

Probing Gauge-Higgs Unification models at the ILC with $q\bar{q} A_{FB}$ at c.m.e. above the Z mass (And other works)

IJCLab 04/07/2024

J. P. Márquez – AITANA Group at IFIC (CSIC/UV) - Valencia



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J. P. Márquez, A. Irles, A. Saibel, H. Yamamoto – AITANA Group at IFIC (CSIC/UV) - Valencia

F. Richard, R. Pöschl – IJCLab - Orsay

N. Yamatsu – Kyoto University



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- ▶ Paper recently published in EPJ-C!
 - DOI: [10.1140/epjc/s10052-024-12918-z](https://doi.org/10.1140/epjc/s10052-024-12918-z)
- ▶ Auxiliary and support studies:
 - ILD note (2022) [2306.11413](#)
 - ▶ ILC250, b and c studies. (A. Irles, F. Richard, R. Pöschl).
 - Proceeding LCWS (2023) [2307.14888](#)
 - ▶ Optimization of flavor tagging, use of dNdx PID and extension to 500 GeV. (J.P. Marquez)
 - Proceeding EPS-HEP (2023) [2310.17617](#)
 - ▶ First phenomenology prospects. (J.P. Marquez)

Eur. Phys. J. C (2024) 84:537
<https://doi.org/10.1140/epjc/s10052-024-12918-z>

THE EUROPEAN
PHYSICAL JOURNAL C



Regular Article - Experimental Physics

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^{1,2}, 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, UCLab, 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

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Abstract The International Linear Collider (ILC) will allow the precise study of $e^-e^+ \rightarrow q\bar{q}$ interactions at different center-of-mass energies from the Z-pole to 1 TeV. In this paper, we discuss the experimental prospects for measuring differential observables in $e^-e^+ \rightarrow b\bar{b}$ and $e^-e^+ \rightarrow c\bar{c}$ at the ILC baseline energies, 250 and 500 GeV. The study is based on full simulation and reconstruction of the International Large Detector (ILD) concept. Two gauge-Higgs unification models predicting new high-mass resonances beyond the Standard Model are discussed. These models predict sizeable deviations of the forward-backward observables at the ILC running above the Z mass and with longitudinally polarized electron and positron beams. The ability of the ILC to probe these models via high-precision measurements of the forward-backward asymmetry is discussed. Alternative scenarios at other energies and beam polarization schemes are also discussed, extrapolating the estimated uncertainties from the two baseline scenarios.

1 Introduction

The Standard Model (SM) is a successful theory, well-established experimentally and theoretically. With the discovery of the Higgs boson [1,2], the structure of the SM seems to be confirmed. However, the SM cannot explain many of its seemingly arbitrary features. An example is the striking mass hierarchy in the fermion sector. Moreover, while the dynamics of the SM gauge bosons, the photon,

W and Z bosons, and gluons are governed by the gauge principle, the dynamics of the Higgs boson are different and unique in the SM. The SM does not predict the strength of the Higgs couplings of quarks and leptons, nor the Higgs self-couplings. Large quantum corrections must be canceled by fine-tuning the parameters to match the measured Higgs boson mass. One possible solution to this issue, achieving stabilization of the Higgs mass against quantum corrections, appears when the Higgs boson is associated with the zeroth mode of a dimension-five component of extensions of the SM gauge group. These models are referred to as gauge-Higgs unification (GHU) models.

The two most precise determinations of $\sin^2 \theta_{\text{eff}}$ by the LEP and SLC differ by 3.7 standard deviations, and neither agrees with the SM prediction [3,4]. In particular, the LEP value was extracted from the forward-backward asymmetry measurement for b-quarks in LEP1 data, and is nearly three standard deviations away from the value predicted by the SM. Clarifying this anomaly and exploring the possibility of BSM physics motivates the study of quark pair production in high energy e^-e^+ collisions at future colliders both at the Z boson mass and higher energies. In the SM, these interactions are mediated by the photon, Z boson, and their interference. Some BSM theories predict deviations of these bosons' couplings or even sizable new contributions to these processes from new mediators (such as heavy Z' resonances). These deviations would be accessible experimentally by performing high precision measurements of $e^-e^+ \rightarrow q\bar{q}$ observables at different center-of-mass energies ($\sqrt{s}$). The work presented here is based on the study of such processes at the ILC.

In parallel to the exploitation of data from the Large Hadron Collider (LHC), the high-energy accelerator-based

H. Yamamoto: On leave from Tohoku University, Sendai, Japan.

* e-mail: adrian.irles@ific.uv.es (corresponding author)

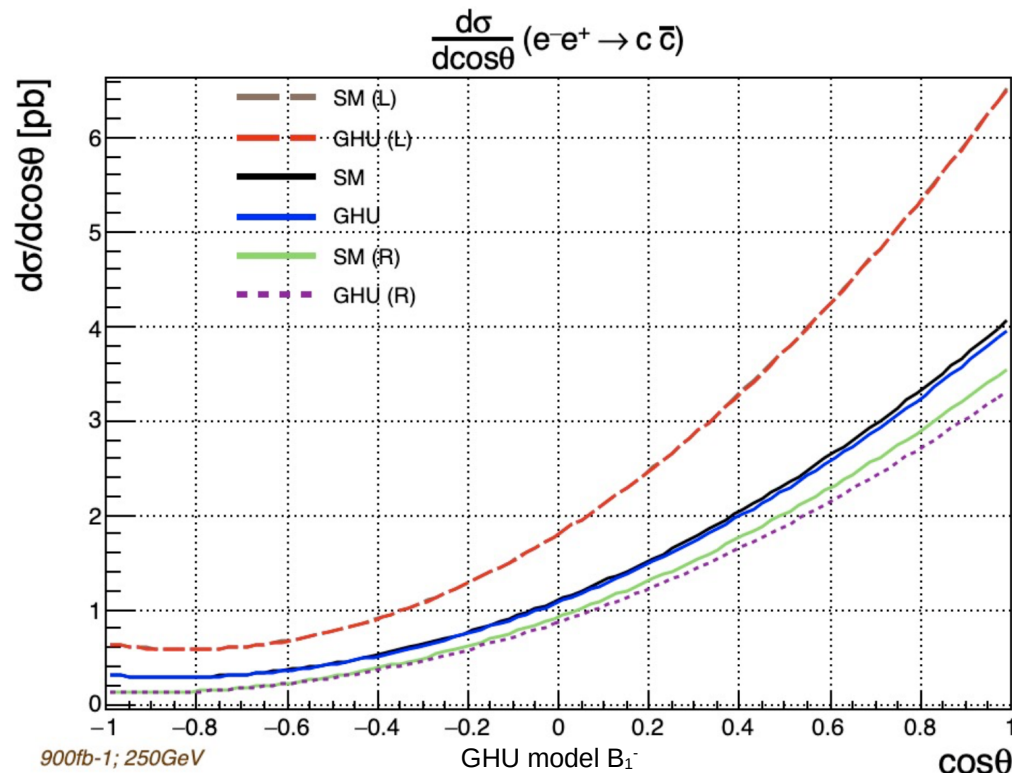
Introduction & Motivation



Gauge-Higgs Unification Models (GHU)

- ▶ Randall-Sundrum metric (5D).
- ▶ The symmetry breaking pattern is different than in the SM and features the *Hosotani mechanism*:
 - Masses are generated dynamically from the extra-dimension properties.
- ▶ Only one parameter, *Hosotani's angle* θ_H , determines the projection of the 5D fields, fixing all physical effects:
 - KK resonances of the Z/ γ with $m_{\text{KK}} \sim 10\text{-}25$ TeV.
 - **Modifications and new EW couplings/helicity amplitudes.**
 - Already visible effects at 250GeV.

As **Benchmark**, we will use the [Funatsu, Hatanaka, Hosotani, Orikasa, Yamatsu] models.



Probing such scenarios require at least
per mil level experimental precision

tt/bb/cc/ss/... Achievable at future colliders?

► A models: ([arxiv:1705.05282](https://arxiv.org/abs/1705.05282))

$$A_1 : \theta_H = 0.0917, m_{KK} = 8.81 \text{ TeV} \rightarrow m_{Z^1} = 7.19 \text{ TeV};$$

$$A_2 : \theta_H = 0.0737, m_{KK} = 10.3 \text{ TeV} \rightarrow m_{Z^1} = 8.52 \text{ TeV},$$

► B models: ([arxiv:2309.01132](https://arxiv.org/abs/2309.01132)) ([arxiv:2301.07833](https://arxiv.org/abs/2301.07833))

$$B_1^\pm : \theta_H = 0.10, m_{KK} = 13 \text{ TeV} \rightarrow m_{Z^1} = 10.2 \text{ TeV};$$

$$B_2^\pm : \theta_H = 0.07, m_{KK} = 19 \text{ TeV} \rightarrow m_{Z^1} = 14.9 \text{ TeV};$$

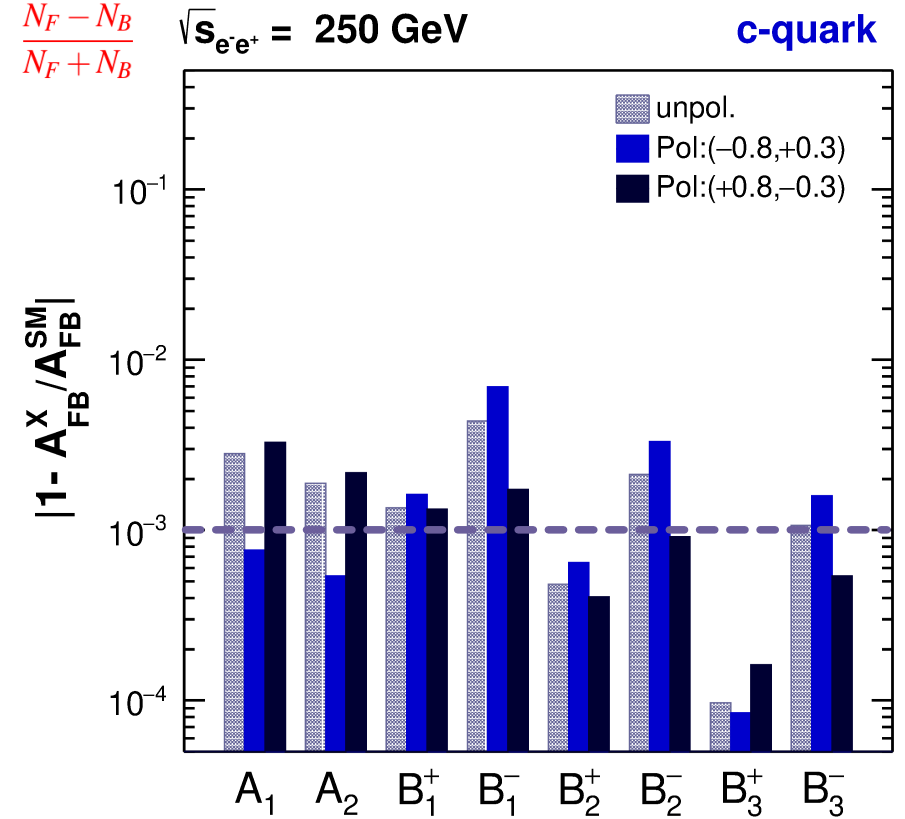
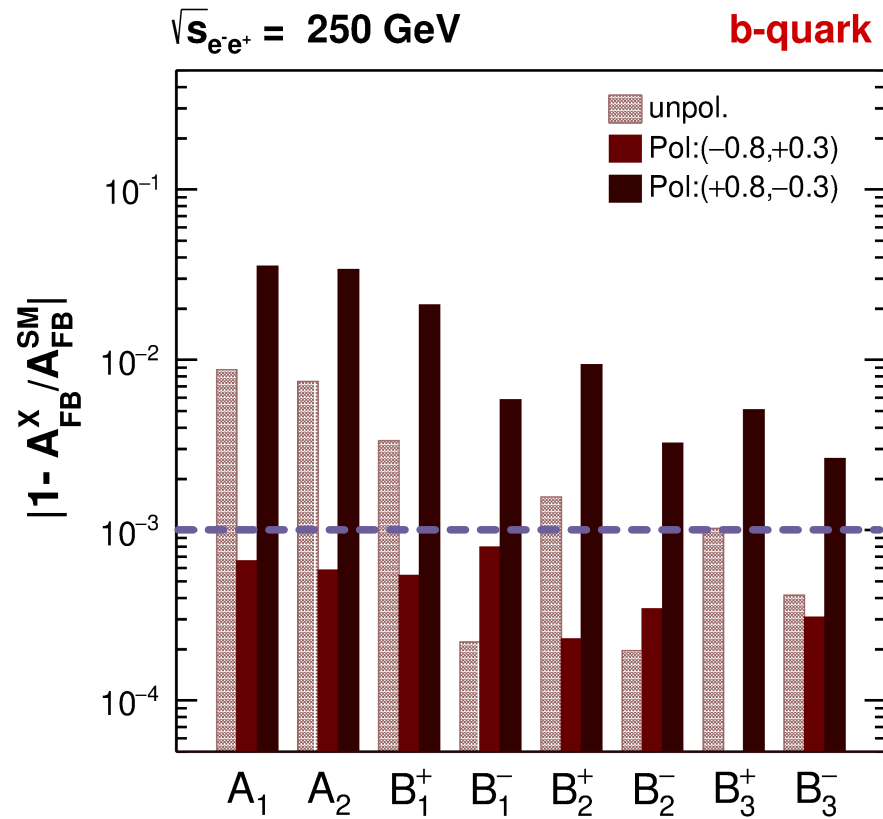
$$B_3^\pm : \theta_H = 0.05, m_{KK} = 25 \text{ TeV} \rightarrow m_{Z^1} = 19.6 \text{ TeV};$$

Resonances of O(10) TeV: Only indirect measurements are possible!

This talk: Phenomenology at ILC H20-staged program.

- Runs at 250, 500, 1000 GeV.
- Polarized e^- and e^+ beams.

GHU vs SM (250 GeV)



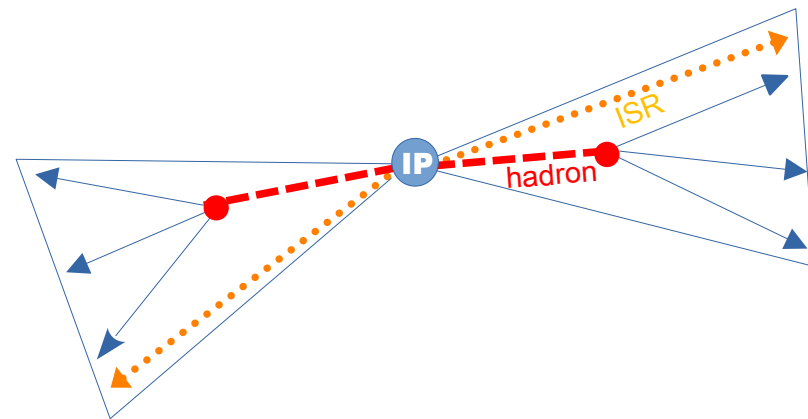
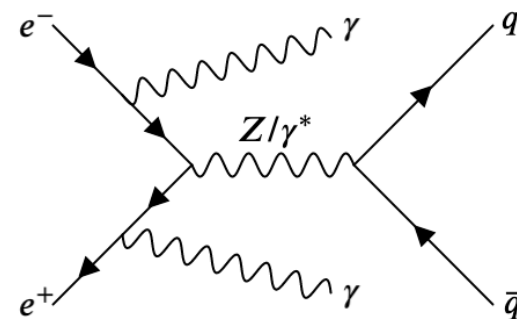
Deviations at the **per mil** level!

Experimental study with full simulation



Heavy flavor production in e^-e^+ collisions

- ▶ We work with A_{FB} for b and c quarks.
 - MC simulations at 250 and 500 GeV.
 - ▶ International Linear Collider (ILC) run plan.
 - **Full simulation** of the International Large Detector (ILD).
- ▶ Topology: Two back-to-back jets.
- ▶ Procedure:
 - 1 Background suppression → Selection of $q\bar{q}$ events.
 - 2 Flavor tagging → Selection of $b\bar{b}$ & $c\bar{c}$ events.
 - ▶ Double tagging.
 - 3 Charge measurement → Quark-Antiquark identification.
 - ▶ Double charge.

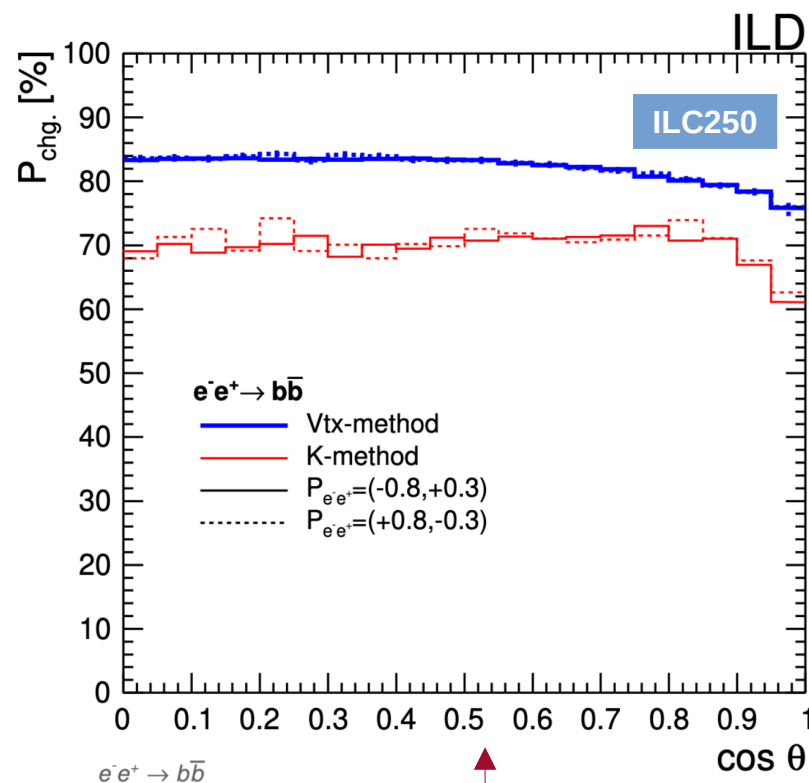
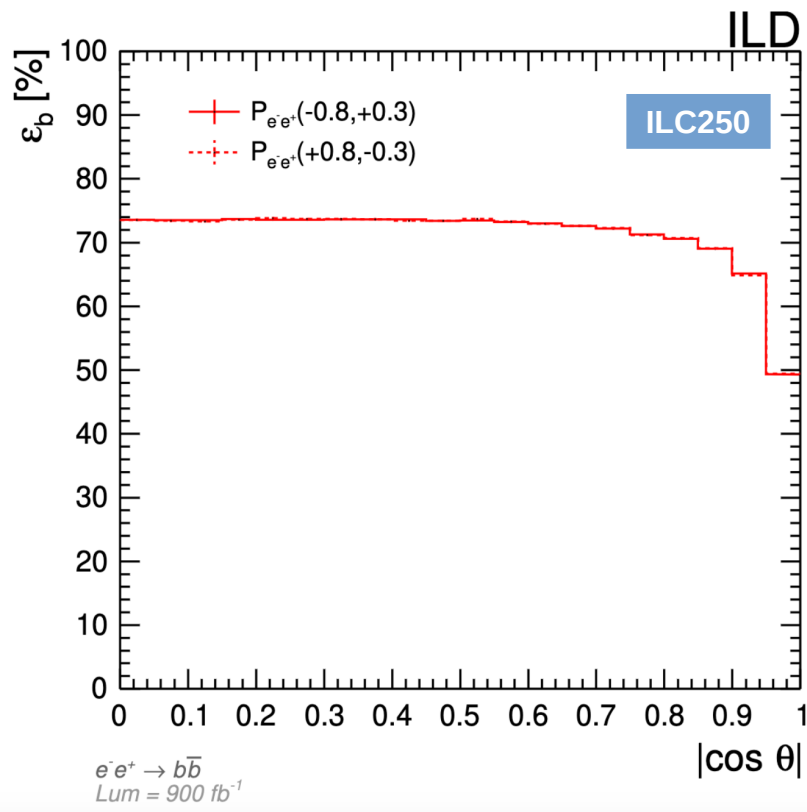


High-purity & independent samples for each quark flavour.

Jet flavour tagging & charge measurement

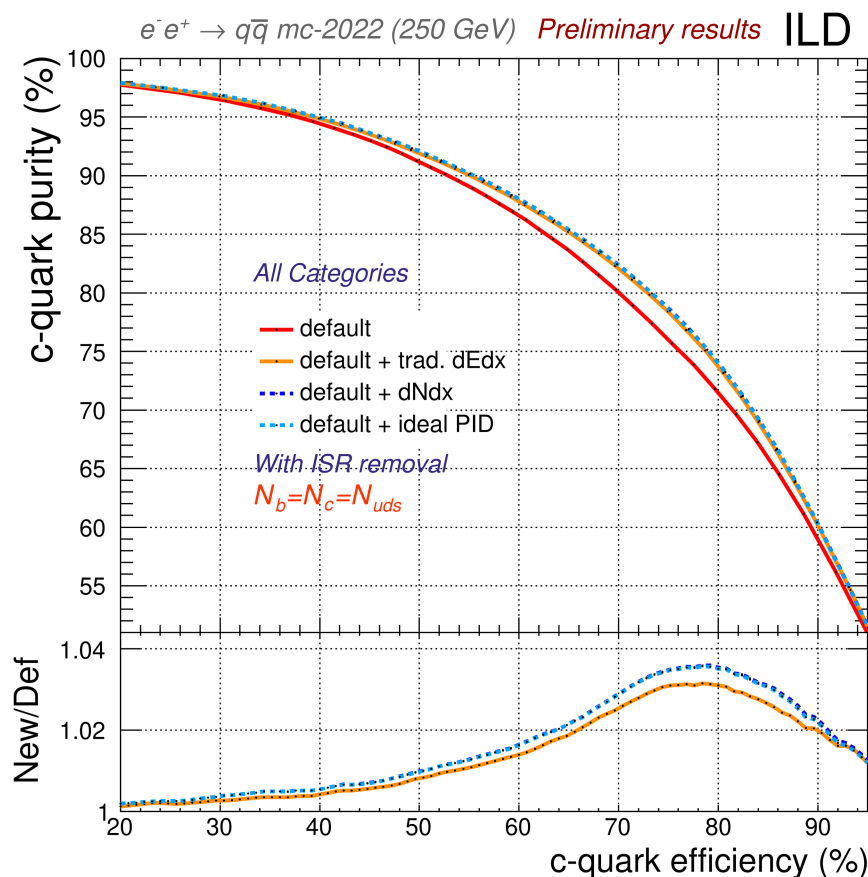
► Double tagging & double charge measurement methods. (described in previous ILD Note [2306.11413 \(2022\)](#))

- To maximally reduce the usage of MC tools (control of fragmentation, QCD correlations... uncertainties)

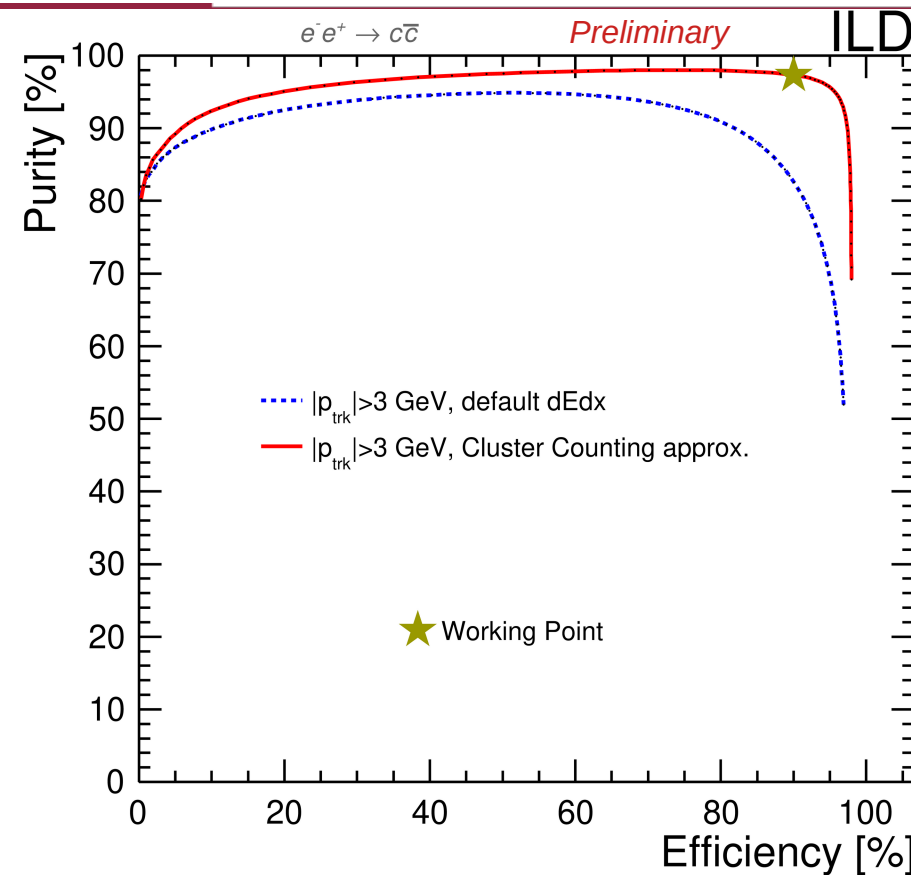


PID is very important
for this measurement!

Effects of improving the use of PID



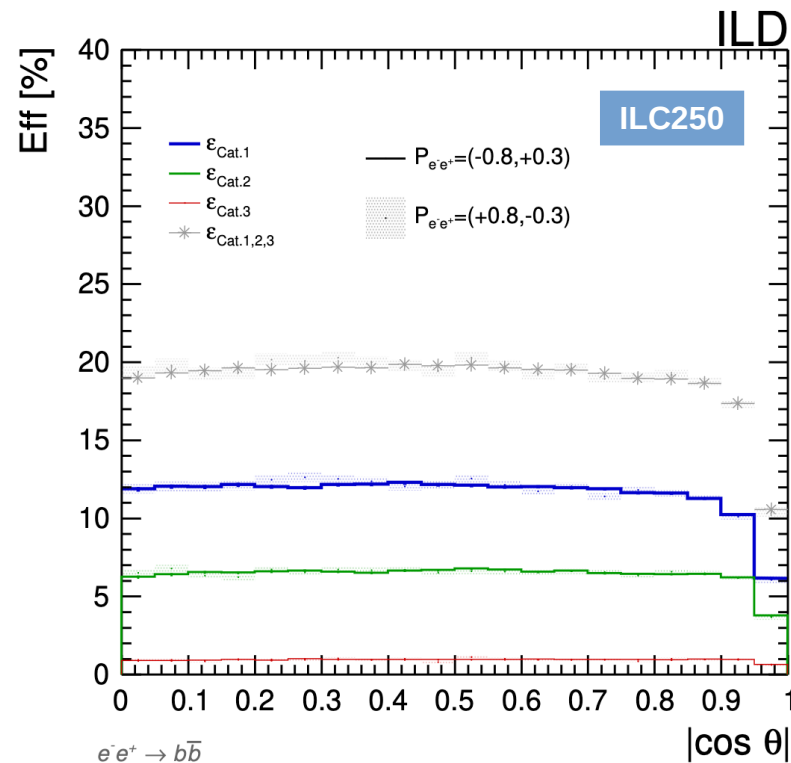
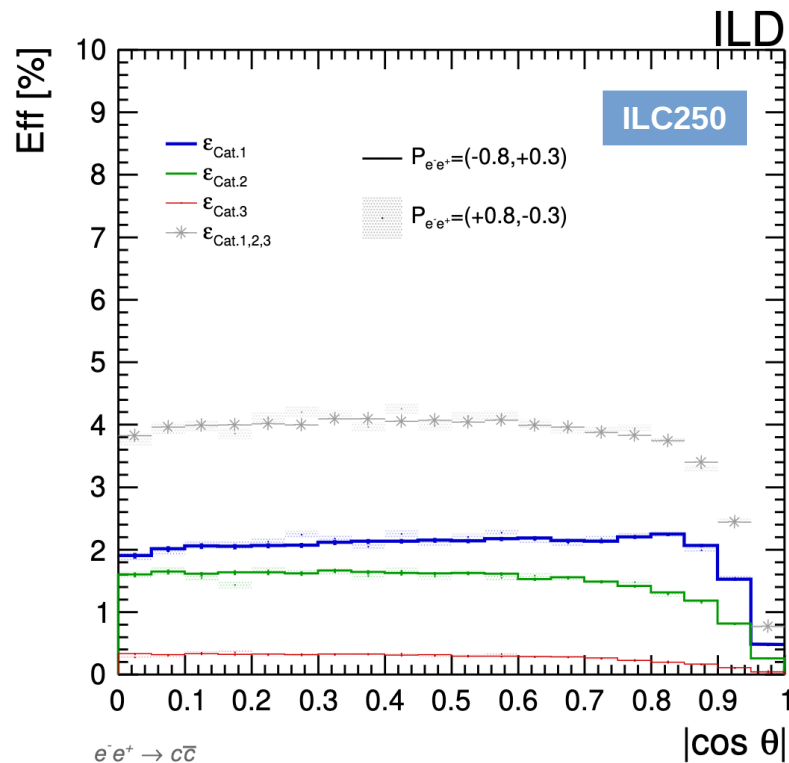
Effects in **Flavour Tagging**



Effects in **Kaon ID** for charge reco.

Jet flavour tagging & charge measurement

- Double tagging & double charge measurement methods. (described in previous ILD Note [2306.11413 \(2022\)](#))



Selection for the A_{FB} measurement at 250 GeV

Results for ILC250 & ILC500

► A_{FB} definition:

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

► At least 4 observables for A_{FB} at ILC per energy point

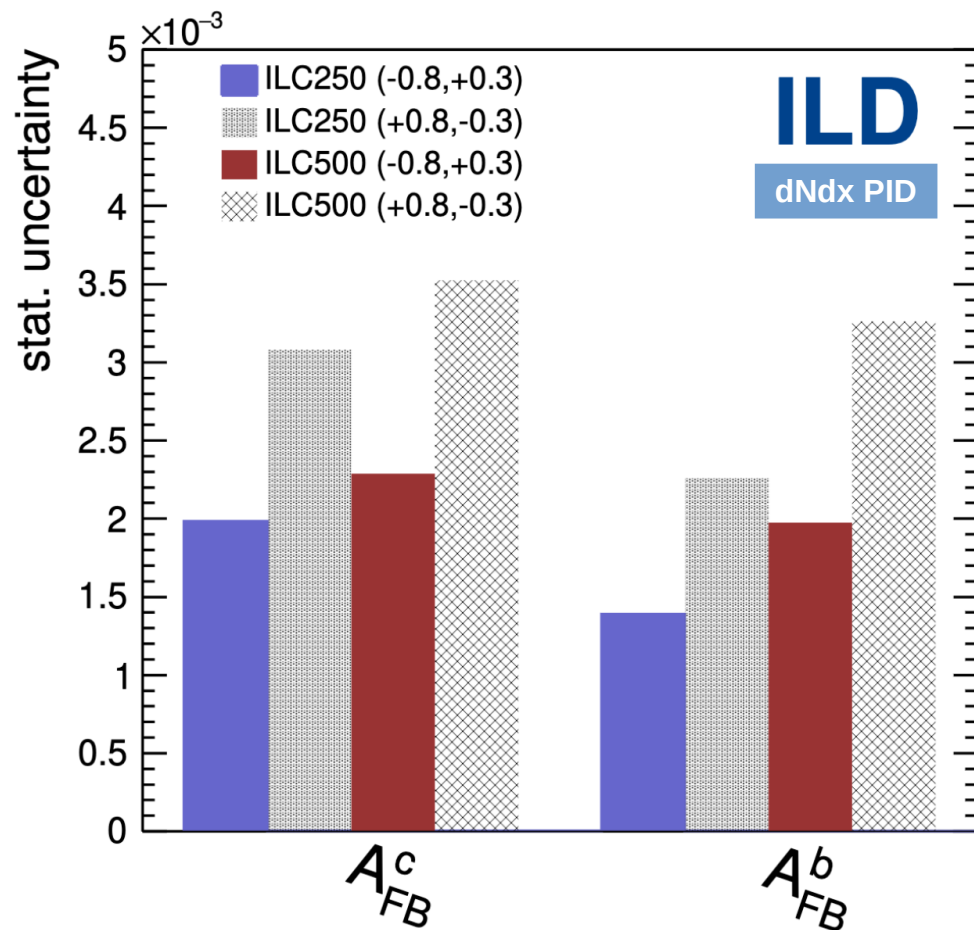
- 2 quarks (b and c).
- 2 polarizations (e_{LP} , e_{RP}).

► Per mil level statistical uncertainties reachable for the nominal ILC program

- **Smaller exp. syst. Uncertainties**

► Running at IL500

- Similar uncertainties but bigger deviations.
- Possibility of combining with the ILC250 results.

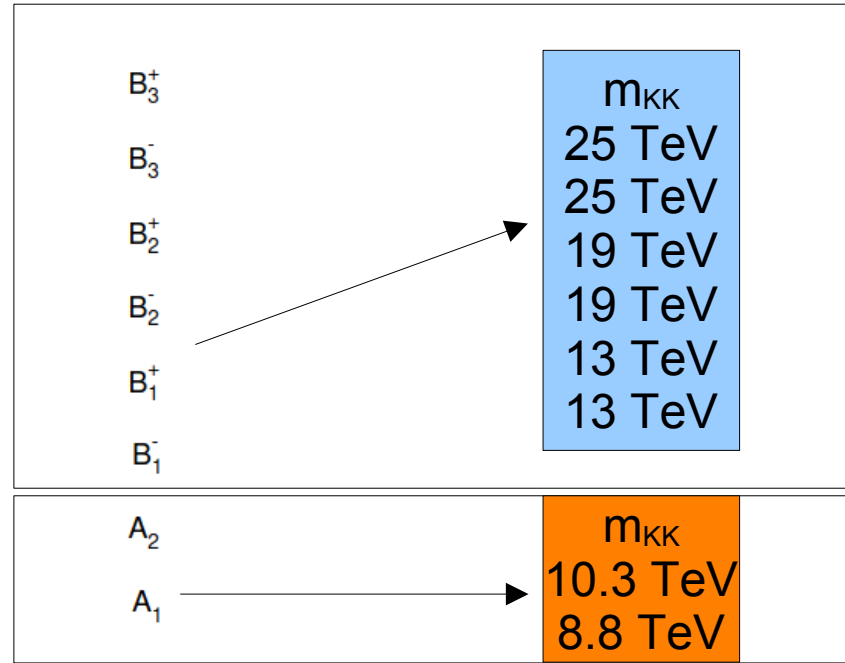


Discrimination power between GHU & SM



- ▶ Procedure: Testing the statistical significance of model AFB_{test} vs a reference model AFB_{ref} assuming that one of them is measured.
- ▶ The uncertainties are considered normally distributed:
 - Significance in σ .
 - P-value: Gaussian at d_σ .
$$d_\sigma = \frac{\|AFB_{\text{test}} - AFB_{\text{ref}}\|}{\Delta_{AFB_{\text{ref}}}}$$
- ▶ Combination of multiple measurements is done with a *multivariate gaussian*.
 - Assuming no correlations for AFB.
- ▶ We also assumed different precisions for the SM Z boson couplings:
 - Current precision, ILC250 and Giga-Z (ILC run at the Z-Pole).

GHU vs SM: GHU energy scale



Similar structure for all plots:

- More massive resonances (hardest to detect models) as we move up.
- Higher energy accessed by the ILC runs as we move to the right.

GHU vs SM: Beam scenarios

H20-staged program

H20 staged program

Hypothetical case
ILC250* no pol.
 $\int L = 2000 \text{ fb}^{-1}$

**Full ILD simulation
assuming
no beam pol.**

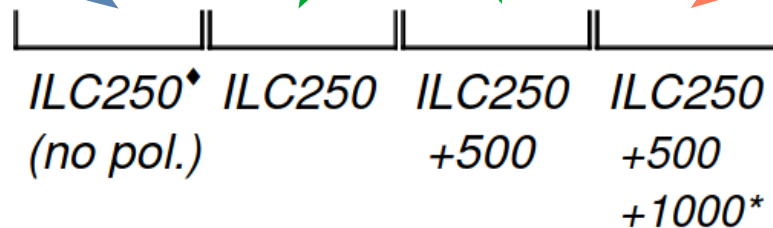
ILC250
($P_{e-}=0.8, P_{e+}=0.3$)
 $\int L = 2000 \text{ fb}^{-1}$

ILC500
($P_{e-}=0.8, P_{e+}=0.3$)
 $\int L = 4000 \text{ fb}^{-1}$

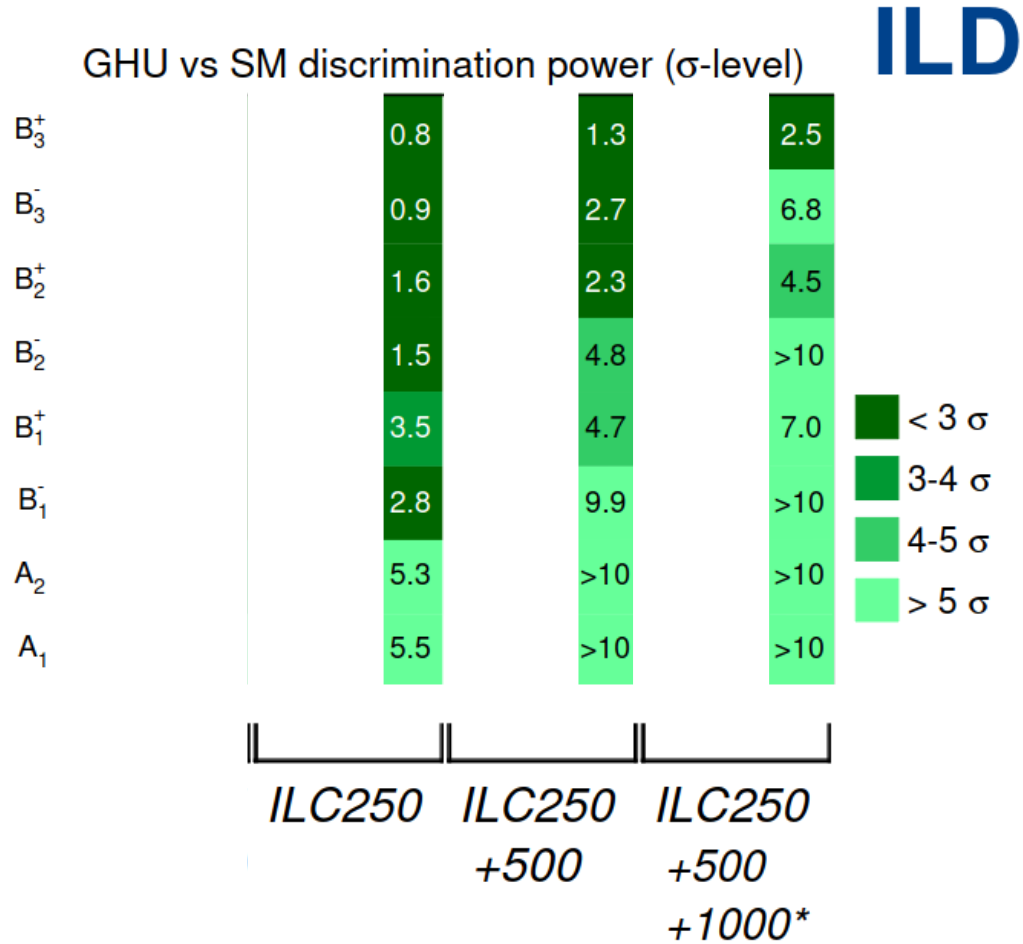
**Full ILD simulation
assuming beam pol.**

ILC1000
($P_{e-}=0.8, P_{e+}=0.2$)
 $\int L = 8000 \text{ fb}^{-1}$

*Not full simulation studies
but extrapolations from ILC500*



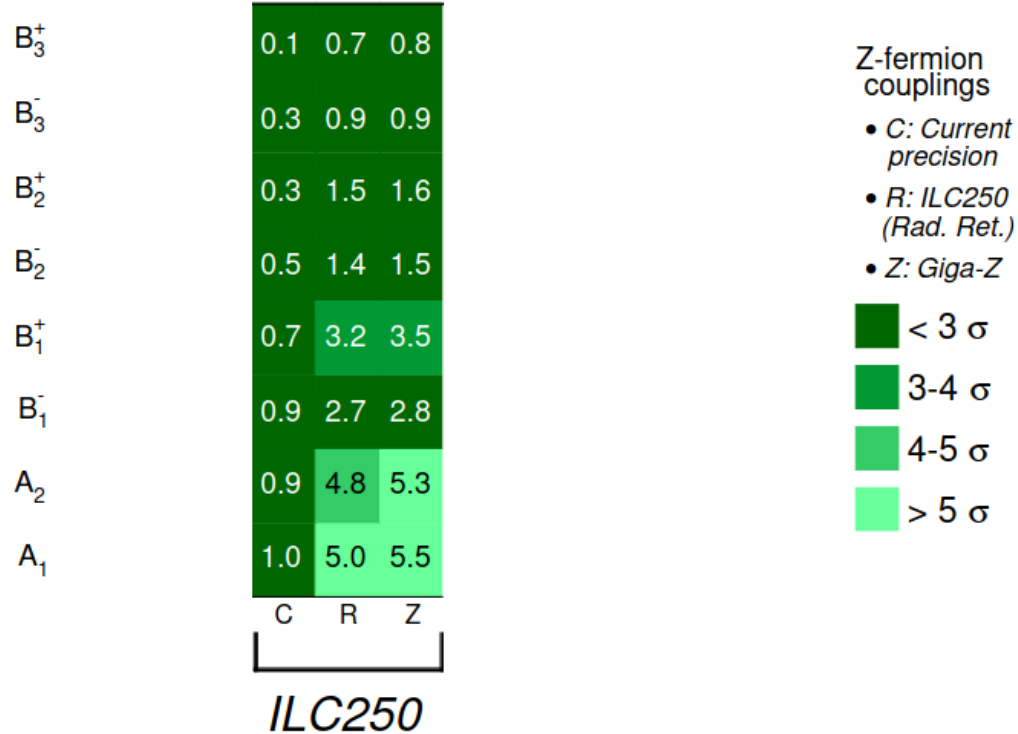
GHU vs SM: center of mass energy



GHU vs SM: Precision on Z-couplings

GHU vs SM discrimination power (σ -level)

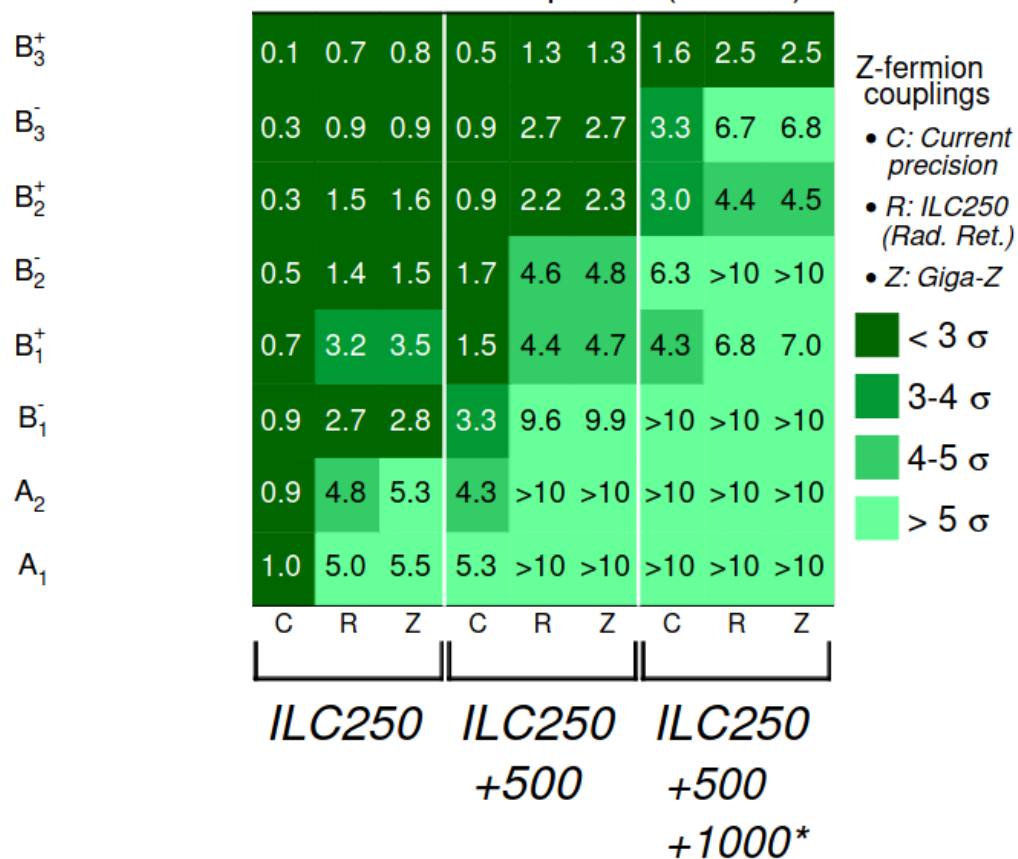
ILD



GHU vs SM: Precision on Z-couplings

ILD

GHU vs SM discrimination power (σ -level)



GHU vs SM: Beam(s) polarization

GHU vs SM discrimination power (σ -level)

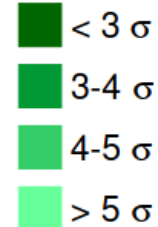
B_3^+	0.1	0.4	0.5	0.1	0.7	0.8
B_3^-	0.1	0.4	0.5	0.3	0.9	0.9
B_2^+	0.2	0.7	0.8	0.3	1.5	1.6
B_2^-	0.2	0.7	0.7	0.5	1.4	1.5
B_1^+	0.3	1.6	1.7	0.7	3.2	3.5
B_1^-	0.5	1.4	1.4	0.9	2.7	2.8
A_2	0.6	3.3	3.6	0.9	4.8	5.3
A_1	0.8	3.9	4.2	1.0	5.0	5.5
	C	R	Z	C	R	Z

$ILC250^*$ $ILC250$
(no pol.)

ILD

Z-fermion
couplings

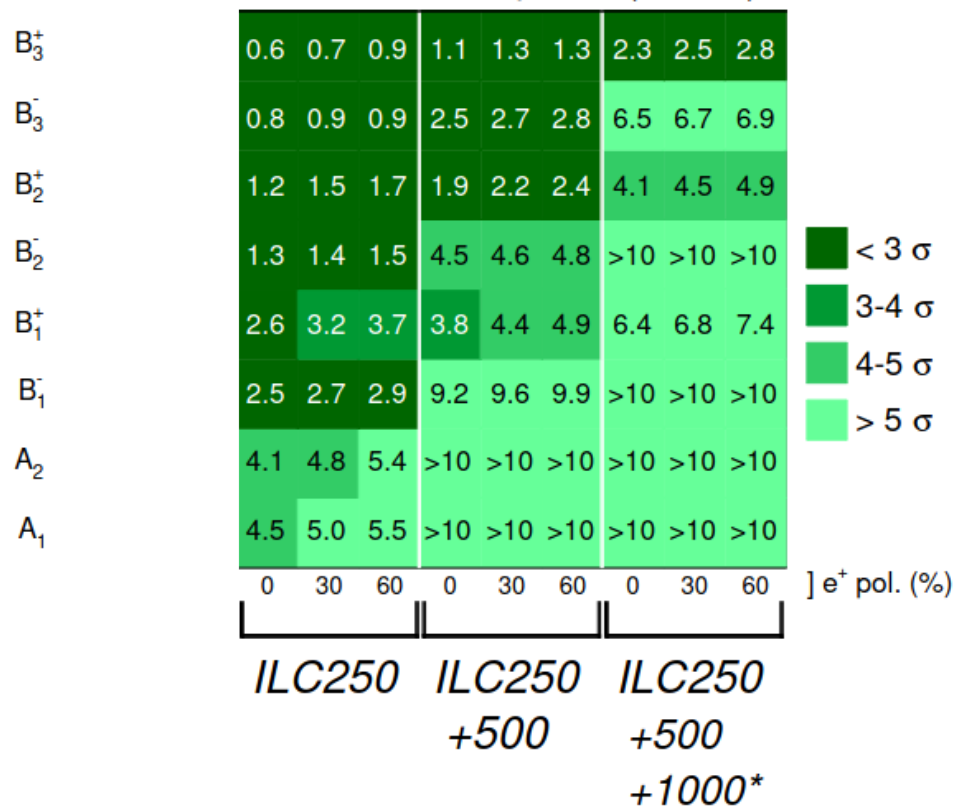
- C: Current precision
- R: ILC250 (Rad. Ret.)
- Z: Giga-Z



GHU vs SM: Positron beam polarization

ILD

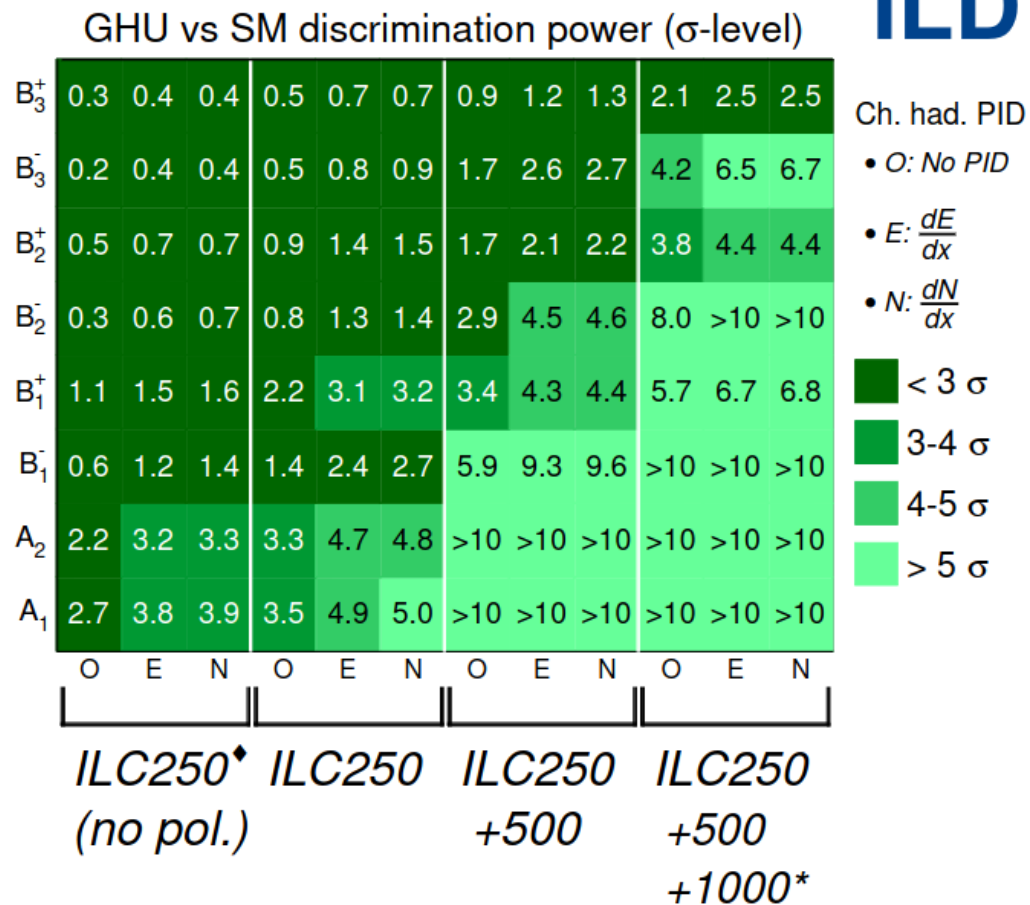
GHU vs SM discrimination power (σ -level)



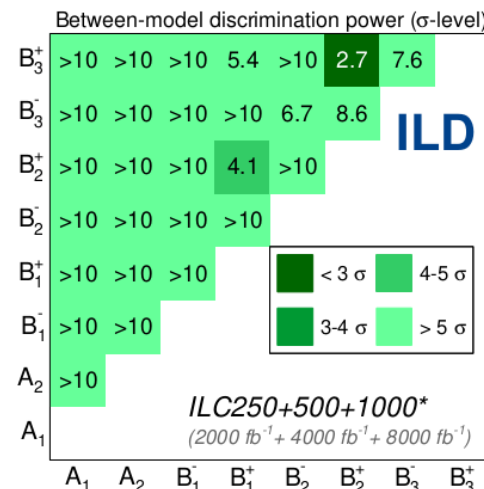
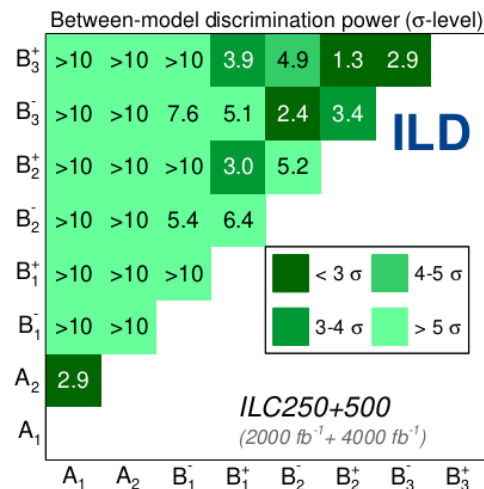
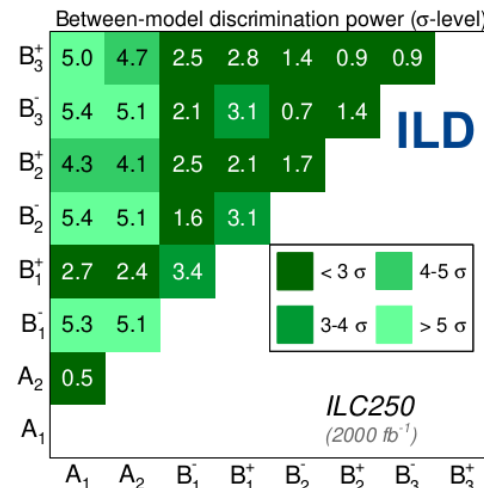
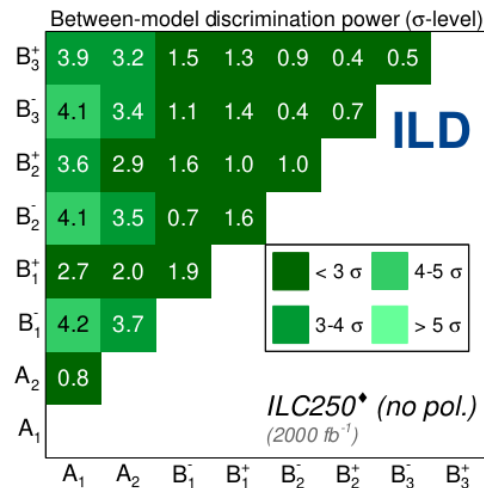
e- polarization at 80% in all of these scenarios

GHU vs SM: Particle ID dependence

ILD



GHU between model discrimination



Conclusion/ summary



- ▶ ILC offers unique capabilities to explore these signatures and discriminate GHU vs SM:
 - **High energy reach.**
 - Electron and positron **beam polarization** → enhancing the sensitivity but also allowing combination of measurements with different BSM sensitivity (for control of systematics).
 - Optimal use of PID via **dN/dx**
- ▶ Comprehensive study done at ILC250/ILC500 with ILD simulations:
 - Backgrounds, beam features, polarization, realistic reconstruction tools.
 - Uncertainties dominated by statistics, above the Z-pole.
 - Room for improvement (modern algorithms for flavour tagging, event selection, etc.)
- ▶ **Full discrimination of almost all of the proposed models (and within models) is possible with the H20-staged (baseline) run plan for ILC!**

Simulation of the SiWECAL + AHCAL TB2022-06 system & PID studies) (yet unfinished)

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AITANA

- ▶ Software review.
 - Made all the ECAL-Sim software more **user-friendly**.
 - Unknown *segmentation errors shouldn't appear* with every small change.
- ▶ Geometry implementation.
 - Both detectors simulated at once, with all the boxes, materials and distances properly adjusted.
- ▶ General studies of the ECAL (at sim. level).
 - Linearity & resolution study.
 - Molière radius.
- ▶ Software for PID studies (NTuples, BDTs with hyper-parameter optimization).
 - So far only for the ECAL. (at sim. Level) - **ongoing**
 - AHCAL implementation and combined ECAL+AHCAL TBD (at sim. Level) - **TBD**

The TB2022-06 geometry (first attempt)

► SiWECAL:

- 15 layers, non-homogeneous Si & W thicknesses.
- File CONF6: 8x4.2mm+7x5.6mm Tungsten absorber.

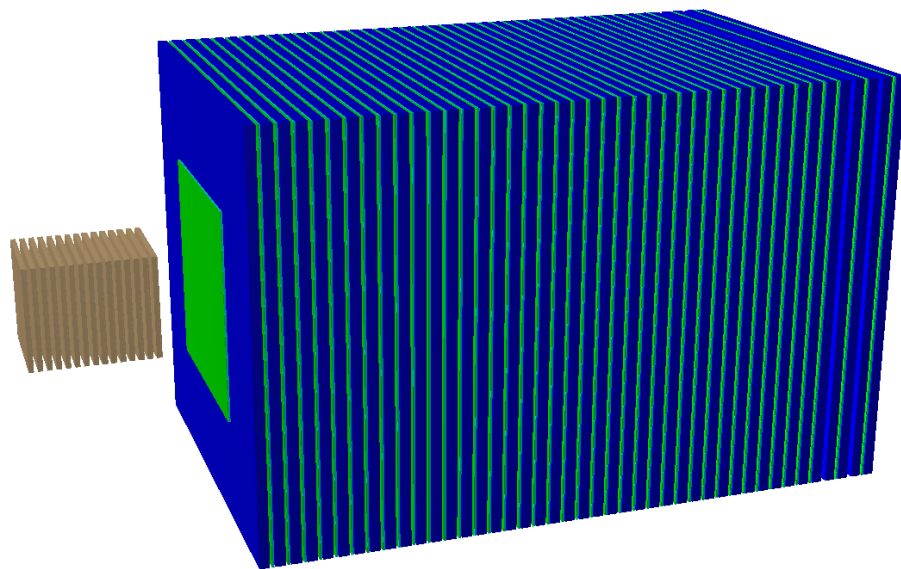
► Between Both detectors:

[10.06.2022 12:40](#) Jiri, Adrian, Malte, Lorentz, Antoine
Distance from ECAL_end to AHCAL_frontAbsorber = 8cm

Distance from ECAL_end to AHCAL_frontAbsorber

► AHCAL:

- 1 pad + 38 layers
- Last 5 segments:
 - ▶ Absorber.
 - ▶ Bad layer.
 - ▶ Absorber.
 - ▶ Tokyo layer.
 - ▶ Absorber.

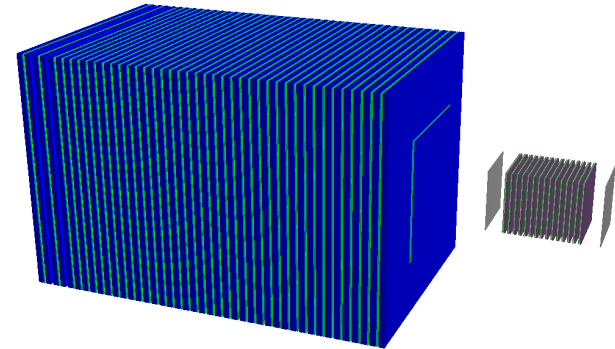
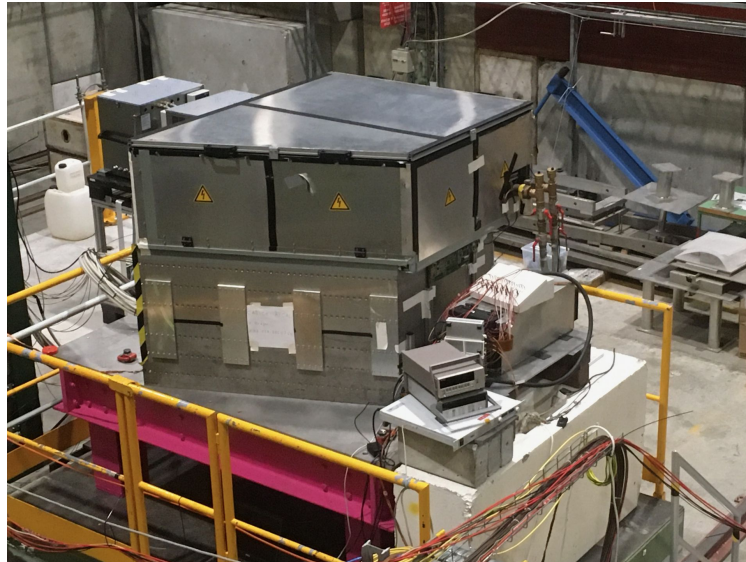


Some SiWECAL-Sim improvements

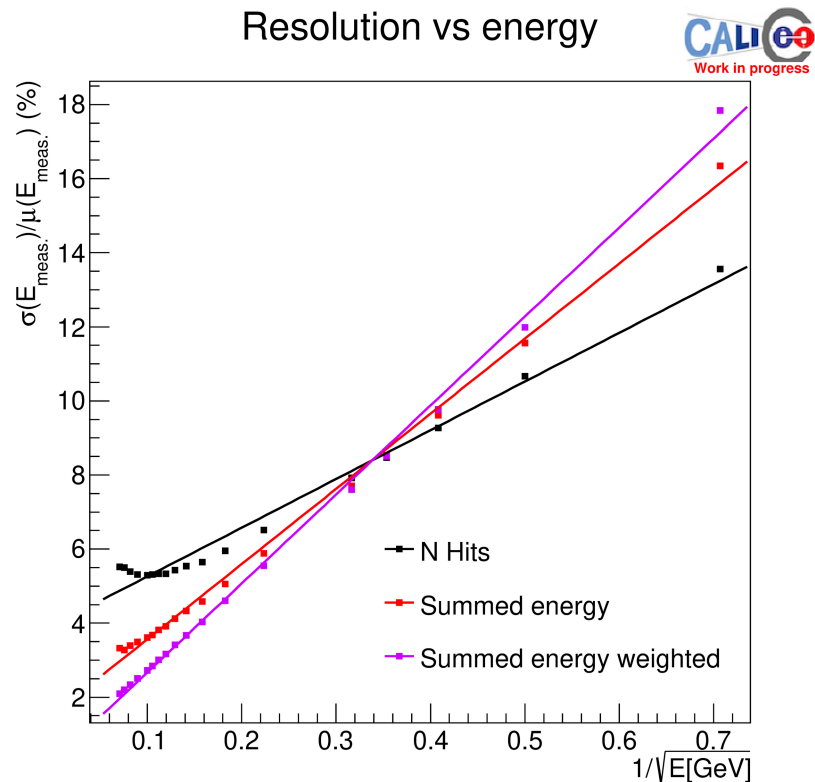
- ▶ The side panels were not included in the simulation!
 - You need to add that material inside a “layer” so dd4hep catches it!
- ▶ New measurements (Alexander Gallas):

- _ first, the hood side panels was first done of 3mm polyethylene black plastic. For the 2nd stack of 7slabs we made Aluminium panels but I think for the last beam test the panels was the plastic one, Am I wrong?
- _ The length between internal face of the side panel and the first wafer is 49mm and not 59.7
- _ The distance between the "entrance face" of the wafer of the last slab and the inside face of the 2nd side panel is 41mm and again 3mm of plastic.

- ▶ New setup:



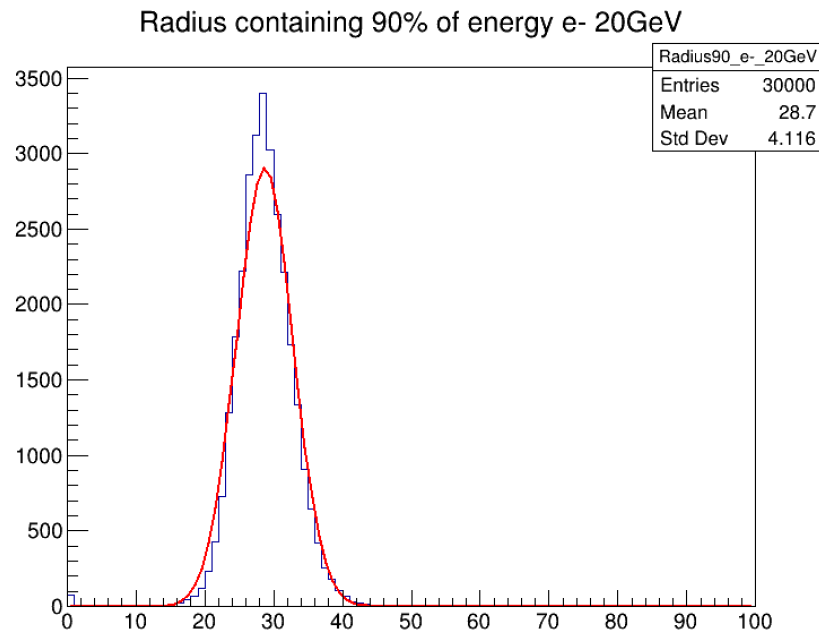
- First resolution plot with the ECAL *without* digitization or masking.
 - Testing N hits, summed energy and summed energy with W thickness weights



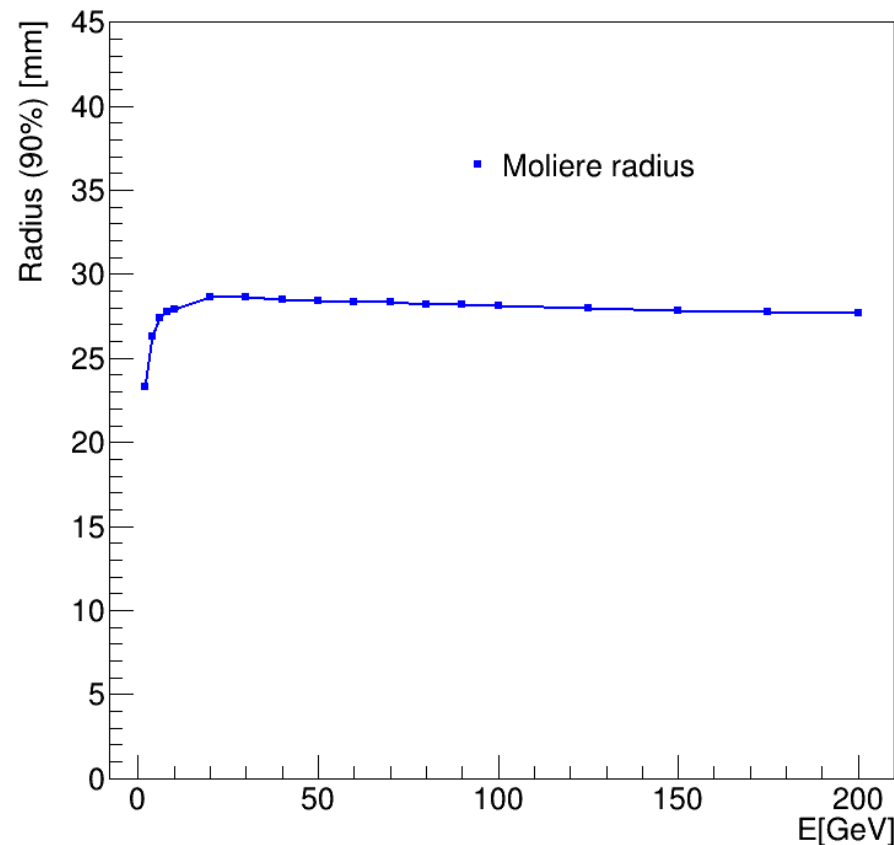
SiWECAL sim: Molière radius (e-)

- ▶ Def: Radius containing 90% of the radiation.
- ▶ Fit: Landau-Gauss convolution.

Example of fitting



Moliere radius vs energy (e-)

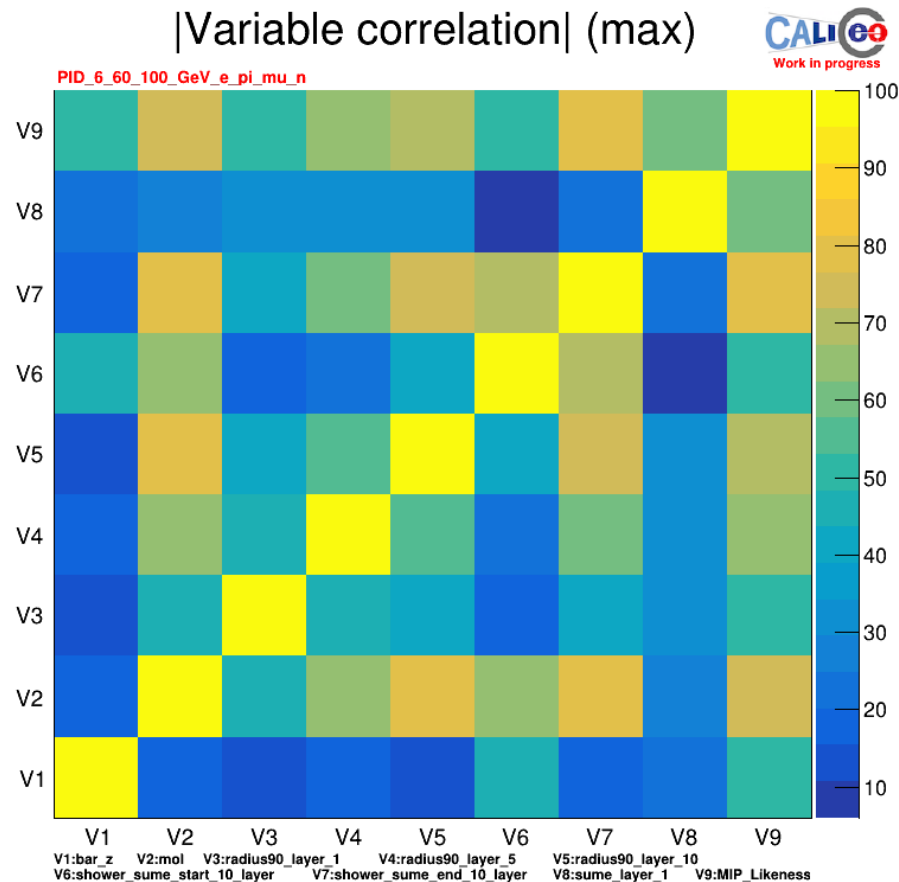


► Initial list of variables for all cases:

```
[ "nhit", "F", "", "nhit" ]
[ "sume", "F", "", "sume" ]
[ "weighte", "F", "", "weighte" ]
[ "bar_z", "F", "", "bar_z" ]
[ "mol", "F", "", "mol" ]
[ "radius90_layer_0", "F", "", "radius90_layer_0" ]
[ "radius90_layer_1", "F", "", "radius90_layer_1" ]
[ "radius90_layer_2", "F", "", "radius90_layer_2" ]
[ "radius90_layer_3", "F", "", "radius90_layer_3" ]
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[ "sume_layer_2", "F", "", "sume_layer_2" ]
[ "sume_layer_3", "F", "", "sume_layer_3" ]
[ "sume_layer_4", "F", "", "sume_layer_4" ]
[ "sume_layer_5", "F", "", "sume_layer_5" ]
[ "sume_layer_6", "F", "", "sume_layer_6" ]
[ "sume_layer_7", "F", "", "sume_layer_7" ]
[ "sume_layer_8", "F", "", "sume_layer_8" ]
[ "sume_layer_9", "F", "", "sume_layer_9" ]
[ "sume_layer_10", "F", "", "sume_layer_10" ]
[ "sume_layer_11", "F", "", "sume_layer_11" ]
[ "sume_layer_12", "F", "", "sume_layer_12" ]
[ "sume_layer_13", "F", "", "sume_layer_13" ]
[ "sume_layer_14", "F", "", "sume_layer_14" ]
```

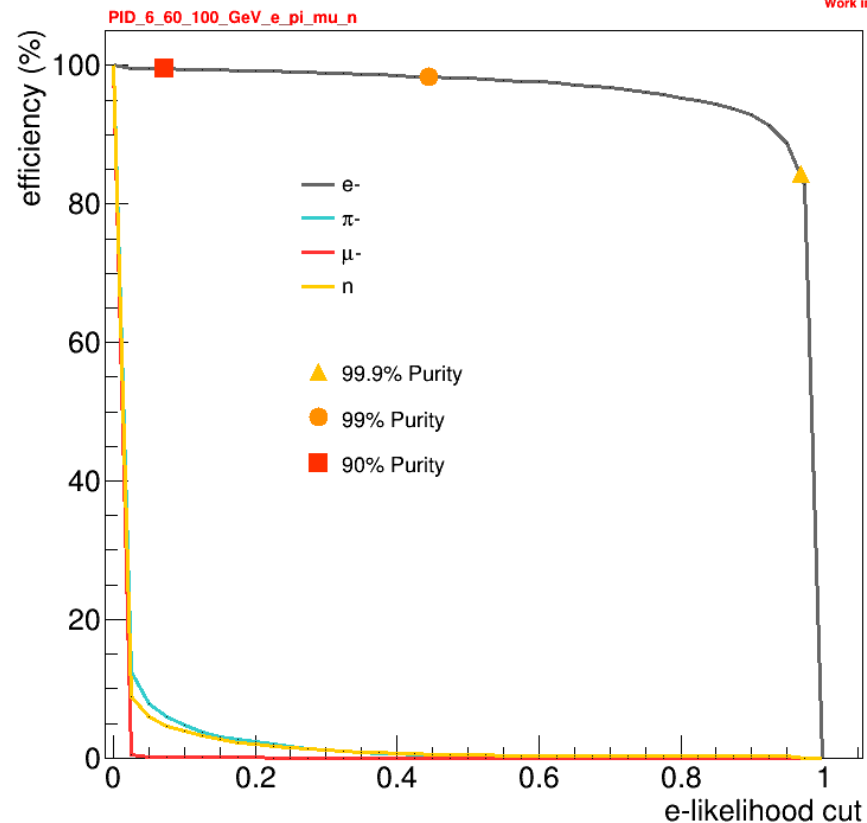
Variable	Definition
nhit	Total number of hits in the detector.
sume	Total energy deposited in the detector.
weighte	Total weighted energy deposited in the detector, Weighting factor per layer: $\frac{W_{thickness}}{W_{x_0}}$.
MIP_Likeness	$\frac{1}{N_{Layers}} \sum_{X=0}^{N_{Layers}-1} \frac{1}{hits_{layer X}}$, where N_{Layers} is the total number of layers.
bar_z	Barycenter in the longitudinal axis of the detector. Using weighted energy.
mol	Molière radius (90 % of the energy). Using weighted energy.
radius90_layer_X	Radius with 90 % of the energy in layer X.
shower_sume_max_layer	Layer with the maximum energy. Condition: is_Shower==true.
shower_sume_start_layer	First layer with > 3 MIPs energy in it. Conditions: is_Shower==true.
shower_sume_start_10_layer	First layer at 10 % of the shower max. Shower built with the energy per layer. Conditions: is_Shower==true, > 3 hits/MIP E. in layer.
shower_sume_end_layer	Last layer with > 3 MIPs energy in it. Conditions: is_Shower==true.
shower_sume_end_10_layer	Last layer at 10 % of the shower max. Shower built with the energy per layer. Conditions: is_Shower==true, > 3 hits/MIP E. in layer.
shower_sume_max	Maximum energy in a layer. Conditions: is_Shower==true, > 3 hits/MIP E. in layer.
shower_sume_average	Average energy in a layer. Defined as the ratio $sume/N_{Layers}$.
sume_layer_X	Energy in the layer X.

- ▶ First we plugged all the variables to (manually) remove high correlations (>90%).
- ▶ Then we run a hyper-parameter optimization
 - *Particle Swarm Optimization.*
- ▶ Then we get the trained samples and prepare performance plots
 - Next slides: e- vs μ - vs π - vs n
 - E = 6, 60 and 100 GeV mix

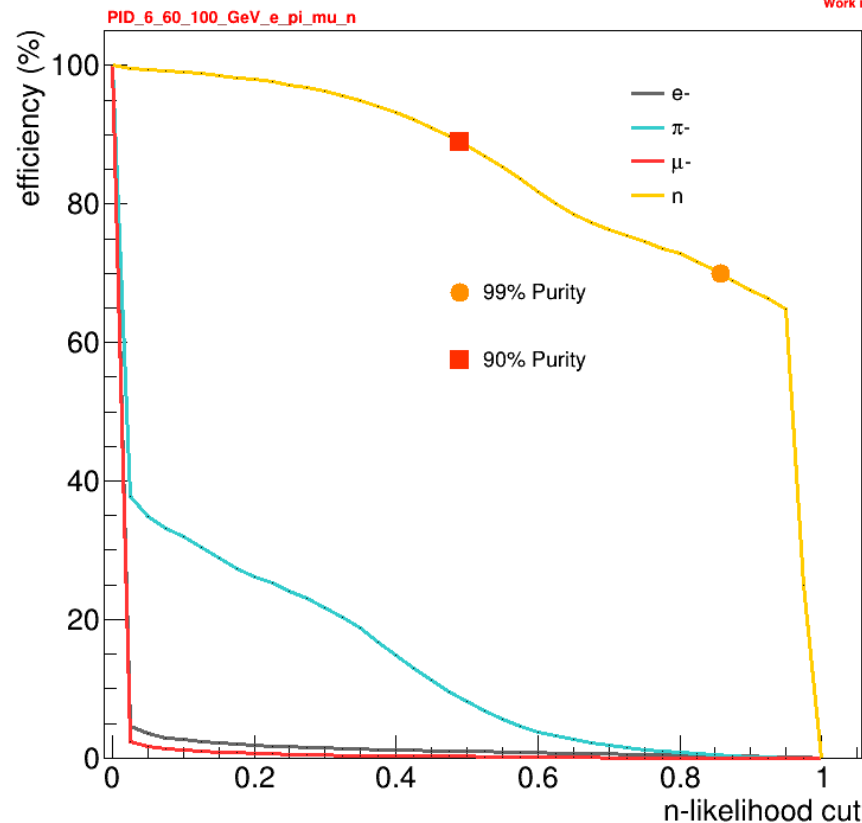


PID performance (only ECAL) – “The good”

Efficiencies for e-likelihood cut

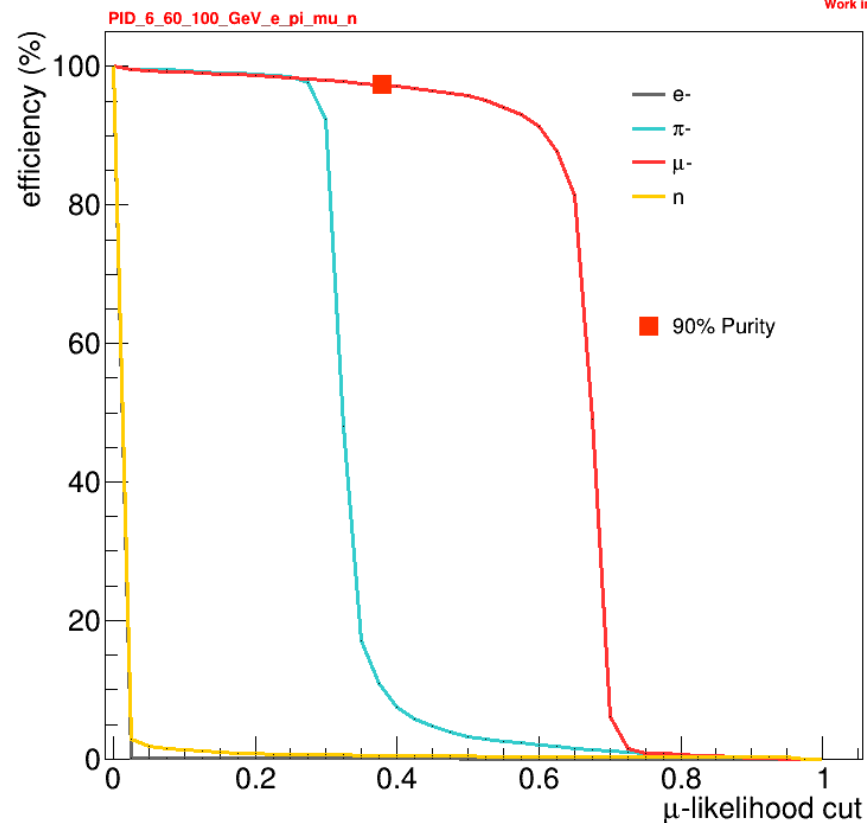


Efficiencies for n-likelihood cut

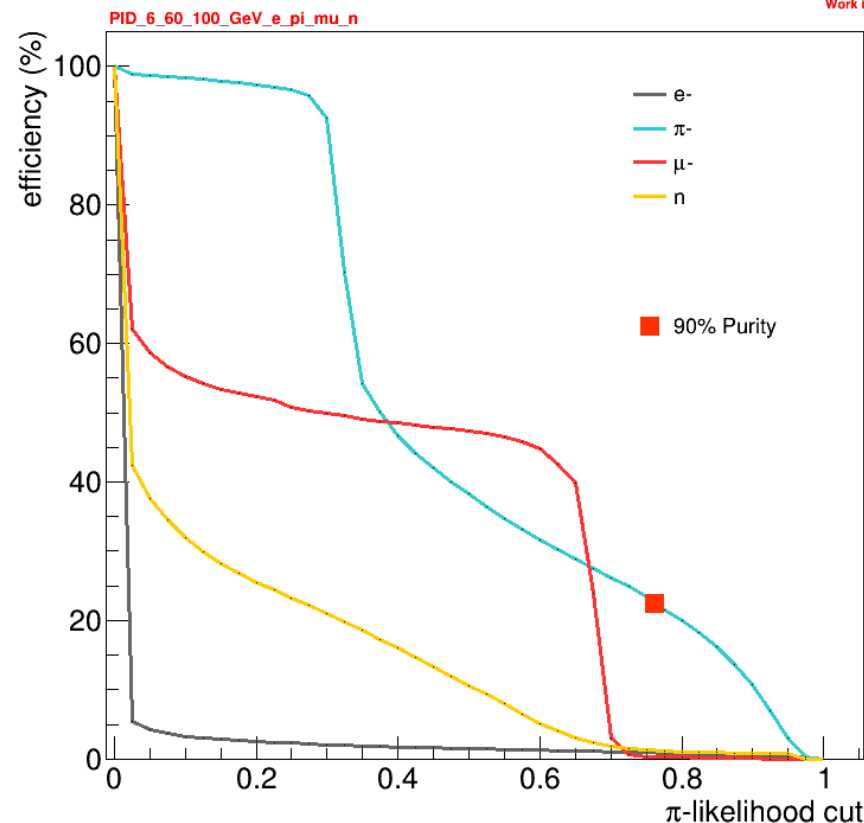


PID performance (only ECAL) – “The bad”

Efficiencies for μ -likelihood cut



Efficiencies for π -likelihood cut



Current situation



- ▶ Lately: Thesis writing.
 - Only the first chapter has been complete
- ▶ Once the writing is advanced I'll come back to the simulations (it's the last chapter!)

1 General context	1	2.3.1 Event generation and detector simulation	31
1.1 The Standard Model in collider physics	2	2.3.2 Experimental methods for R_q and A_{FB} reconstruction . . .	32
1.1.1 The Standard Model	2	2.3.3 Optimization of the A_{FB} reconstruction at the ILC	32
1.1.2 Open problems in particle physics	2	2.3.4 Prospects for R_q and A_{FB} at ILC250 and ILC500	32
1.1.3 The past and future of collider physics	3	2.4 Conclusions & Outlook	32
1.2 The International Linear Collider (ILC)	6	3 Statistical discrimination power for GHU models at ILC	33
1.2.1 Introduction	6	3.1 Theory	33
1.2.2 The ILC Physics case	7	3.2 Experimental prospects	33
1.2.3 The ILC layout	10	3.2.1 Statistical approach	33
1.3 The International Large Detector (ILD)	16	3.2.2 Estimation on theoretical errors	34
1.3.1 Introduction	16	3.3 Results	34
1.3.2 Experimental requirements	17	3.3.1 SM vs GHU discrimination power	34
1.3.3 Particle flow concept	18	3.3.2 Discrimination power between GHU models	34
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2 Heavy quark production at the ILC	31	4 Calorimetry study	35
2.1 Introduction	31	4.1 Introduction to calorimetry	35
2.2 Physical observables	31	4.2 The CALICE 2022 calorimeter prototype	35
2.2.1 Differential and total cross-section	31	4.2.1 The SiW-ECAL	35
2.2.2 Forward-Backward asymmetry (A_{FB})	31	4.2.2 The AHCAL	35
2.2.3 Hadronic fraction (R_q)	31	4.2.3 Beam test simulation	37
2.3 Full Simulation study	31	4.3 SiW ECAL simulation study	37
		4.3.1 Calorimeter characterization	37
		4.3.2 Particle Identification	37
		4.4 AHCAL simulation study (PID) ?	37
		4.5 Combined PID of the SiW ECAL + AHCAL simulation ?	37

Thanks for your attention!

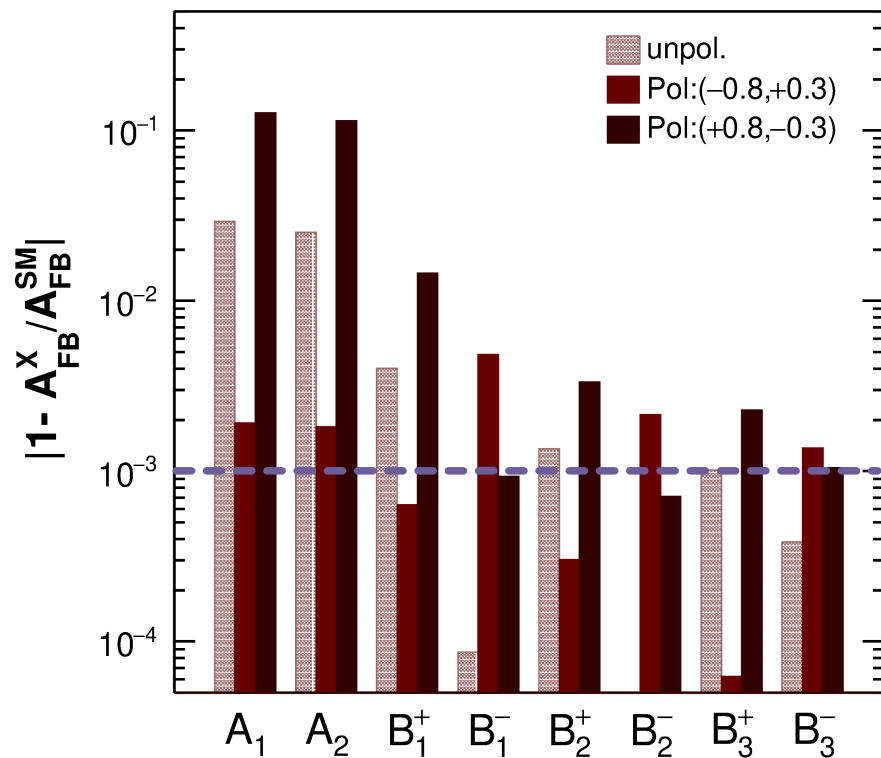
back-up



GHU vs SM (500 GeV)

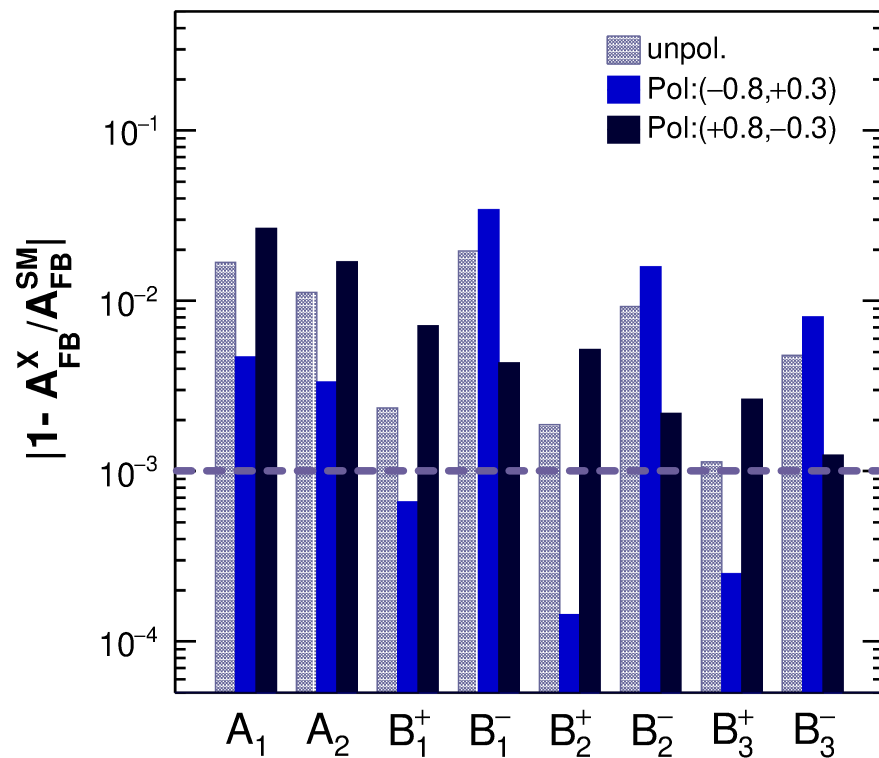
$\sqrt{s_{e^+e^-}} = 500 \text{ GeV}$

b-quark



$\sqrt{s_{e^+e^-}} = 500 \text{ GeV}$

c-quark



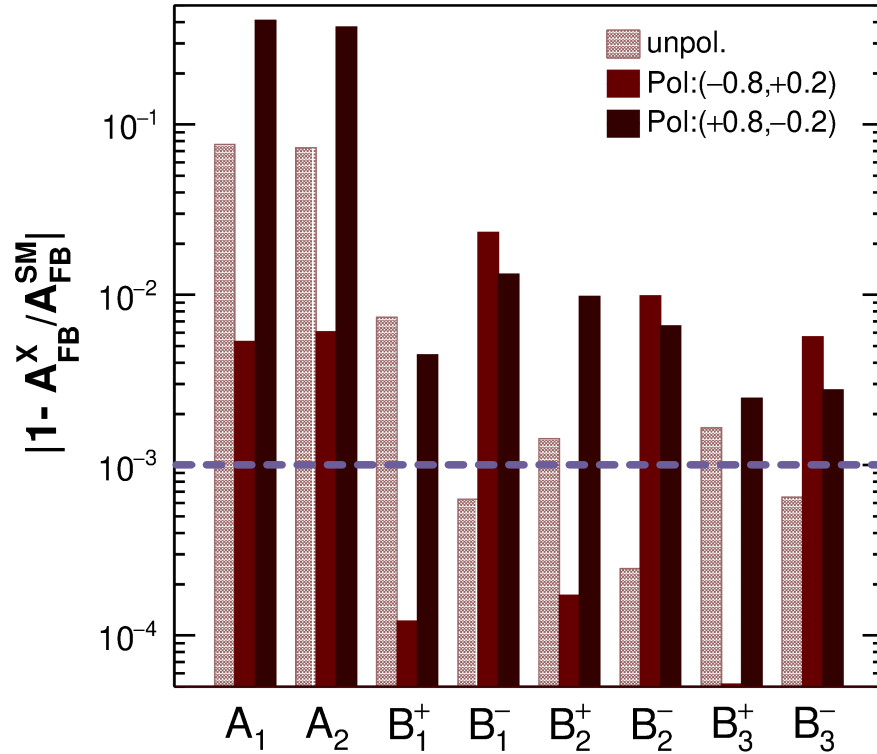
Deviations at the **per mil** level

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

GHU vs SM (1 TeV)

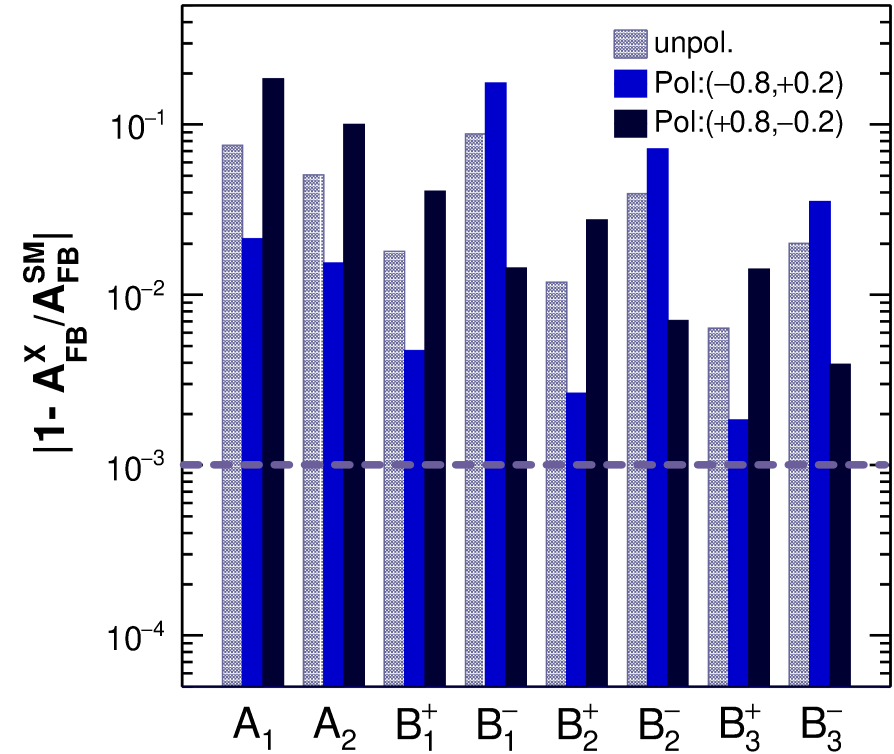
$\sqrt{s_{e^+e^-}} = 1000 \text{ GeV}$

b-quark



$\sqrt{s_{e^+e^-}} = 1000 \text{ GeV}$

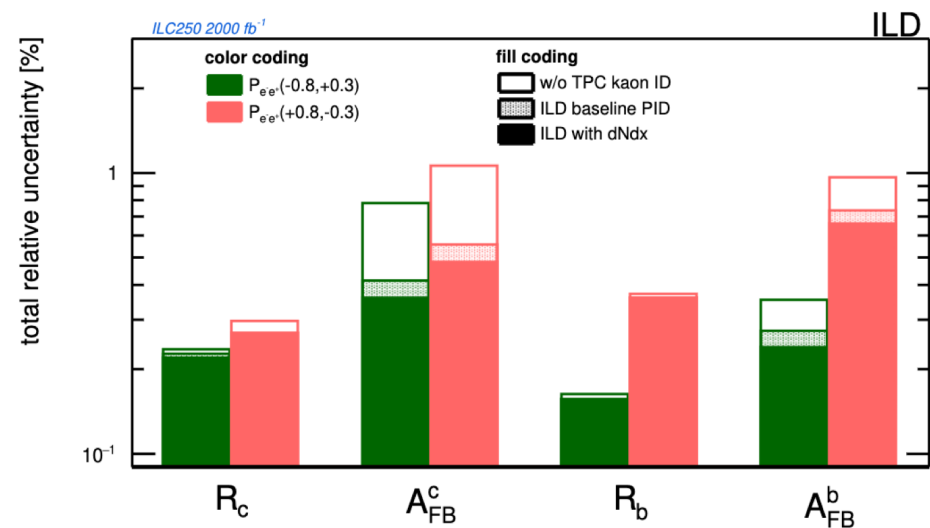
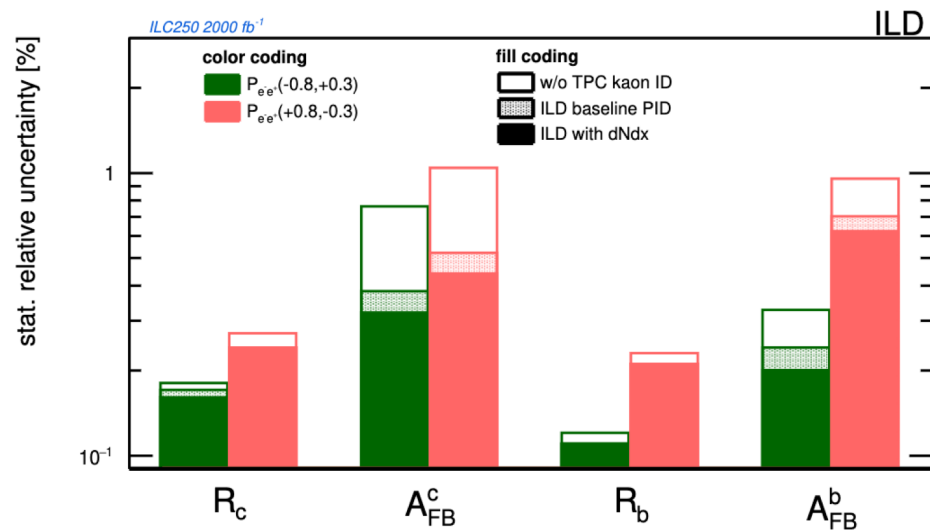
c-quark



Deviations at the **per mil** level

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

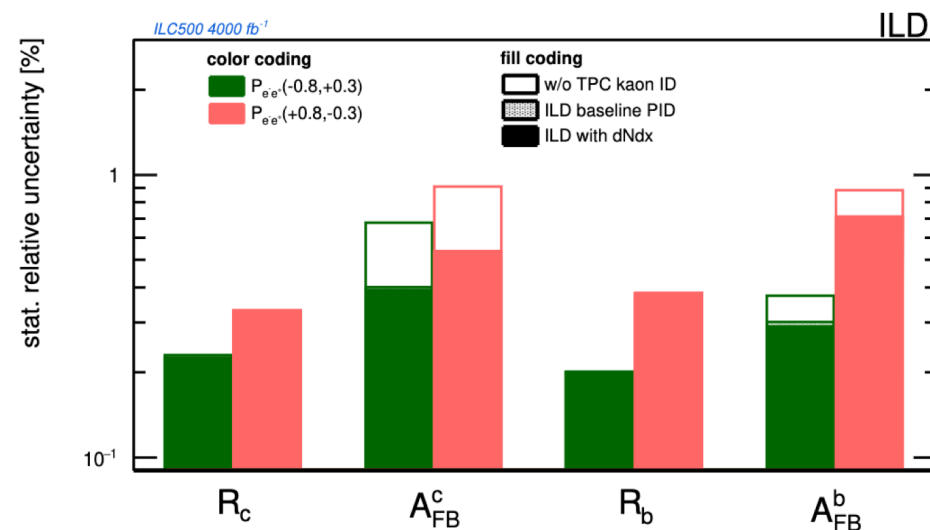
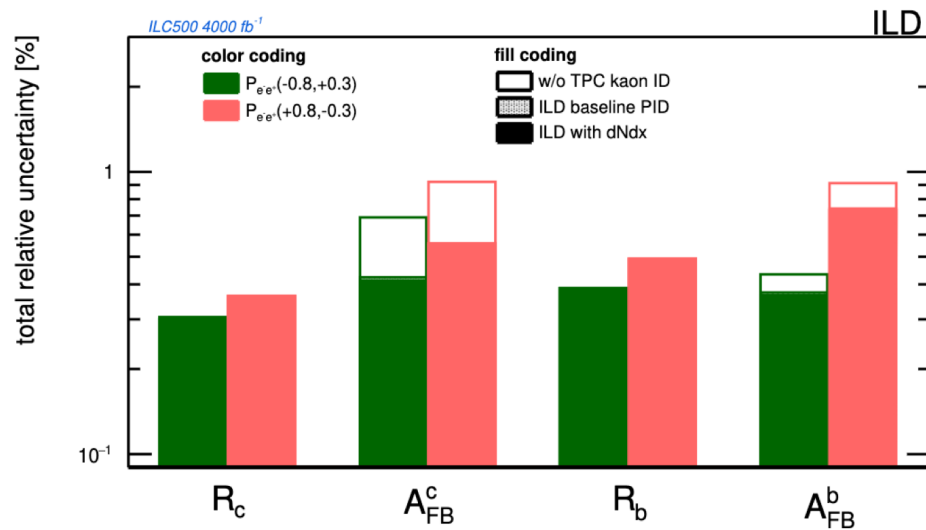
► Presented in LCWS (2023) [2307.14888](#)



Statistical uncertainties dominate over systematic uncertainties

► Presented in LCWS (2023) [2307.14888](#)

- Less benefit from the use of PID, but the A_{FB} uncertainties are in the same level.



Statistical uncertainties dominate over systematic uncertainties

► <https://arxiv.org/pdf/2203.07622.pdf>

Quantity	Value	current	Z pole		ILC250	
		$\delta[10^{-4}]$	$\delta_{stat}[10^{-4}]$	$\delta_{sys}[10^{-4}]$	$\delta_{stat}[10^{-4}]$	$\delta_{sys}[10^{-4}]$
boson properties						
m_W	80.379	1.5	-	-		0.3
m_Z	91.1876	0.23		0.022	0.08	-
Γ_Z	2.4952	9.4	0.5	-	6	-
$\Gamma_Z(had)$	1.7444	11.5		4.	-	-
Z-e couplings						
$1/R_e$	0.0482	24.	2.	5	5.5	10
A_e	0.1513	139.	1.5	1.2	12.	9.
g_L^e	-0.632	16.	1.0	3.2	2.8	7.6
g_R^e	0.551	18.	1.0	3.2	2.9	7.6
Z- ℓ couplings						
$1/R_\mu$	0.0482	16.	2.	2.	5.5	10
$1/R_\tau$	0.0482	22.	2.	2.	5.7	10
A_μ	0.1515	991.	2.	5	54.	3.
A_τ	0.1515	271.	2.	5.	57.	3
g_L^μ	-0.632	66.	1.0	2.3	4.5	7.6
g_R^μ	0.551	89.	1.0	2.3	5.5	7.6
g_L^τ	-0.632	22.	1.0	2.8	4.7	7.6
g_R^τ	0.551	27.	1.0	3.2	5.8	7.6
Z-b couplings						
R_b	0.2163	31.	0.4	7.	3.5	10
A_b	0.935	214.	1.	5.	5.7	3
g_L^b	-0.999	54.	0.32	4.2	2.2	7.6
g_R^b	0.184	1540	7.2	36.	41.	23.
Z-c couplings						
R_c	0.1721	174.	2.	30	5.8	50
A_c	0.668	404.	3.	5	21.	3
g_L^c	0.816	119.	1.2	15.	5.1	26.
g_R^c	-0.367	416.	3.1	17.	21.	26.

GHU vs SM: Beam scenarios

Hypothetical case
ILC250^{*} no pol
 $\int L = 2000\text{fb}^{-1}$
OSP|SSP [%] = 45 | 5
Full ILD simulation
assuming
no beam pol

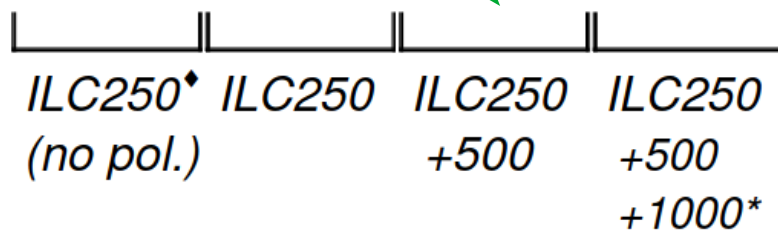
H20 nominal program

ILC250
($P_{e-}=0.8, P_{e+}=0.3$)
 $\int L = 2000\text{fb}^{-1}$
OSP|SSP [%] = 45 | 5
ILC500
($P_{e-}=0.8, P_{e+}=0.3$)
 $\int L = 4000\text{fb}^{-1}$
OSP|SSP [%] = 40 | 10
Full ILD simulation
assuming beam pol.

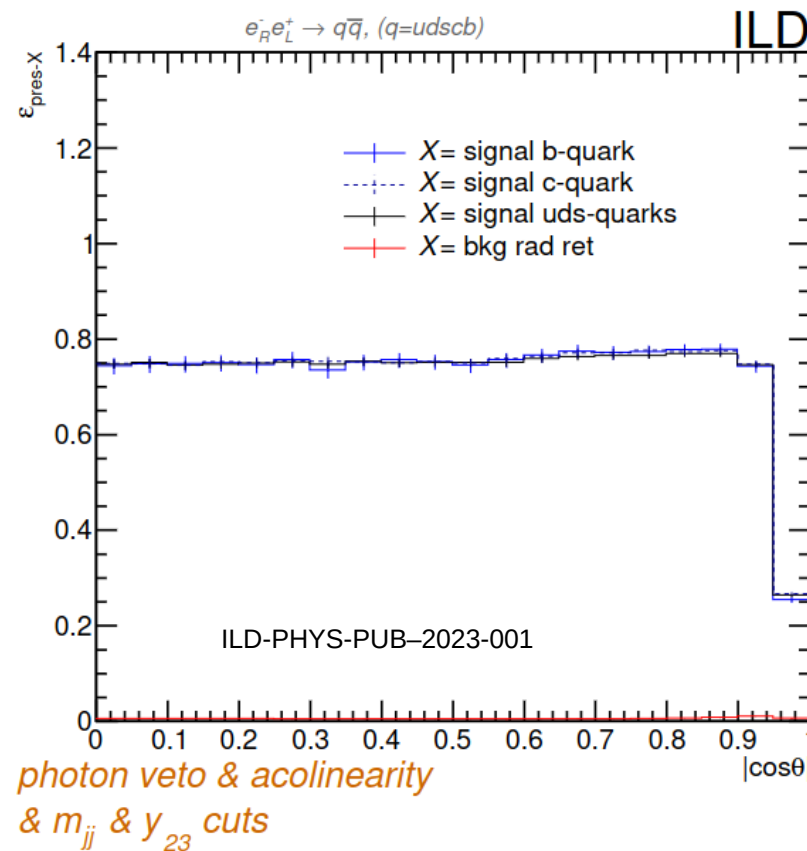
H20 nominal program

ILC1000
($P_{e-}=0.8, P_{e+}=0.2$)
 $\int L = 8000\text{fb}^{-1}$
OSP|SSP [%] = 40 | 10

Not full simulation studies
but extrapolations from ILC500



- ▶ **Topology: 2 back-to-back jets (pencil-like topology)**
- ▶ **Preselection aiming for high background rejection and high efficiency.**
- ▶ Main bkg $ee \rightarrow Z\gamma$ (radiative return through ISR)
 - ~ 10 larger than signal
 - **$\sim 90\%$ of such ISR photons are lost in the beam pipe** $\rightarrow$ events filtered by energy & angular mom. conservation arguments
 - The **remaining $\sim 10\%$ are filtered by identifying photons** in the detector (efficiency of $> 90\%$)
 - PFA detector!!
- ▶ Other backgrounds from diboson production decaying hadronically are removed with extra topological cuts.



Double-Tag method

- Compare samples with 1 tag vs 2 tags (after preselection)

$$\begin{aligned} f_{1b} &= \varepsilon_c \overline{R_b} + \widetilde{\varepsilon_c} \overline{R_c} + \widetilde{\varepsilon_{uds}} (1 - \overline{R_b} - \overline{R_c}) \\ f_{2b} &= \varepsilon_b^2 (1 + \rho) \overline{R_b} + \widetilde{\varepsilon_c}^2 \overline{R_c} + \widetilde{\varepsilon_{uds}}^2 (1 - \overline{R_b} - \overline{R_c}) \end{aligned}$$

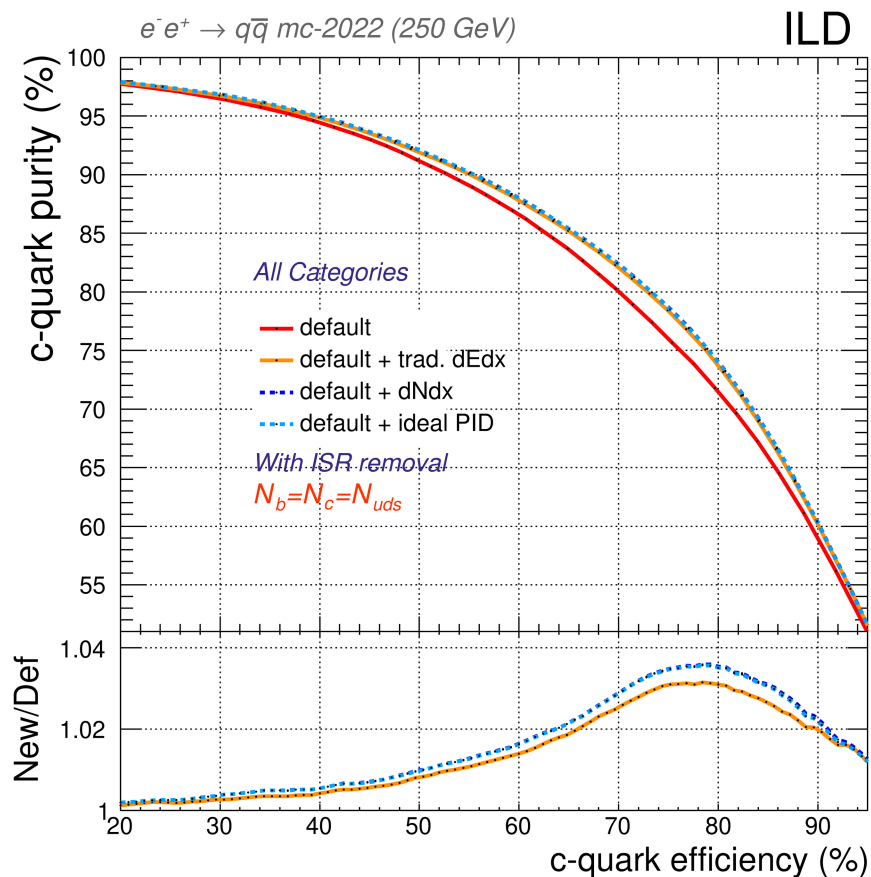
Measured observables

PHYSICS!
Indirect observables

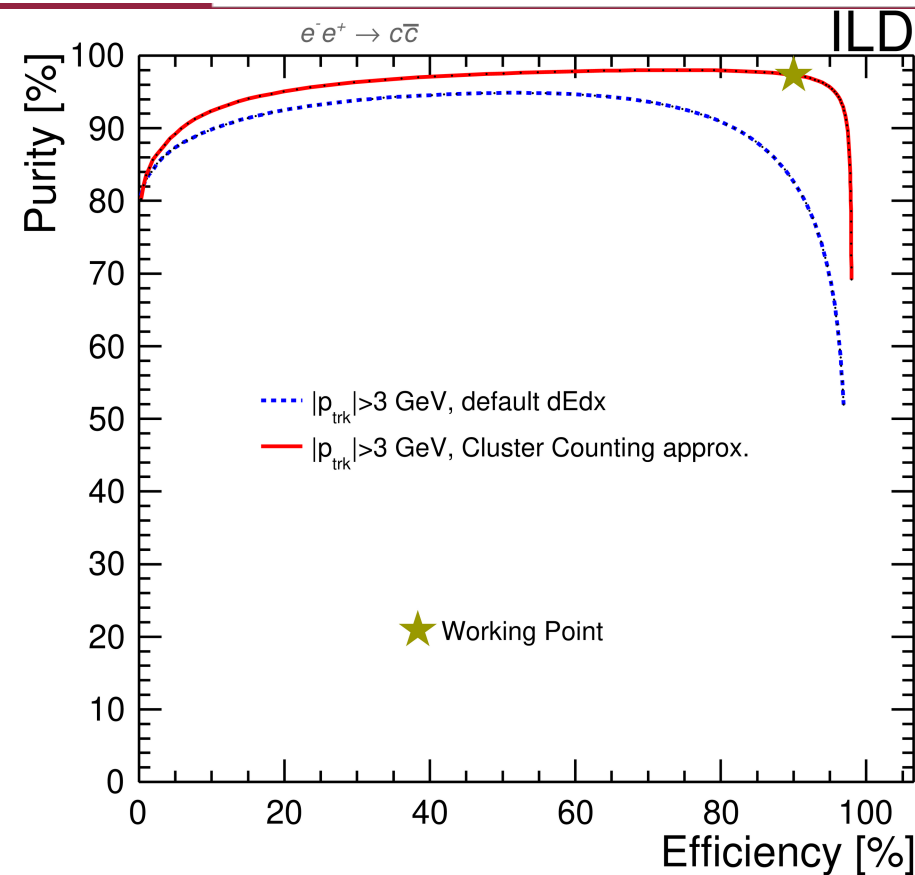
Inputs (MC or independent measurements)

**Similar set of equations
for the c-quark
solved simultaneously**

PID: From dEdx to dNdx

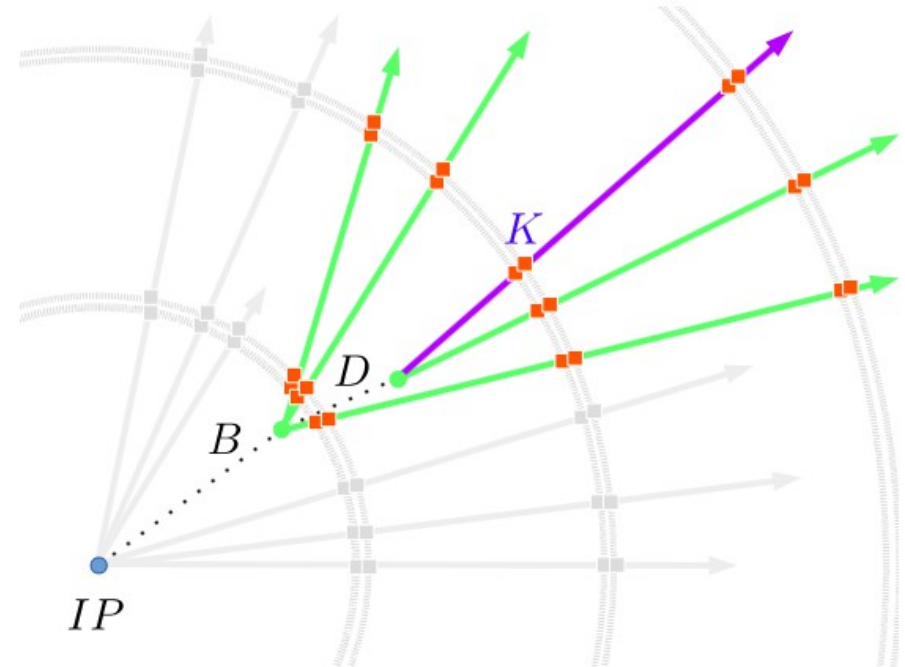


Effects in **Flavour Tagging**



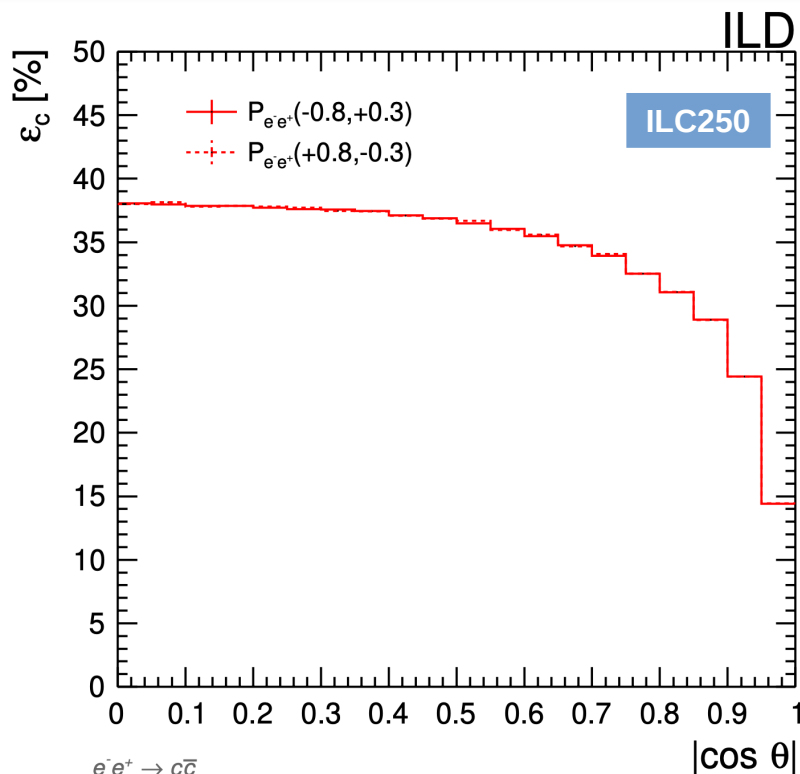
Effects in **Kaon ID** for charge reco.

- ▶ We start from a very pure & background-free **double tagged** sample
- ▶ We are required to **measure the jet charge**
 - Using K-ID and/or full Vtx charge measurement
 - K-ID is better suited for the C-quark (Vtx is better suited for b-quark)
- ▶ We use the **double charge** measurements
 - To control / reduce the systematic uncertainties

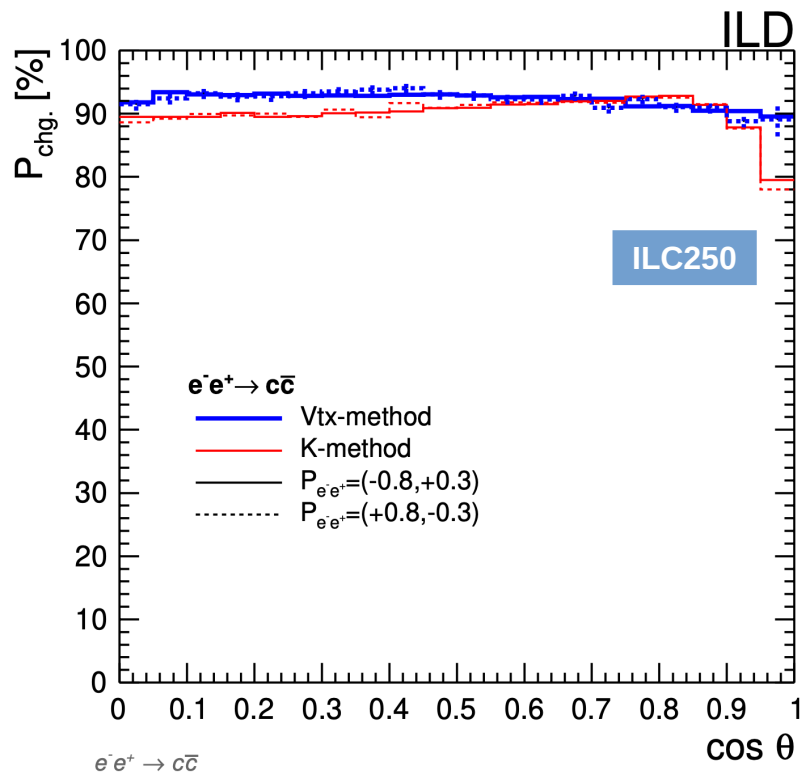


► Double tagging & double charge measurement methods. (described in previous ILD Note [2306.11413 \(2022\)](#))

- To maximally reduce the usage of MC tools (control of fragmentation, QCD correlations... uncertainties)



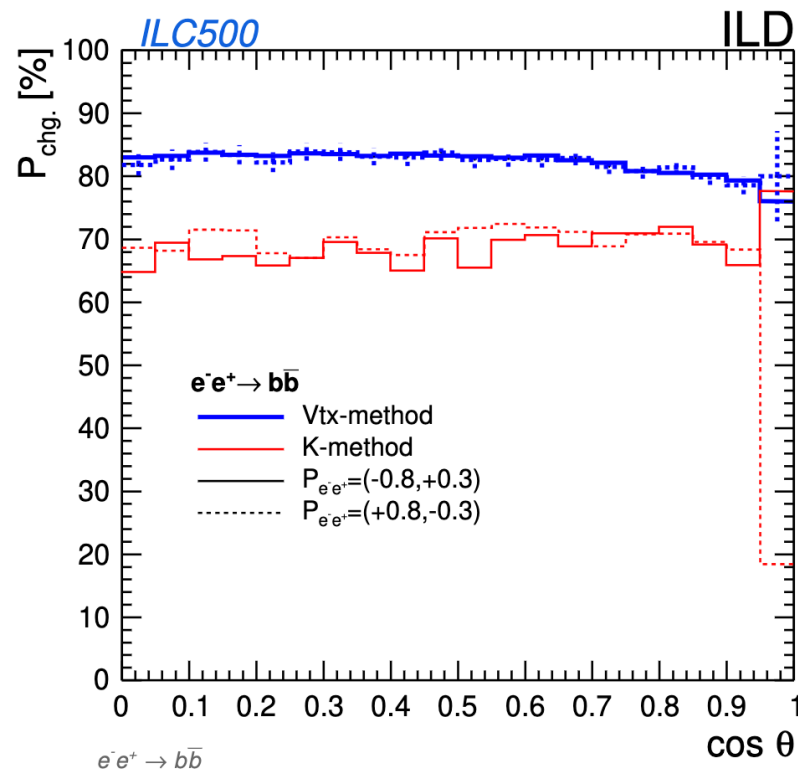
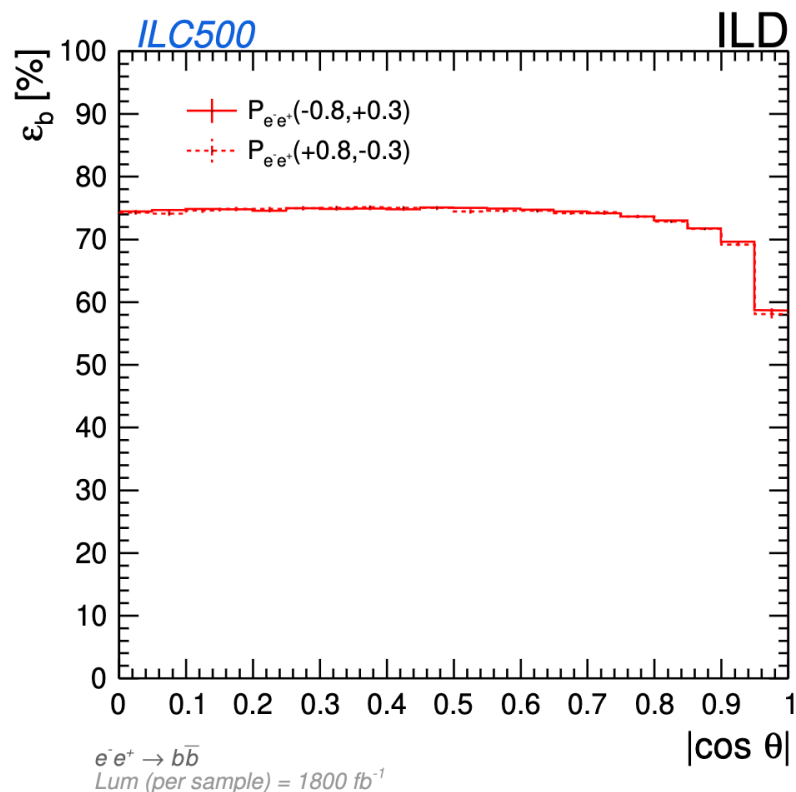
$e^+e^- \rightarrow c\bar{c}$
Lum = 900 fb⁻¹



$e^+e^- \rightarrow c\bar{c}$

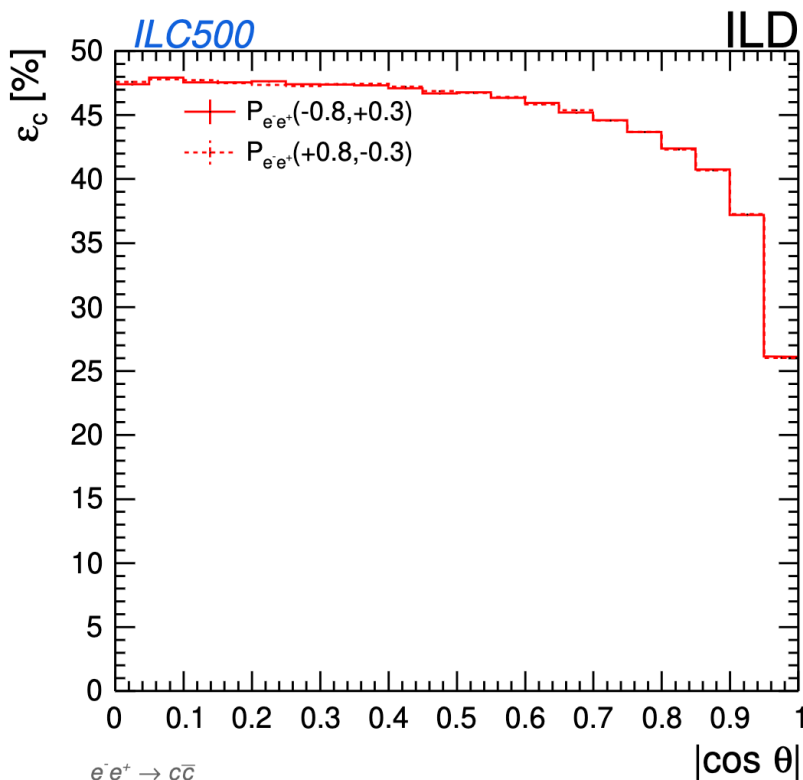
Jet flavour tagging & charge measurement

- Double tagging & double charge measurement methods (Plots from LCWS proceeding: 2307.14888).

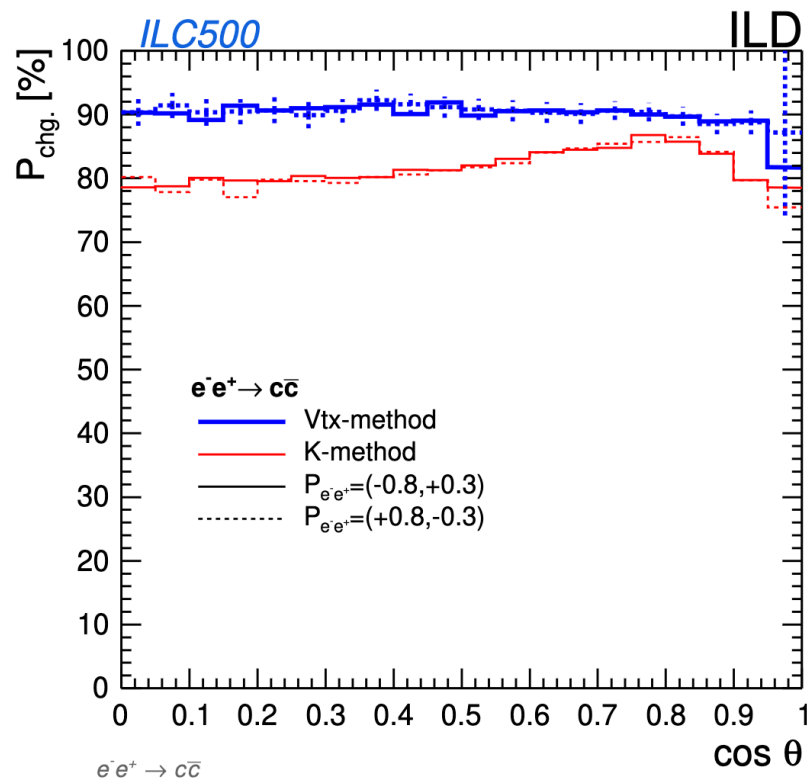


Jet flavour tagging & charge measurement

- Double tagging & double charge measurement methods (Plots from LCWS proceeding: [2307.14888](#)).



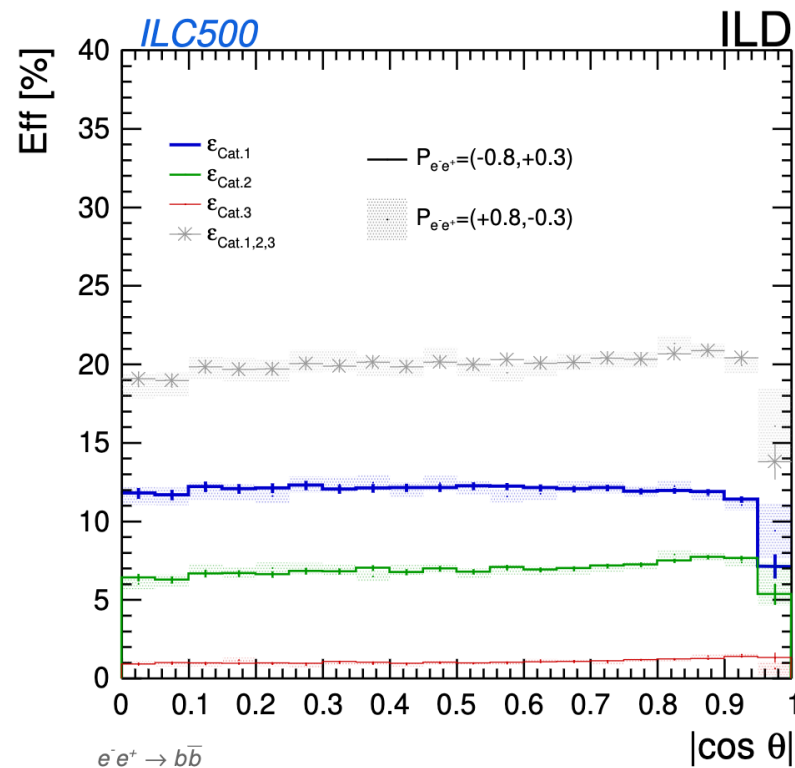
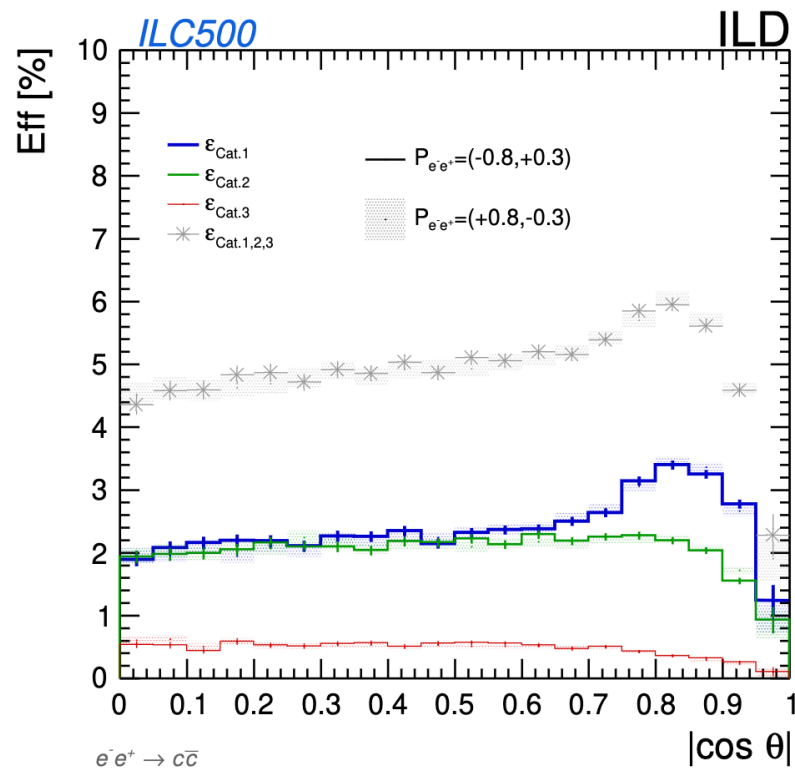
$e^-e^+ \rightarrow c\bar{c}$
Lum (per sample) = 1800 fb^{-1}



$e^-e^+ \rightarrow c\bar{c}$

Jet flavour tagging & charge measurement

- Double tagging & double charge measurement methods (Plots from LCWS proceeding: [2307.14888](#)).



Selection for the A_{FB} measurement at 500 GeV

Fit and results

- **Results for ILC250 and ILC500:**
 - Presented in LCWS (2023) [2307.14888](#)
- **At least 4 observables for AFB at ILC per energy point**
 - 2 quarks (b and c).
 - 2 polarizations (e_{LpR} , e_{RpL}).
- **Per mil level statistical uncertainties** reachable for the nominal **ILC** program
 - **Smaller exp syst. Uncertainties.**
 - Fragmentation, angular correlations, preselection efficiency, mistag, etc.

