuming int. lumi of 100 fb^{-1}



Search for dark photons at future e^+e^- colliders

Mikael Berggren¹, Sepideh Hosseini-Senvan^{1,2}

¹DESY, Hamburg, ²Universität Hamburg

LCWS2025, Valencia, October 2025



CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG



Dark Photons at e^+e^- beyond SuperKEKB

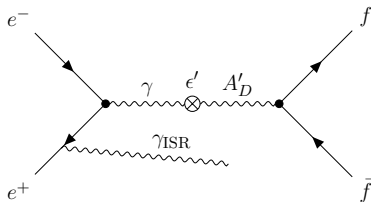
- Signal process:

$e^+e^- \rightarrow \gamma_{ISR} A_D \rightarrow \mu^+\mu^- \gamma_{ISR}$,
 where E_{ISR} is such that the
 recoil-mass against the ISR is
 M_{A_D}

- NB: the production-vertex is the **SM** $e^+e^- Z^{(*)}$ one !

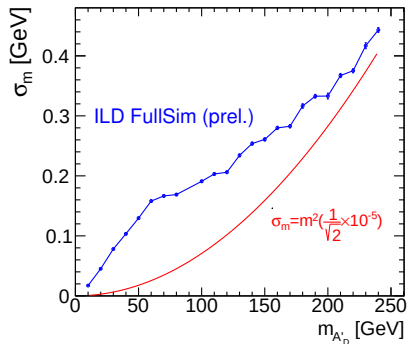
- Both σ and Γ **scales with ϵ^2** .

- One could hope to exclude $\sigma > \mathcal{O}(1 \text{ fb})$
- For the corresponding ϵ^2 , Γ is $\mathcal{O}(10 \text{ keV})$ to $\mathcal{O}(10 \text{ MeV})$.
- $\Rightarrow$ **detector resolution** will determine the peak-width
- $\Rightarrow$ **decay is prompt**



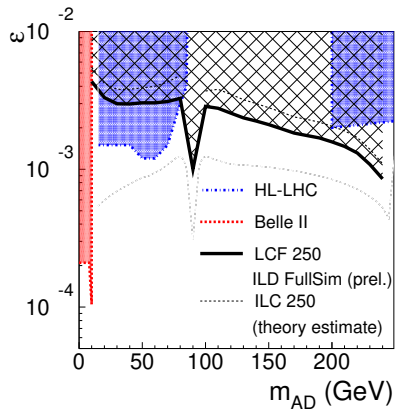
Dark Photons in a real detector

- Bottom line: **None** of the assumptions on the mass-resolution - the **red** curve - used for the EPPSU curve are valid. The **correct** full simulation values are the **blue** curve.
- The resolution will **vary a lot event-by-event** - with angle and momentum of the muons, and the angle of the ISR.
- ⇒ **Event-by-event simulation is essential.**



Recast to ILC250 to LCF250

- **More luminosity:**
 $2 \text{ ab}^{-1} \rightarrow 3 \text{ ab}^{-1}$. But
 $1/\sqrt[4]{1.5}=0.90 \dots$
- **Likelihood-weighting** of the different polarisation samples.
 - Note that since signal and the background from $e^+e^- \rightarrow \mu^+\mu^-$ has the same polarisation dependence, Likelihood-weighting only helps a lower masses, where other backgrounds dominate.



ESPP Briefing Book

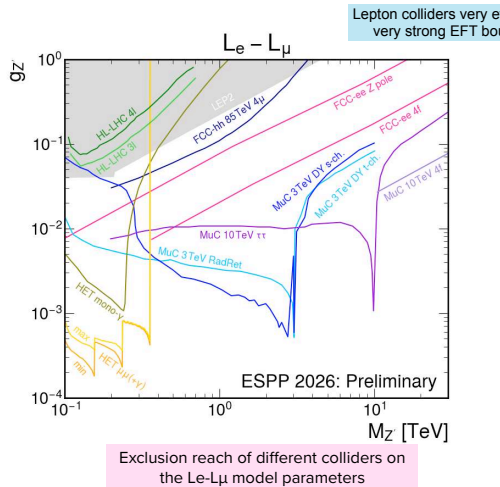
As presented at Open Symposium in Venice, **Leptophilic Z' model** was selected as one of the benchmark models.

Only monophoton results available for ILC, not competitive with FCC-ee direct search

Le- L_μ

- Leptophilic Z' with gauge group $U(1)$ L_x-L_y and vector couplings to the SM leptons
 - g' and $m_{Z'}$ are the effective coupling of Z' to leptons and the mass of Z'
- **New figure**, includes:
 - Higgs Electroweak Top factory (HET): FCC-ee (4f, $\mu\mu \gamma + \text{mono } \gamma$), ILC Delphes (mono γ)
 - FCChh (result from 2205.13552 for 100 TeV rescaled to 85 TeV)
 - MuC 2308.12804, 2205.13552 (EFT, direct 3 TeV, 10 TeV(TBU))

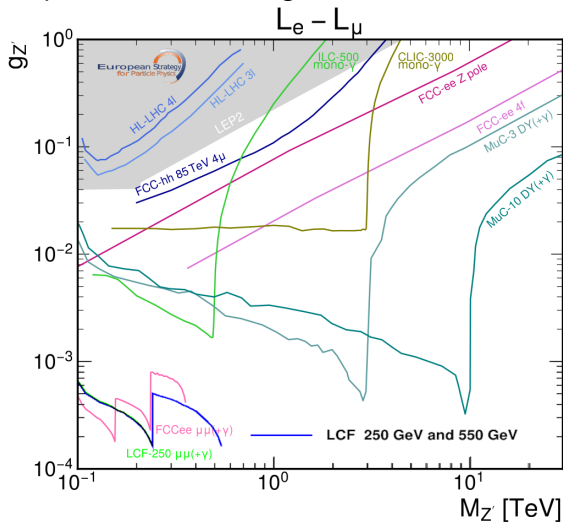
Another scenario under consideration B3-L3
(B-L only in the third generation)



Rebeca Gonzalez Suarez (Uppsala University) - Open Symposium ESPP, Venice (2025)

Coupling limits

Comparison with Briefing Book results



Determining Triple Gauge Couplings at Future e^+e^- Higgs Factories using Optimal Observables

Leonhard Reichenbach

University of Bonn

Promotionskolloquium

2026-09-01

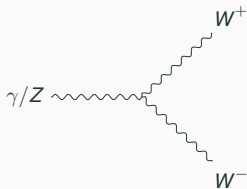
With funding from the:



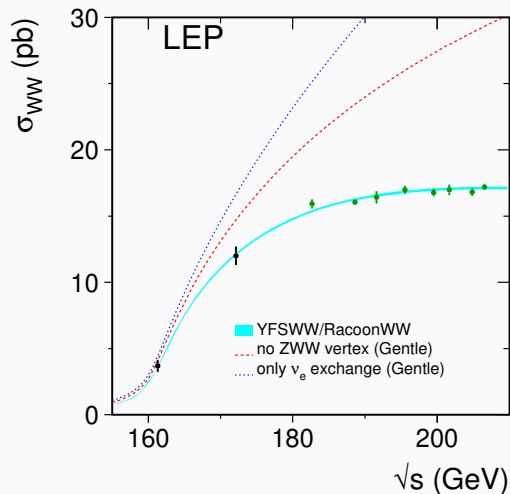
Federal Ministry
of Research, Technology
and Space

Triple Gauge Couplings (TGC)

- SM Lagrangian contains interaction:

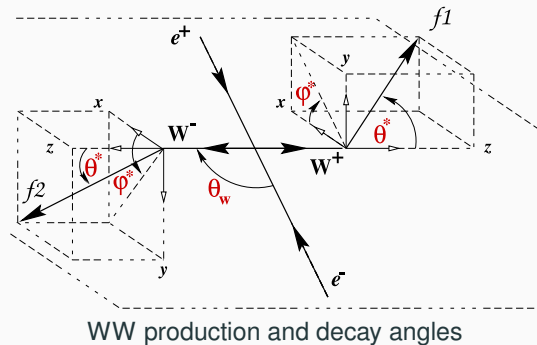


- Regularises $e^+e^- \rightarrow W^+W^-$ cross-section
- Observed and compatible with SM
- Dim.-6 SMEFT: 3 additional operators
- LEP parametrisation: $g_1^Z, \kappa_\gamma, \lambda_\gamma$
- *Anomalous* triple gauge couplings (aTGC)



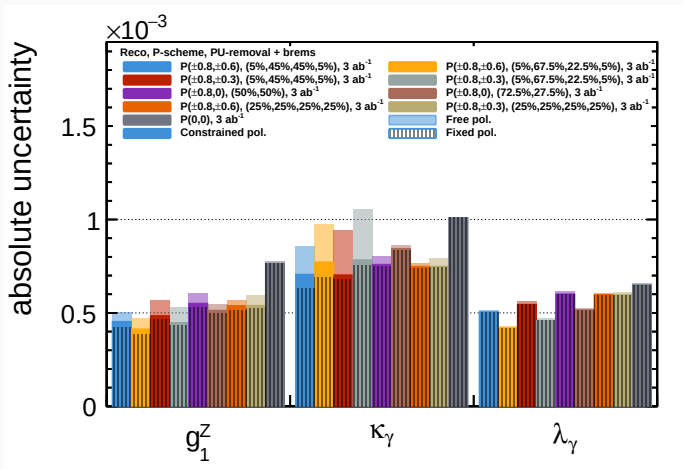
Extracting the Parameters

- Full final state sensitive to TGC (W-spins)
- W production and decay angles, $m_{\ell\nu}$, m_{jj}
- More than narrow-width on-shell WW
- How to perform a fit on a 5–8 dimensions?
- Binned: too many bins
- Unbinned: too slow?
- Alternatives?



Effect of Polarised Beams

- Better than none (grey bar)
- Behaviour varies a lot
- In-situ determination not always good enough*
- *could likely be fixed



Many diverse topics studied within ILD, many interesting results...

We made significant contribution to ECFA study report
and also other submissions to the ESPPU'2026 (LCVision, Briefing Book,...)

It is only a pity this was not seriously taken into account...

Many diverse topics studied within ILD, many interesting results...

We made significant contribution to ECFA study report
and also other submissions to the ESPPU'2026 (LCVision, Briefing Book,...)

It is only a pity this was not seriously taken into account...

I decided to step down as physics coordinator to let younger people to lead ILD in the new era.

I enjoyed these years a lot, I learned a lot,
I would like to thank all of you for your enthusiasm and devotion.

I do not quit ILD, I stay around, please contact me if you need help,
or just like to discuss something.

I like sharing experience with others, that is what university professors are for ...

Thank you!