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

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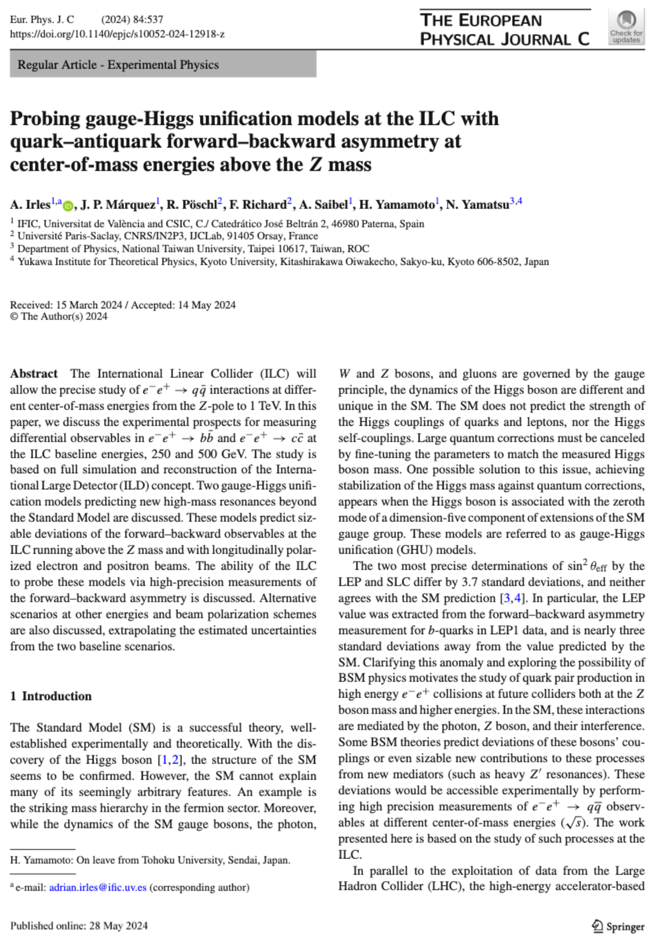
- Auxiliary and support studies:
  - ILD note (2022) 2306.11413
    - ILC250, b and c studies. (A. Irles, F. Richard, R. Pöschl).
  - Proceeding LCWS (2023) 2307.14888
    - Optimization of flavor tagging, use of dNdx PID and extension to 500 GeV. (J.P. Marquez)
  - Proceeding EPS-HEP (2023) 2310.17617
    - First phenomenology prospects. (J.P. Marquez)



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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

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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 sizable 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

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Introduction & motivation

Motivation: BSM Z' resonances

- Many **BSM scenarios** (i.e. Randal Sundrum, compositeness, Gauge Higgs unification models…) predict heavy resonances coupling to the (t,b) doublet and also lighter fermions (i.e. c/s quarks)
  - Only coupling to (t,b) doublet
    - → Peskin, Yoon arxiv:1811.07877
    - → Djouadi et al arxiv:hep-ph/0610173
  - Coupling also to lighter fermions [Funatsu, Hatanaka, Hosotani, Orikasa, Yamatsu]

(arxiv:1705.05282) (arxiv:2309.01132) (arxiv:2301.07833)

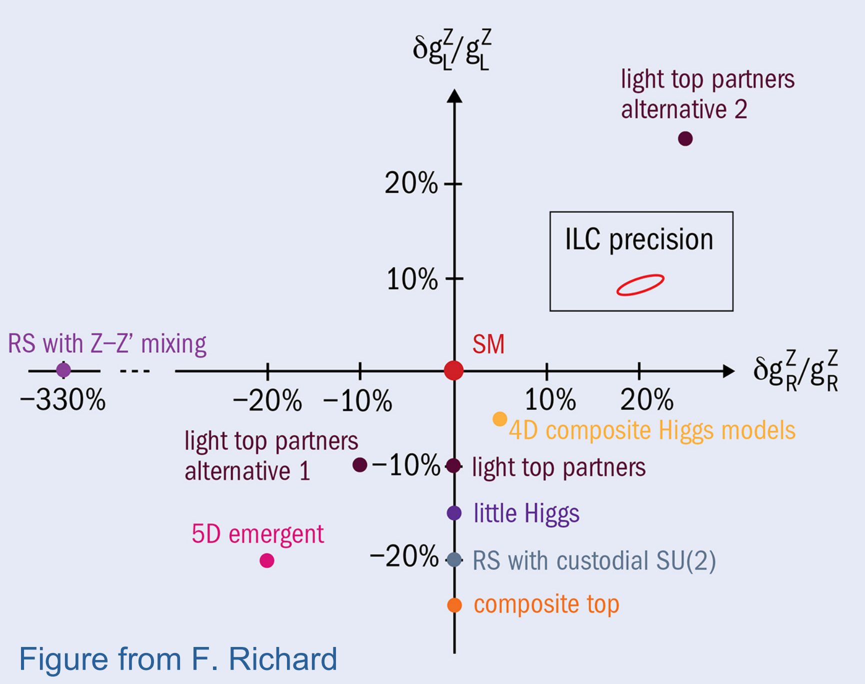


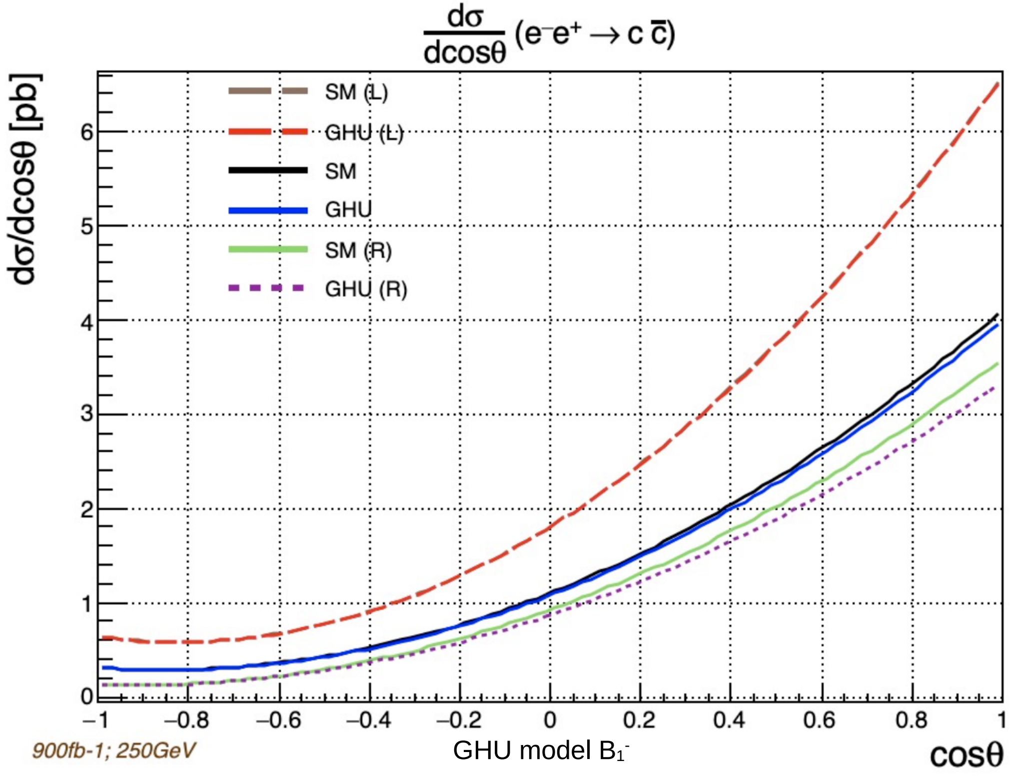
Figure from F. Richard

Probing such scenarios require at least per mil level experimental precision
tt/**bb**/**cc**/ss/… **Achievable at future colliders?**

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_{kk} ~ 10-25 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.



900fb-1; 250GeV

GHU model B_1^-

Gauge-Higgs Unification Models (GHU)

- A models: (arxiv:1705.05282)

$$
\begin{aligned}
A_1 &: \theta_H = 0.0917, m_{KK} = 8.81\ \text{TeV} \rightarrow m_{Z^1} = 7.19\ \text{TeV};\\
A_2 &: \theta_H = 0.0737, m_{KK} = 10.3\ \text{TeV} \rightarrow m_{Z^1} = 8.52\ \text{TeV},
\end{aligned}
$$

- B models: (arxiv:2309.01132) (arxiv:2301.07833)

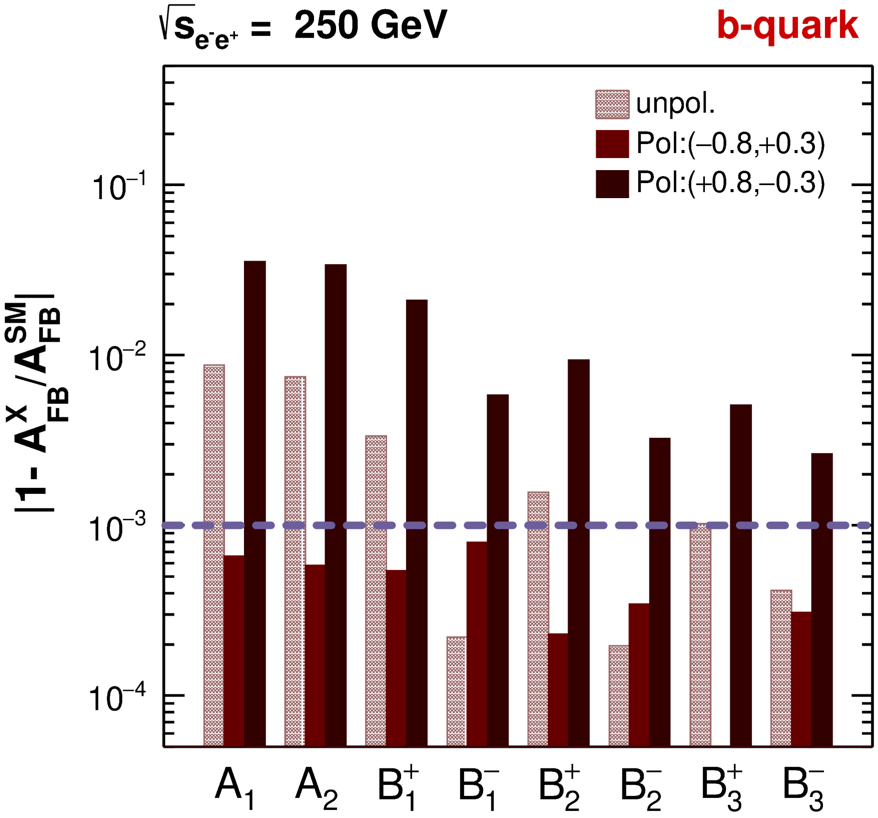
$$
\begin{aligned}
B_1^{\pm} &: \theta_H = 0.10, m_{KK} = 13\ \text{TeV} \rightarrow m_{Z^1} = 10.2\ \text{TeV};\\
B_2^{\pm} &: \theta_H = 0.07, m_{KK} = 19\ \text{TeV} \rightarrow m_{Z^1} = 14.9\ \text{TeV};\\
B_3^{\pm} &: \theta_H = 0.05, m_{KK} = 25\ \text{TeV} \rightarrow m_{Z^1} = 19.6\ \text{TeV};
\end{aligned}
$$

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

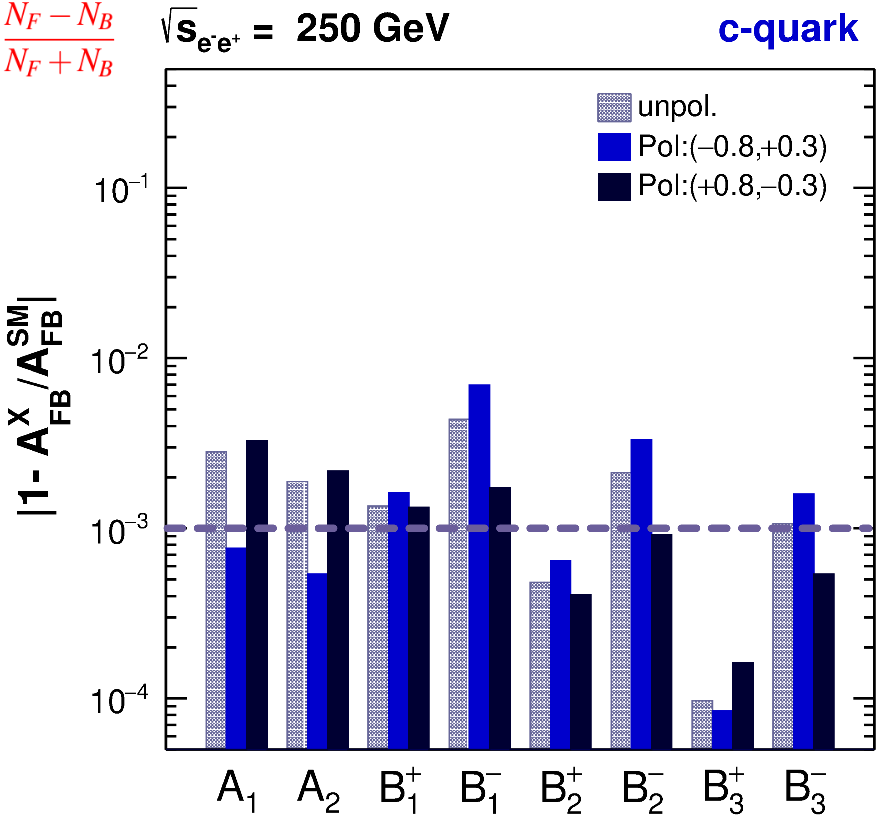
This talk: Phenomenology at ILC H20-staged program.

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

GHU vs SM (250 GeV)



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

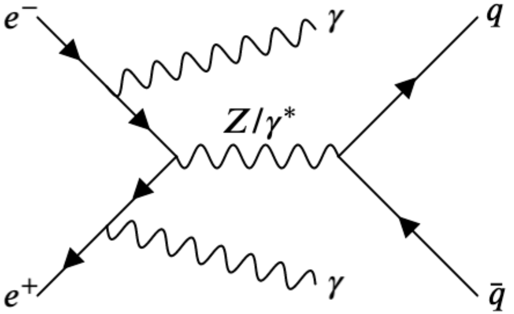


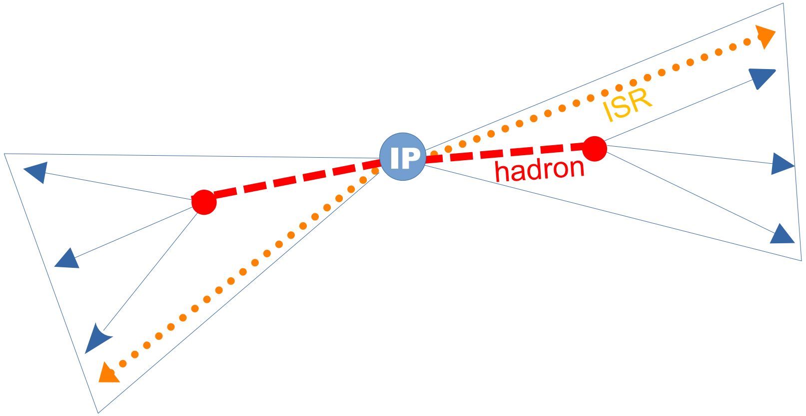
Deviations at the per mil level!

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.

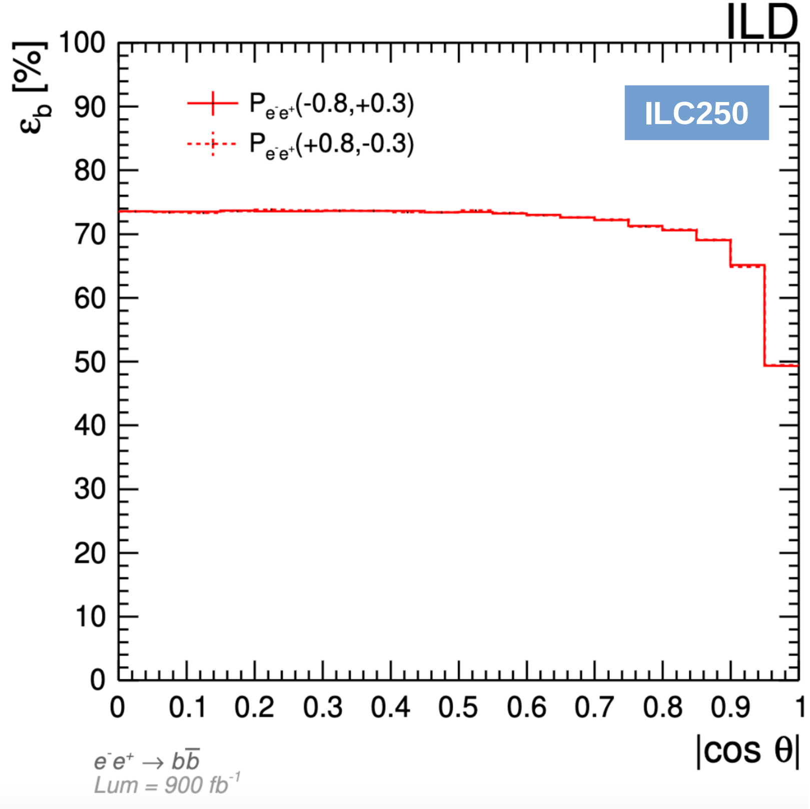


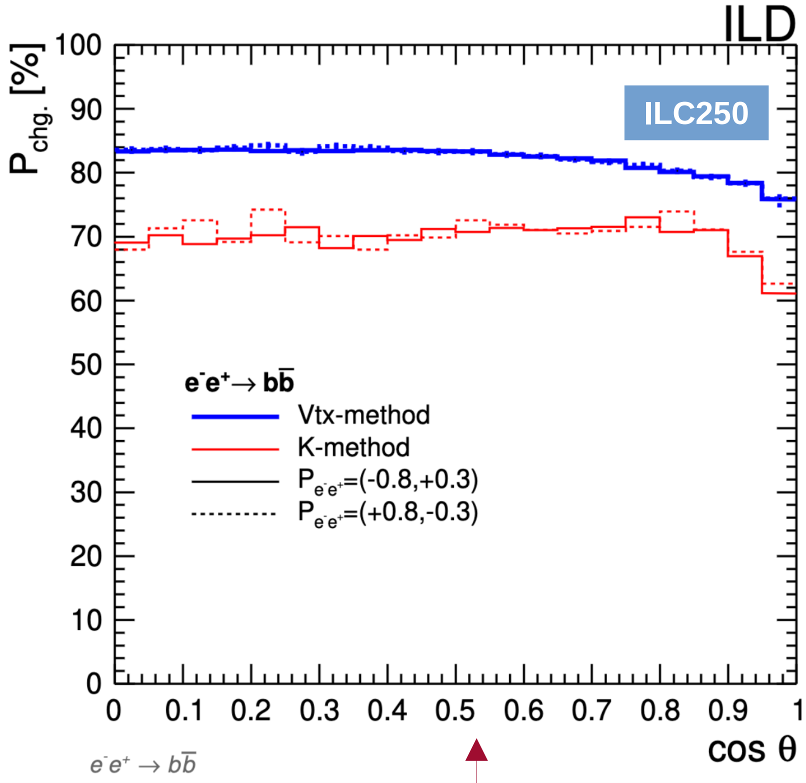


High-purity & independent samples for each quark flavour.

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)

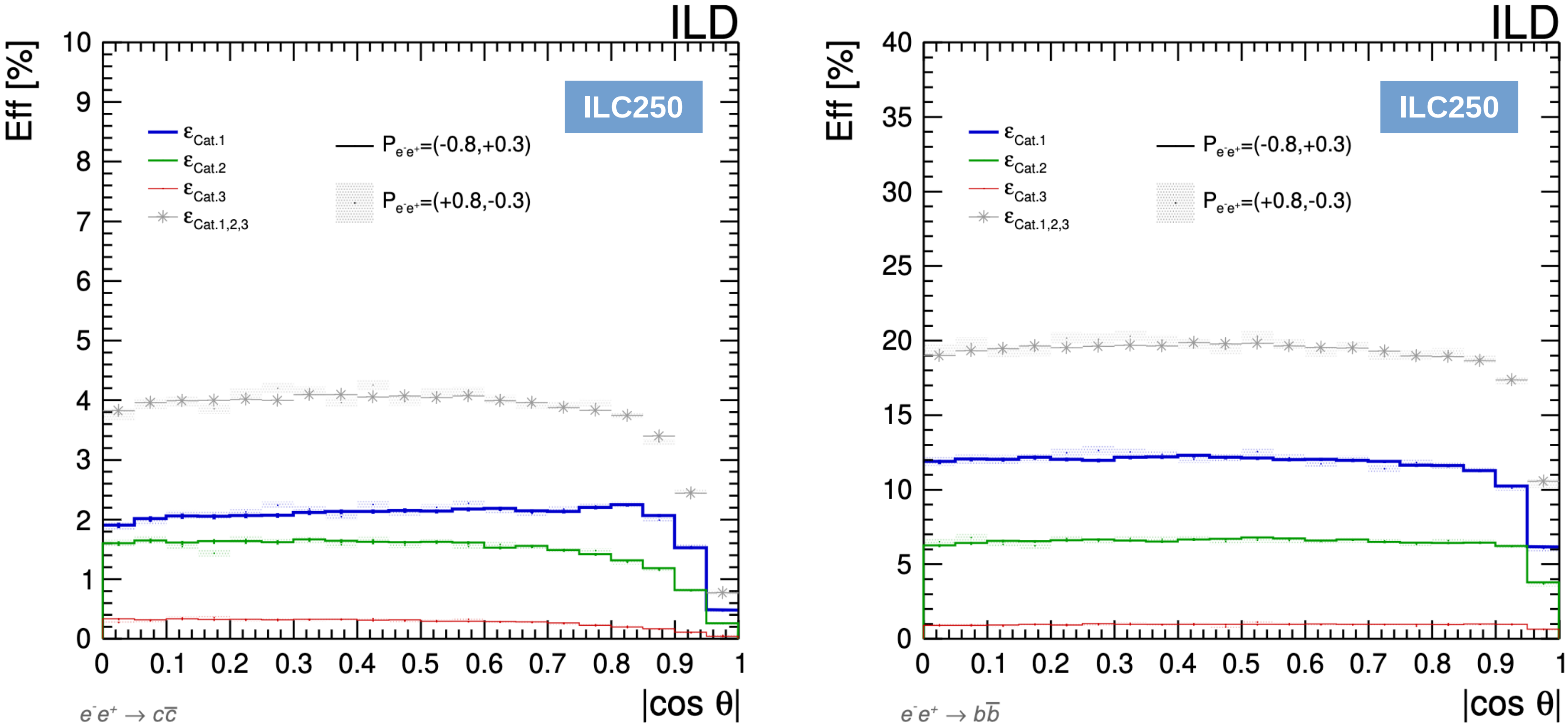




PID is very important for this measurement!

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

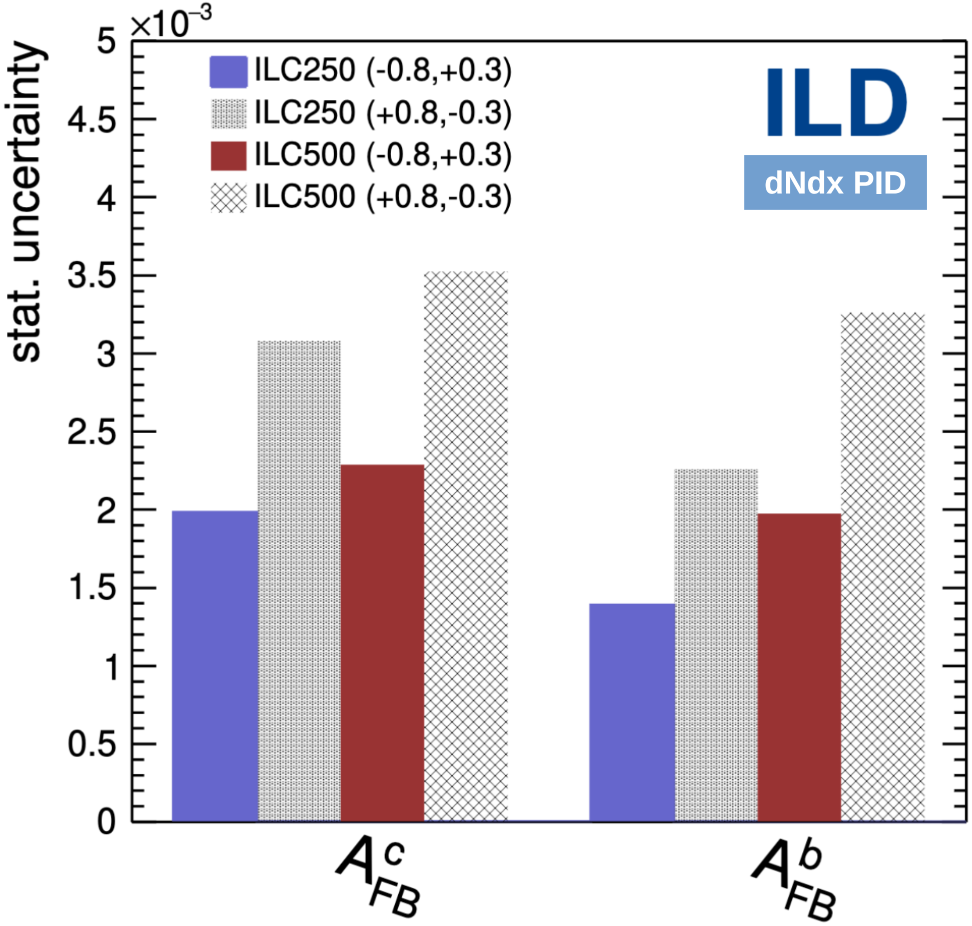
Results for ILC250 & ILC500

- **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 ($e_L p_R$, $e_R p_L$).

- **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

GHU vs SM: discrimination power

- Procedure: Testing the statistical significance of model AFB_{test} vs a reference model AFB_{ref} assuming that one of then is measured.

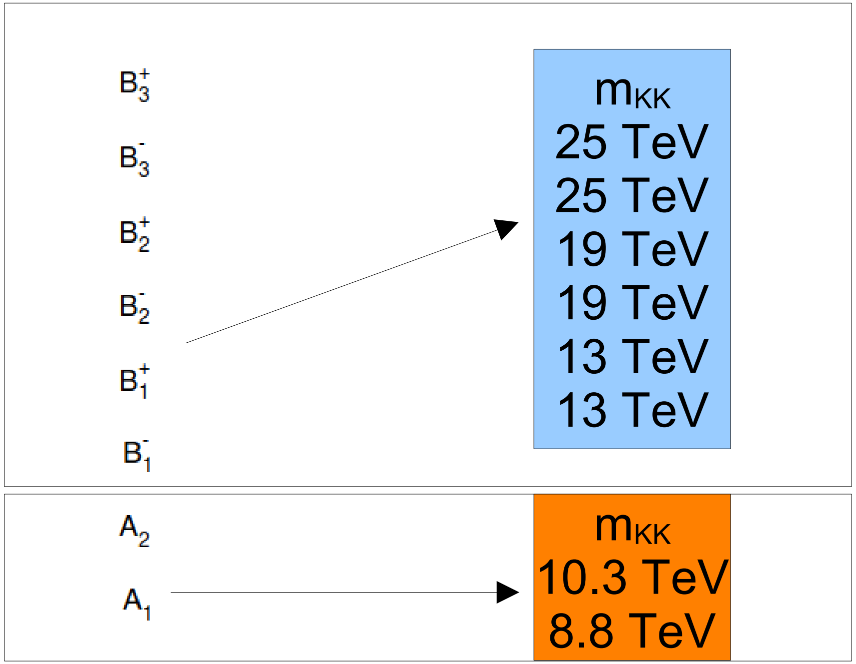
- The uncertainties are considered normally distributed:
  - Significance in σ.
  - P-value: Gaussian at d_σ.

$$d_\sigma = \frac{||AFB_{test} - AFB_{ref}||}{\Delta_{AFB_{ref}}}$$

- 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



B_3^+
B_3^-
B_2^+
B_2^-
B_1^+
B_1^-

m_{KK}
25 TeV
25 TeV
19 TeV
19 TeV
13 TeV
13 TeV

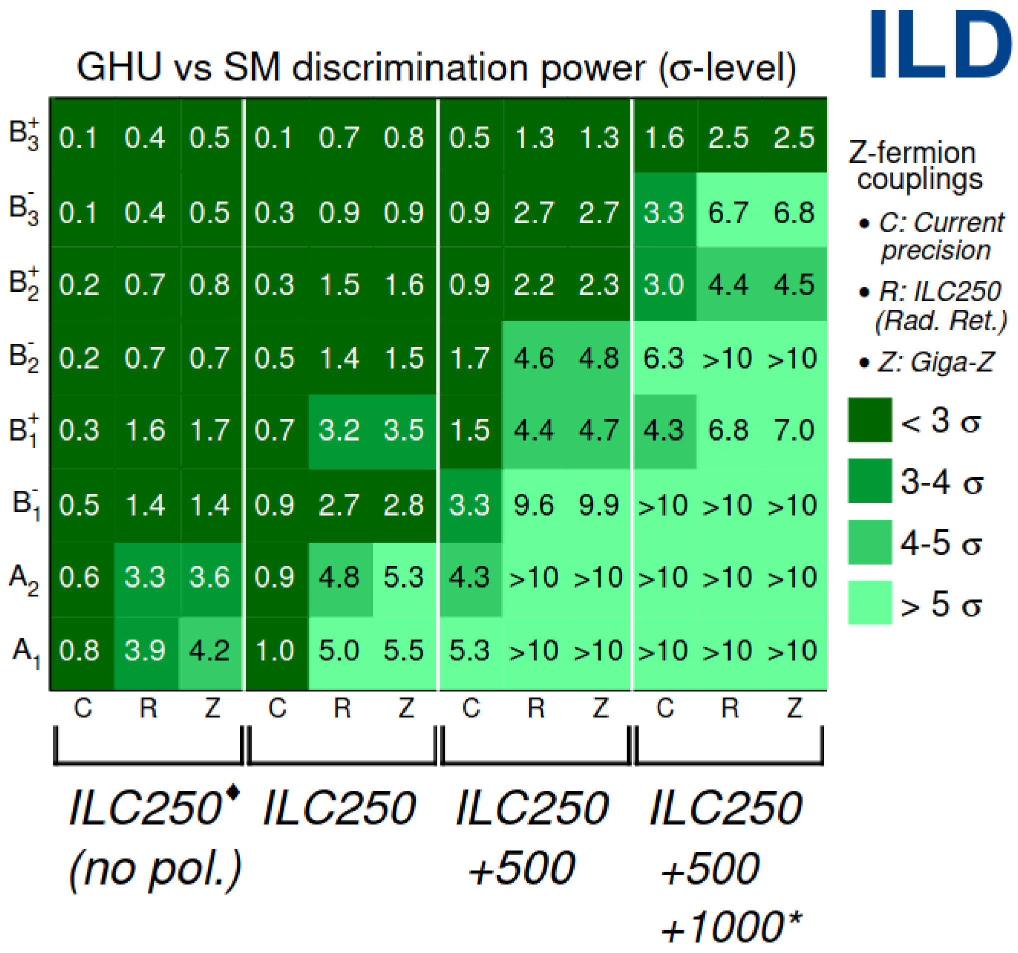
A_2
A_1

m_{KK}
10.3 TeV
8.8 TeV

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: discrimination power plots



ILD

GHU vs SM discrimination power (σ-level)

	ILC250♦ (no pol.)			ILC250			ILC250 +500			ILC250 +500 +1000*		
	C	R	Z	C	R	Z	C	R	Z	C	R	Z
B_3^+	0.1	0.4	0.5	0.1	0.7	0.8	0.5	1.3	1.3	1.6	2.5	2.5
B_3^-	0.1	0.4	0.5	0.3	0.9	0.9	0.9	2.7	2.7	3.3	6.7	6.8
B_2^+	0.2	0.7	0.8	0.3	1.5	1.6	0.9	2.2	2.3	3.0	4.4	4.5
B_2^-	0.2	0.7	0.7	0.5	1.4	1.5	1.7	4.6	4.8	6.3	>10	>10
B_1^+	0.3	1.6	1.7	0.7	3.2	3.5	1.5	4.4	4.7	4.3	6.8	7.0
B_1^-	0.5	1.4	1.4	0.9	2.7	2.8	3.3	9.6	9.9	>10	>10	>10
A_2	0.6	3.3	3.6	0.9	4.8	5.3	4.3	>10	>10	>10	>10	>10
A_1	0.8	3.9	4.2	1.0	5.0	5.5	5.3	>10	>10	>10	>10	>10

Z-fermion couplings

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

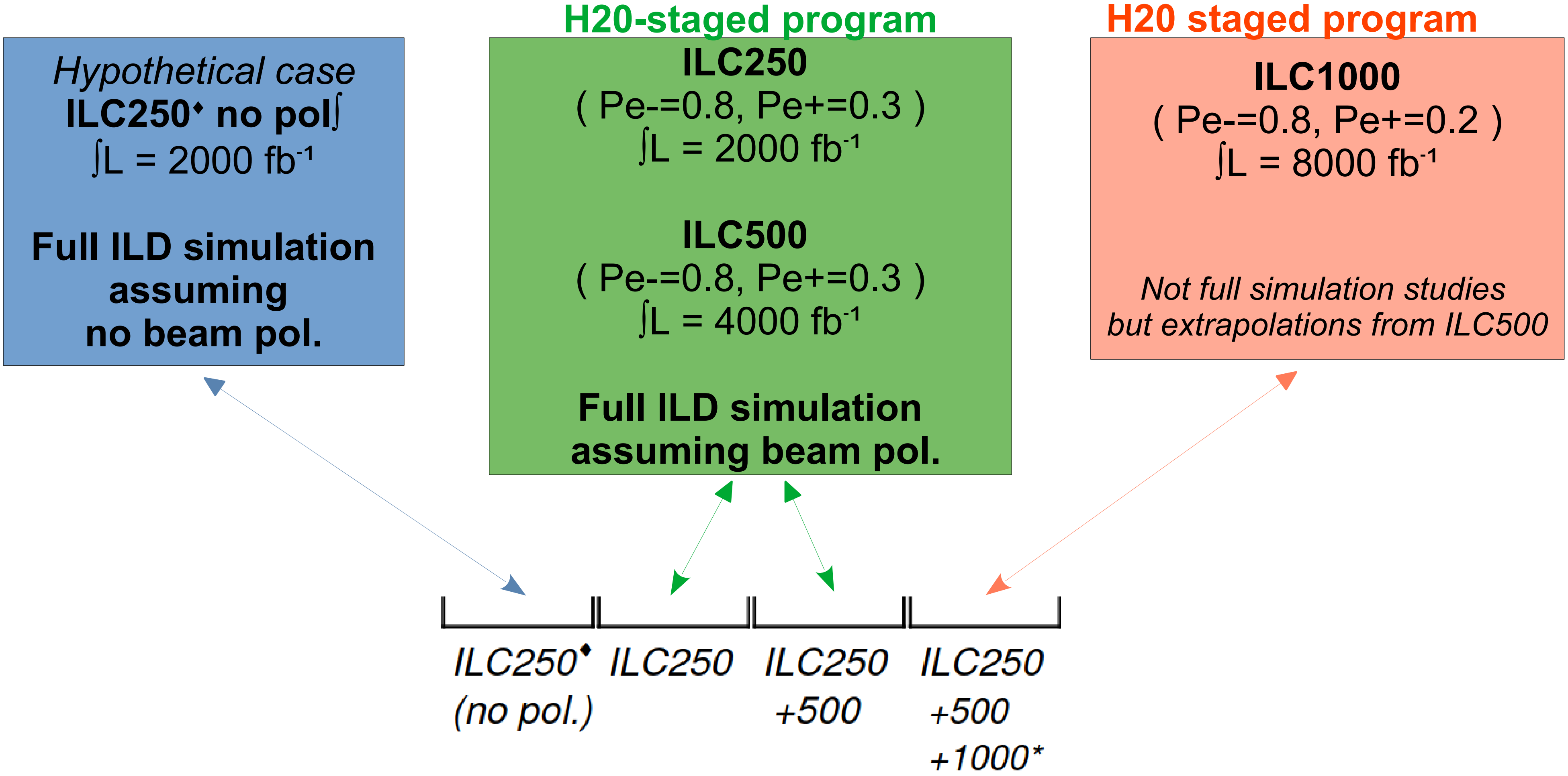
🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

GHU vs SM: Beam scenarios



Hypothetical case
ILC250♦ no pol∫
$\int L$ = 2000 fb^{-1}

Full ILD simulation assuming no beam pol.

H20-staged program

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

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

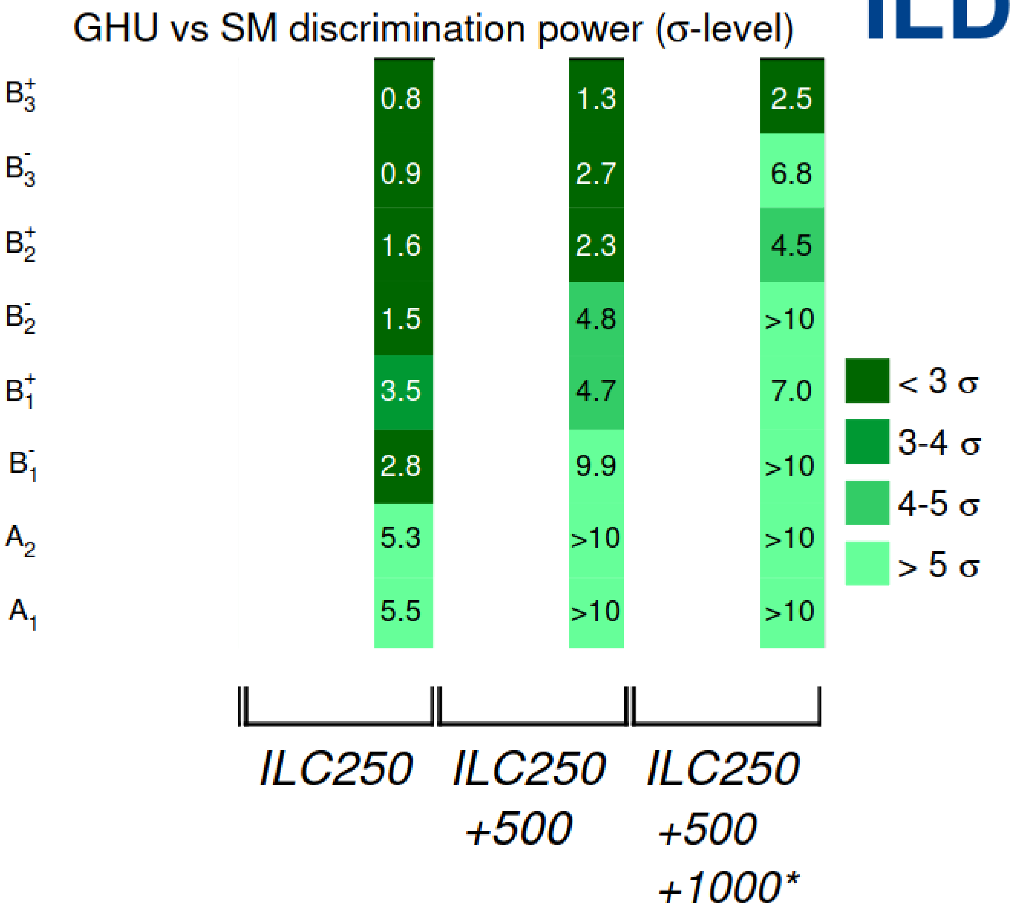
Full ILD simulation assuming beam pol.

H20 staged program

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

Not full simulation studies but extrapolations from ILC500

GHU vs SM: center of mass energy



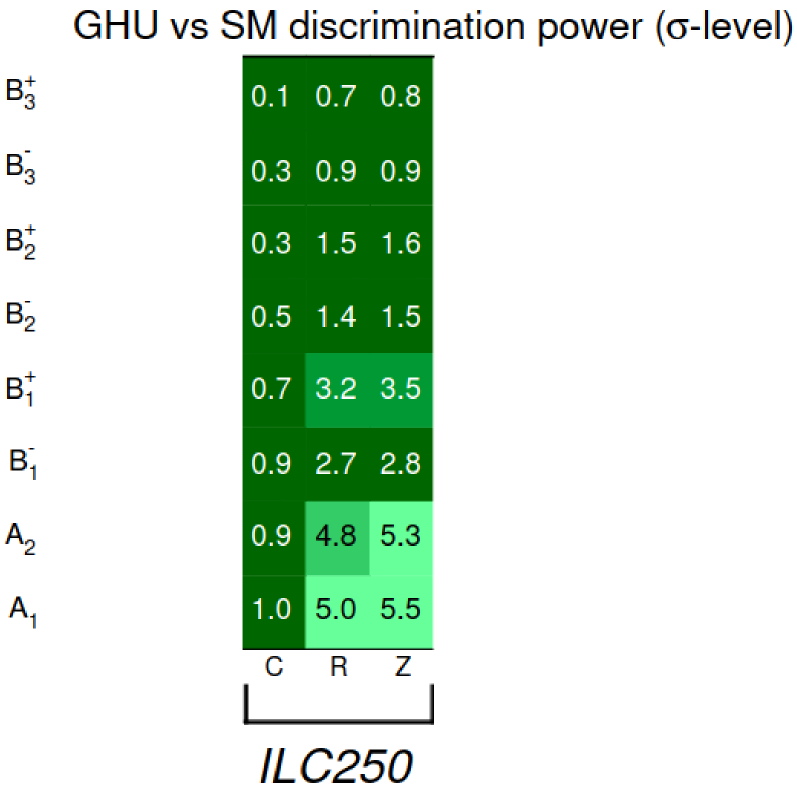
ILD

GHU vs SM discrimination power (σ-level)

	ILC250	ILC250 +500	ILC250 +500 +1000*
B_3^+	0.8	1.3	2.5
B_3^-	0.9	2.7	6.8
B_2^+	1.6	2.3	4.5
B_2^-	1.5	4.8	>10
B_1^+	3.5	4.7	7.0
B_1^-	2.8	9.9	>10
A_2	5.3	>10	>10
A_1	5.5	>10	>10

- 🟩 < 3 σ
- 🟩 3-4 σ
- 🟩 4-5 σ
- 🟩 > 5 σ

GHU vs SM: Precision on Z-couplings



GHU vs SM discrimination power (σ-level)

	C	R	Z
B_3^+	0.1	0.7	0.8
B_3^-	0.3	0.9	0.9
B_2^+	0.3	1.5	1.6
B_2^-	0.5	1.4	1.5
B_1^+	0.7	3.2	3.5
B_1^-	0.9	2.7	2.8
A_2	0.9	4.8	5.3
A_1	1.0	5.0	5.5

ILC250

ILD

Z-fermion couplings

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

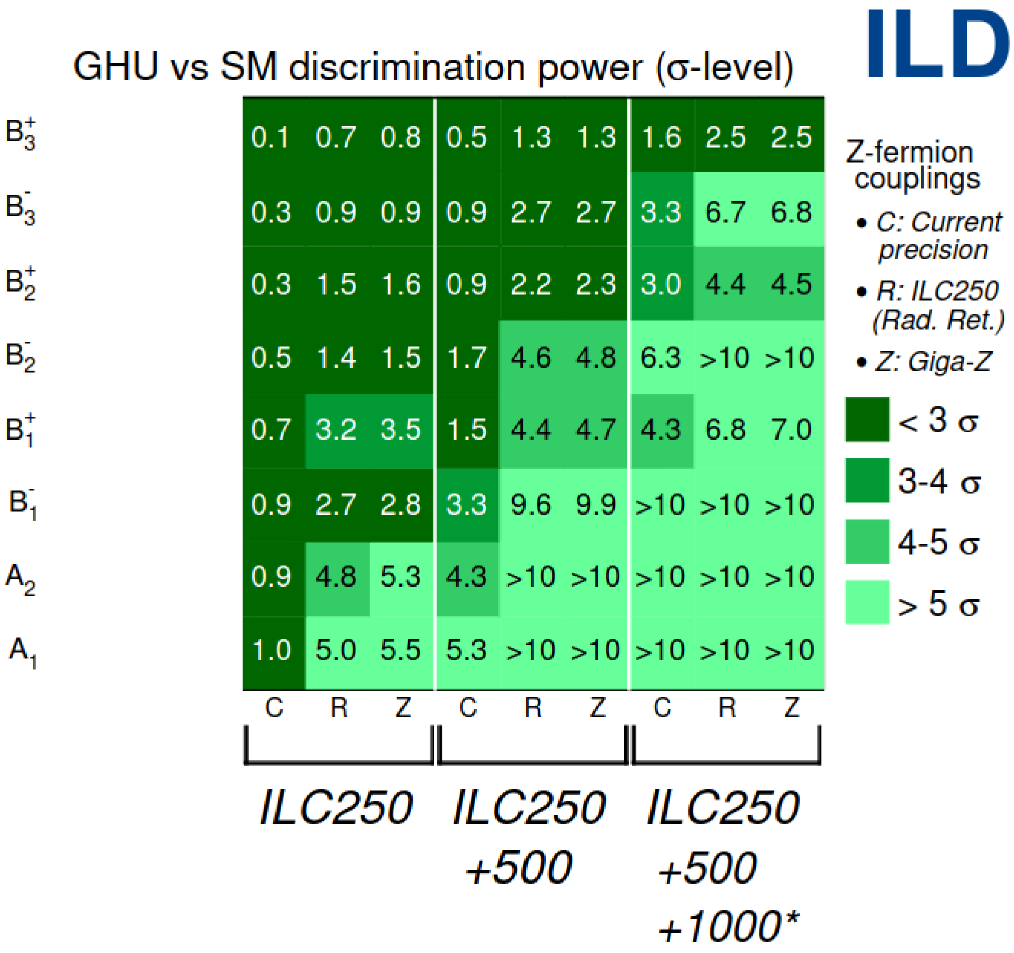
🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

GHU vs SM: Precision on Z-couplings



ILD

GHU vs SM discrimination power (σ-level)

	ILC250			ILC250 +500			ILC250 +500 +1000*		
	C	R	Z	C	R	Z	C	R	Z
B_3^+	0.1	0.7	0.8	0.5	1.3	1.3	1.6	2.5	2.5
B_3^-	0.3	0.9	0.9	0.9	2.7	2.7	3.3	6.7	6.8
B_2^+	0.3	1.5	1.6	0.9	2.2	2.3	3.0	4.4	4.5
B_2^-	0.5	1.4	1.5	1.7	4.6	4.8	6.3	>10	>10
B_1^+	0.7	3.2	3.5	1.5	4.4	4.7	4.3	6.8	7.0
B_1^-	0.9	2.7	2.8	3.3	9.6	9.9	>10	>10	>10
A_2	0.9	4.8	5.3	4.3	>10	>10	>10	>10	>10
A_1	1.0	5.0	5.5	5.3	>10	>10	>10	>10	>10

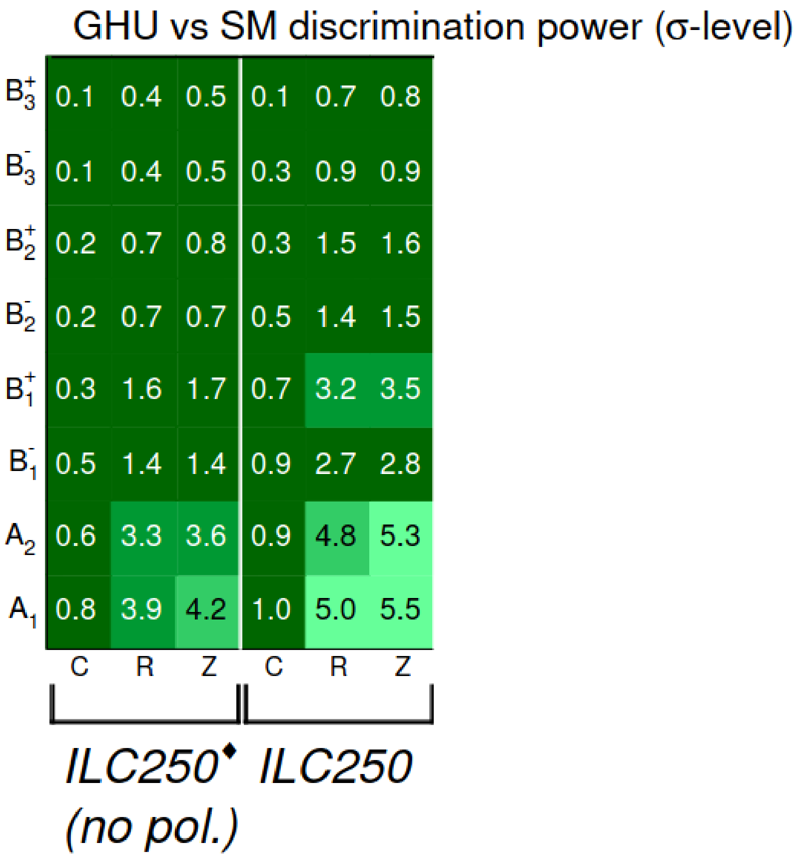
Z-fermion couplings

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

🟩 < 3 σ
🟩 3-4 σ
🟩 4-5 σ
🟩 > 5 σ

GHU vs SM: Beam(s) polarization

ILD



GHU vs SM discrimination power (σ-level)

	ILC250♦ (no pol.)			ILC250		
	C	R	Z	C	R	Z
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

Z-fermion couplings

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

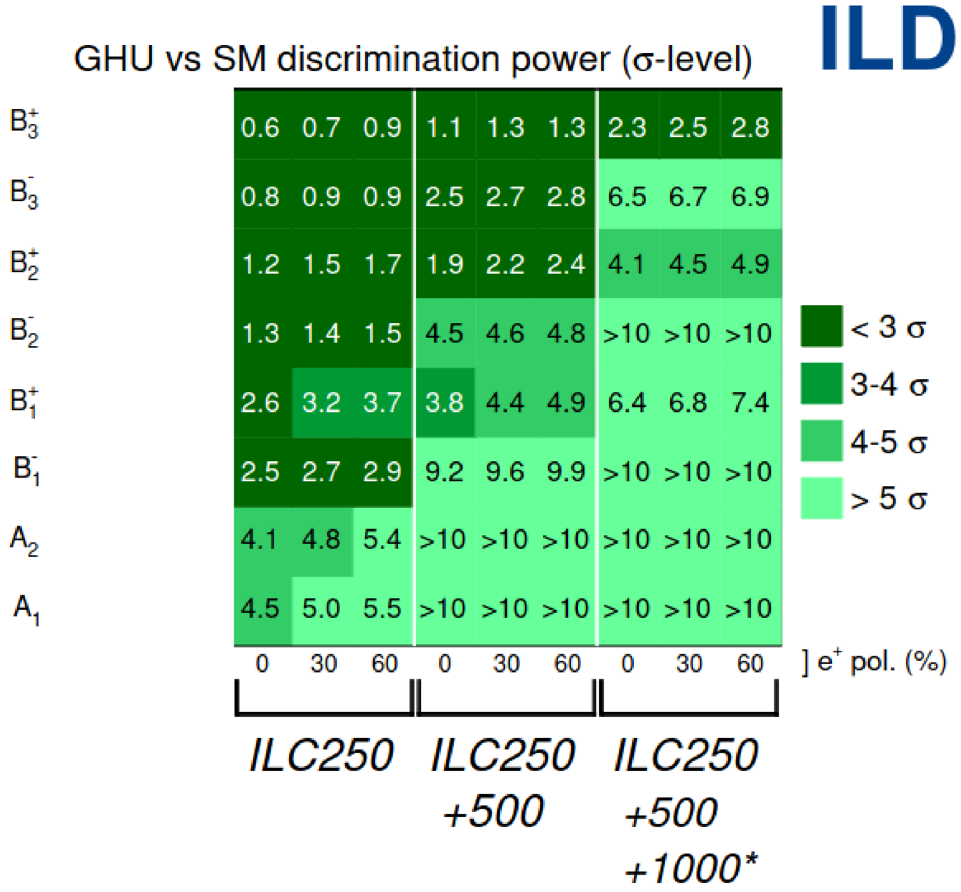
🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

GHU vs SM: Positron beam polarization



GHU vs SM discrimination power (σ-level)

	ILC250			ILC250 +500			ILC250 +500 +1000*		
] e^+ pol. (%)	0	30	60	0	30	60	0	30	60
B_3^+	0.6	0.7	0.9	1.1	1.3	1.3	2.3	2.5	2.8
B_3^-	0.8	0.9	0.9	2.5	2.7	2.8	6.5	6.7	6.9
B_2^+	1.2	1.5	1.7	1.9	2.2	2.4	4.1	4.5	4.9
B_2^-	1.3	1.4	1.5	4.5	4.6	4.8	>10	>10	>10
B_1^+	2.6	3.2	3.7	3.8	4.4	4.9	6.4	6.8	7.4
B_1^-	2.5	2.7	2.9	9.2	9.6	9.9	>10	>10	>10
A_2	4.1	4.8	5.4	>10	>10	>10	>10	>10	>10
A_1	4.5	5.0	5.5	>10	>10	>10	>10	>10	>10

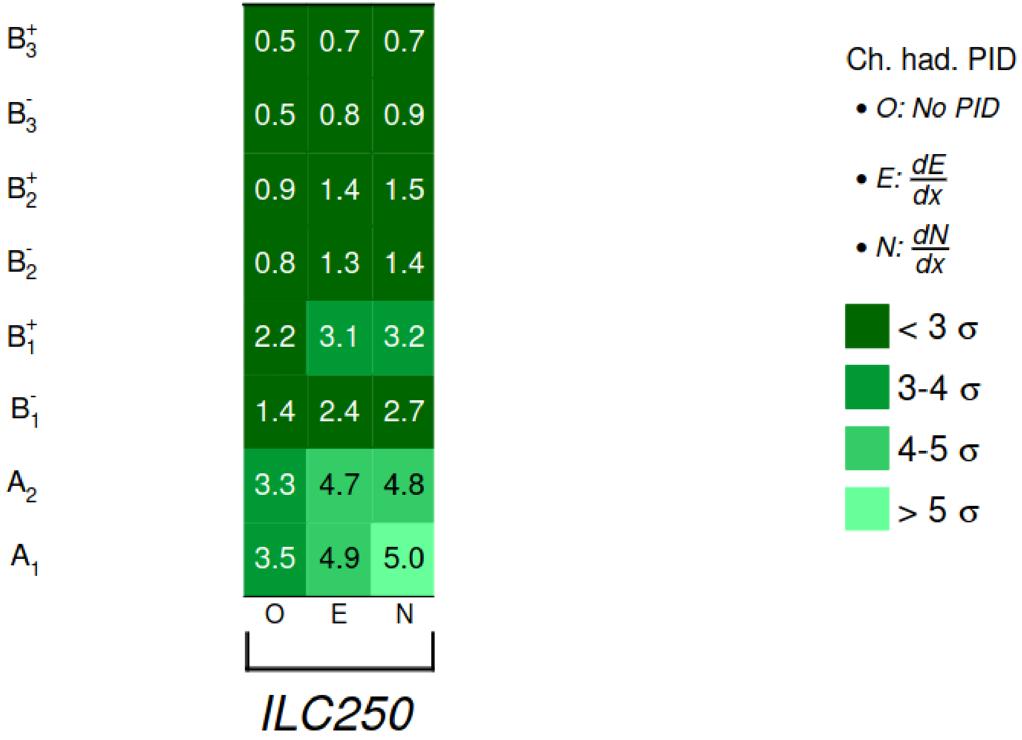
🟩 < 3 σ
🟩 3-4 σ
🟩 4-5 σ
🟩 > 5 σ

e- polarization at 80% in all of these scenarios

GHU vs SM: Particle ID dependence

ILD

GHU vs SM discrimination power (σ-level)



	O	E	N
B_3^+	0.5	0.7	0.7
B_3^-	0.5	0.8	0.9
B_2^+	0.9	1.4	1.5
B_2^-	0.8	1.3	1.4
B_1^+	2.2	3.1	3.2
B_1^-	1.4	2.4	2.7
A_2	3.3	4.7	4.8
A_1	3.5	4.9	5.0

ILC250

Ch. had. PID

- *O: No PID*
- *E:* $\frac{dE}{dx}$
- *N:* $\frac{dN}{dx}$

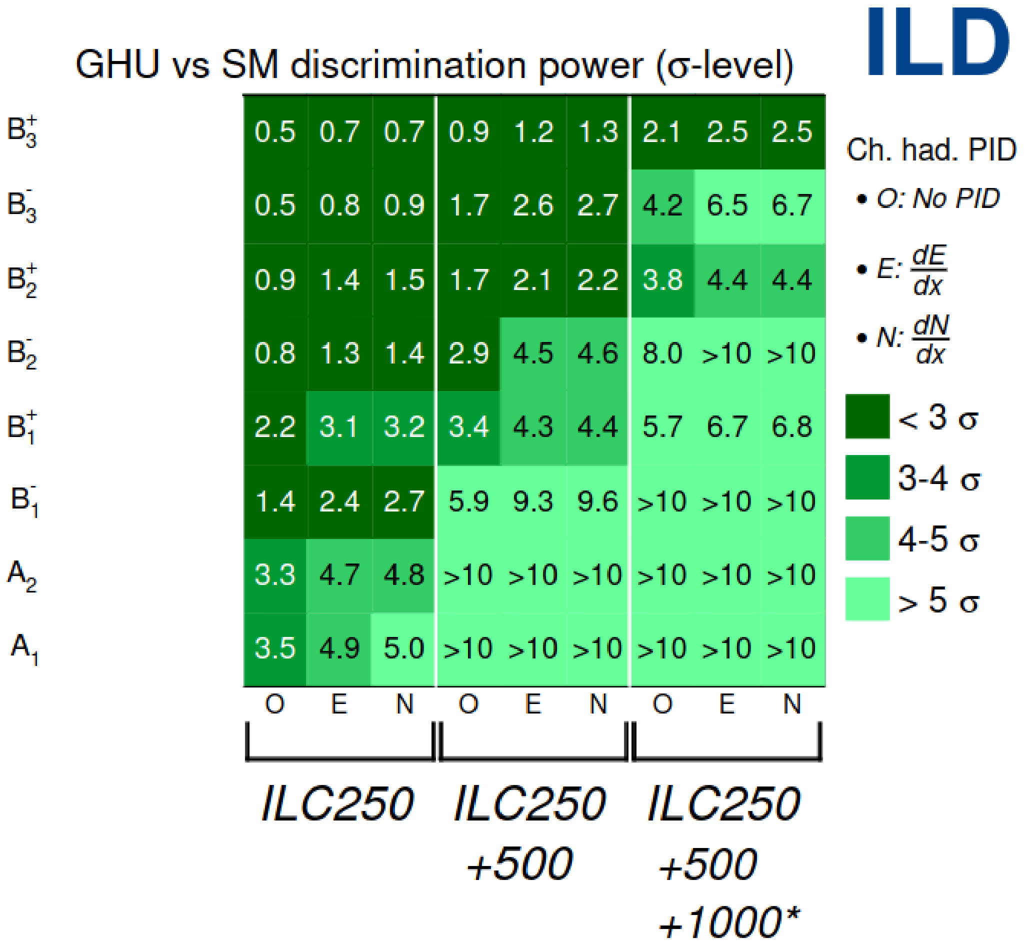
🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

GHU vs SM: Particle ID dependence



ILD

GHU vs SM discrimination power (σ-level)

	ILC250			ILC250 +500			ILC250 +500 +1000*		
	O	E	N	O	E	N	O	E	N
B_3^+	0.5	0.7	0.7	0.9	1.2	1.3	2.1	2.5	2.5
B_3^-	0.5	0.8	0.9	1.7	2.6	2.7	4.2	6.5	6.7
B_2^+	0.9	1.4	1.5	1.7	2.1	2.2	3.8	4.4	4.4
B_2^-	0.8	1.3	1.4	2.9	4.5	4.6	8.0	>10	>10
B_1^+	2.2	3.1	3.2	3.4	4.3	4.4	5.7	6.7	6.8
B_1^-	1.4	2.4	2.7	5.9	9.3	9.6	>10	>10	>10
A_2	3.3	4.7	4.8	>10	>10	>10	>10	>10	>10
A_1	3.5	4.9	5.0	>10	>10	>10	>10	>10	>10

Ch. had. PID

- *O: No PID*
- *E:* $\frac{dE}{dx}$
- *N:* $\frac{dN}{dx}$

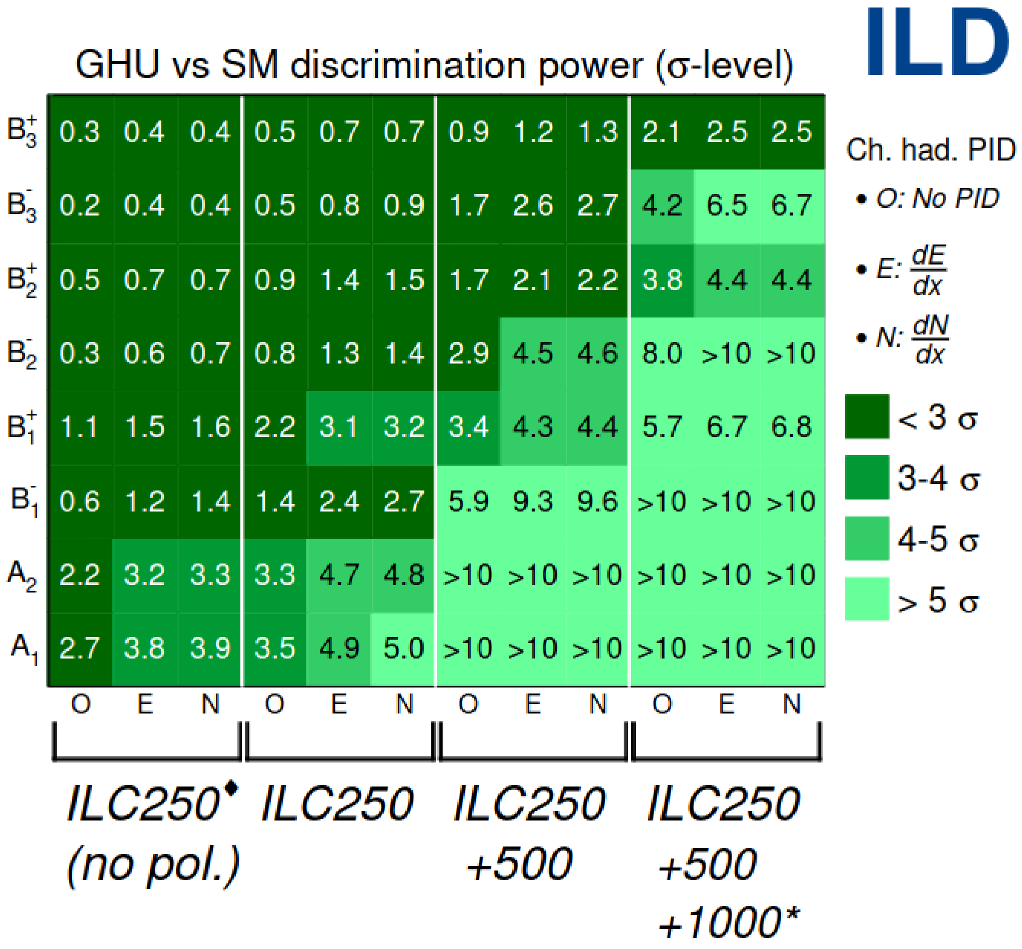
🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

GHU vs SM: Particle ID dependence



ILD

GHU vs SM discrimination power (σ-level)

	ILC250♦ (no pol.)			ILC250			ILC250 +500			ILC250 +500 +1000*		
	O	E	N	O	E	N	O	E	N	O	E	N
B_3^+	0.3	0.4	0.4	0.5	0.7	0.7	0.9	1.2	1.3	2.1	2.5	2.5
B_3^-	0.2	0.4	0.4	0.5	0.8	0.9	1.7	2.6	2.7	4.2	6.5	6.7
B_2^+	0.5	0.7	0.7	0.9	1.4	1.5	1.7	2.1	2.2	3.8	4.4	4.4
B_2^-	0.3	0.6	0.7	0.8	1.3	1.4	2.9	4.5	4.6	8.0	>10	>10
B_1^+	1.1	1.5	1.6	2.2	3.1	3.2	3.4	4.3	4.4	5.7	6.7	6.8
B_1^-	0.6	1.2	1.4	1.4	2.4	2.7	5.9	9.3	9.6	>10	>10	>10
A_2	2.2	3.2	3.3	3.3	4.7	4.8	>10	>10	>10	>10	>10	>10
A_1	2.7	3.8	3.9	3.5	4.9	5.0	>10	>10	>10	>10	>10	>10

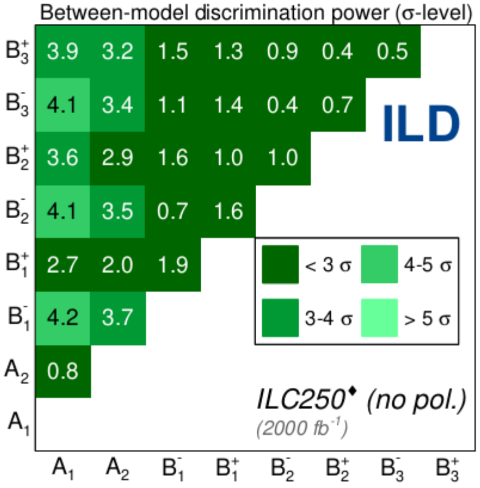
Ch. had. PID

- *O: No PID*
- *E:* $\frac{dE}{dx}$
- *N:* $\frac{dN}{dx}$

- 🟩 < 3 σ
- 🟩 3-4 σ
- 🟩 4-5 σ
- 🟩 > 5 σ

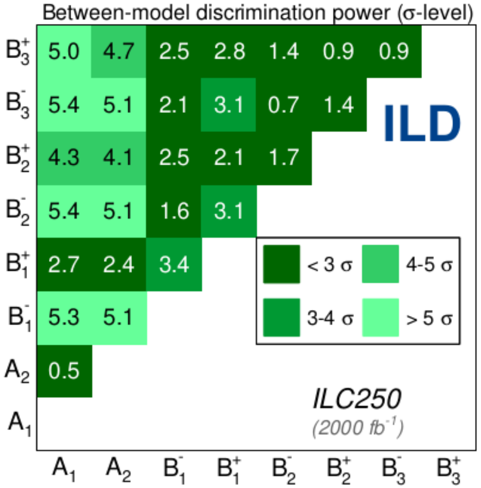
SUSY 2024
Theory meets Experiment

GHU between model discrimination


Between-model discrimination power (σ-level)

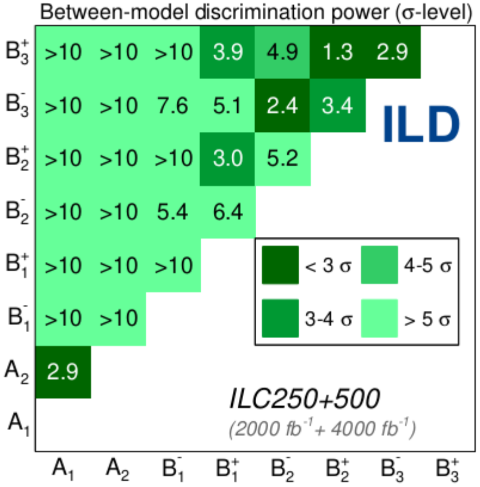
ILC250♦ (no pol.)
(2000 fb^{-1})

	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+
B_3^+	3.9	3.2	1.5	1.3	0.9	0.4	0.5	
B_3^-	4.1	3.4	1.1	1.4	0.4	0.7		
B_2^+	3.6	2.9	1.6	1.0	1.0			
B_2^-	4.1	3.5	0.7	1.6				
B_1^+	2.7	2.0	1.9					
B_1^-	4.2	3.7						
A_2	0.8							
A_1								


Between-model discrimination power (σ-level)

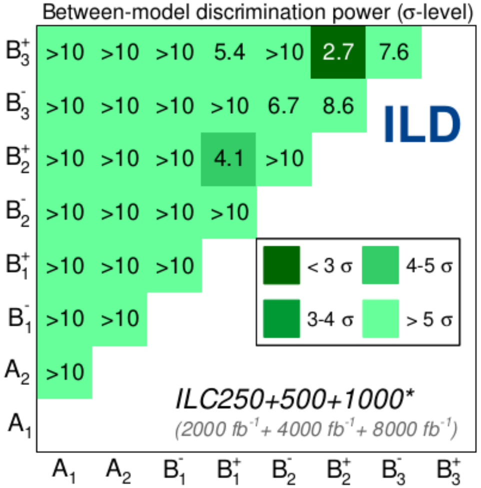
ILC250
(2000 fb^{-1})

	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+
B_3^+	5.0	4.7	2.5	2.8	1.4	0.9	0.9	
B_3^-	5.4	5.1	2.1	3.1	0.7	1.4		
B_2^+	4.3	4.1	2.5	2.1	1.7			
B_2^-	5.4	5.1	1.6	3.1				
B_1^+	2.7	2.4	3.4					
B_1^-	5.3	5.1						
A_2	0.5							
A_1								


Between-model discrimination power (σ-level)

ILC250+500
(2000 fb^{-1} + 4000 fb^{-1})

	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+
B_3^+	>10	>10	>10	3.9	4.9	1.3	2.9	
B_3^-	>10	>10	7.6	5.1	2.4	3.4		
B_2^+	>10	>10	>10	3.0	5.2			
B_2^-	>10	>10	5.4	6.4				
B_1^+	>10	>10	>10					
B_1^-	>10	>10						
A_2	2.9							
A_1								


Between-model discrimination power (σ-level)

ILC250+500+1000*
(2000 fb^{-1} + 4000 fb^{-1} + 8000 fb^{-1})

	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+
B_3^+	>10	>10	>10	5.4	>10	2.7	7.6	
B_3^-	>10	>10	>10	>10	6.7	8.6		
B_2^+	>10	>10	>10	4.1	>10			
B_2^-	>10	>10	>10	>10				
B_1^+	>10	>10	>10					
B_1^-	>10	>10						
A_2	>10							
A_1								

Conclusion/ summary

Conclusions and summary

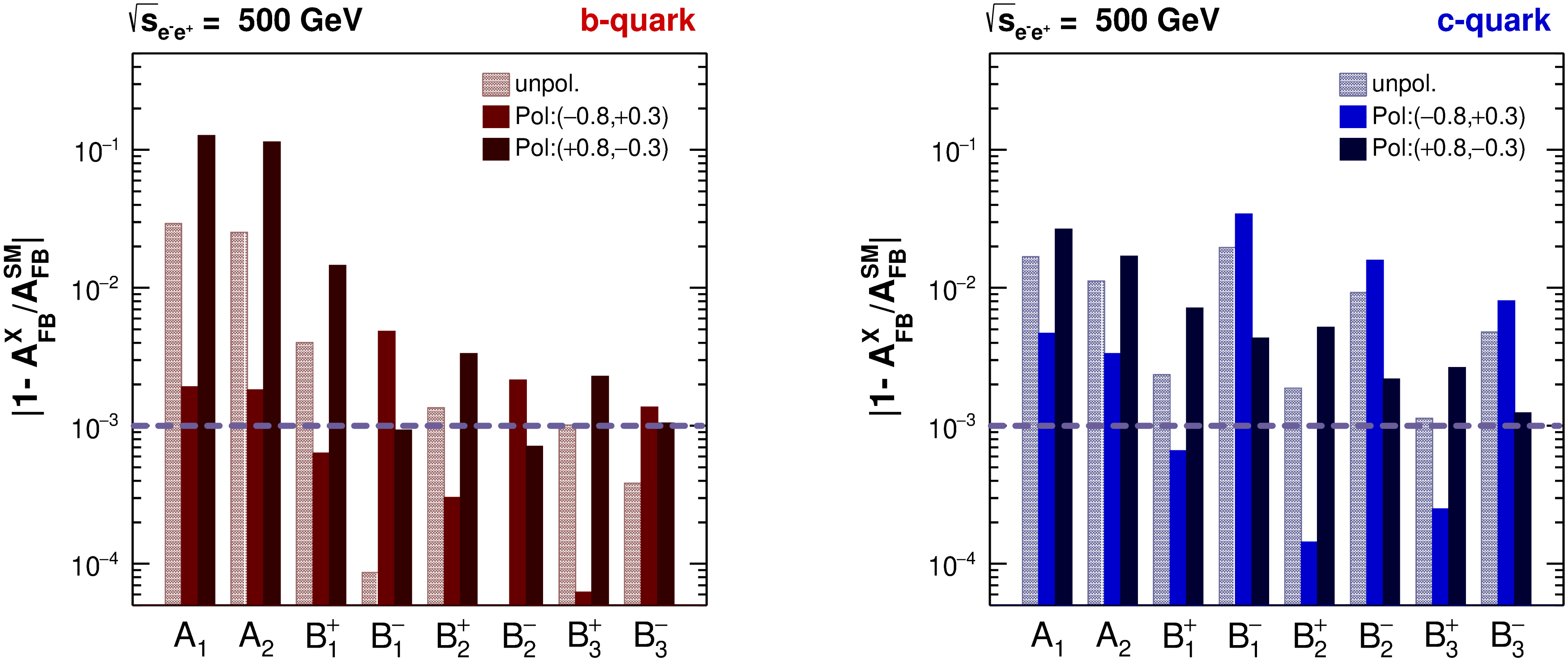
- ILC offers unique capabilities to explore these signatures and discriminate GHU vs SM:
  - **High energy reach**.
  - Electron and positron **beam polarization** → enhancing the sensitivity but also allowing combination of measurements with different BSM sensitivity (for control of systematics).
  - 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!**

Thanks for your attention!

back-up

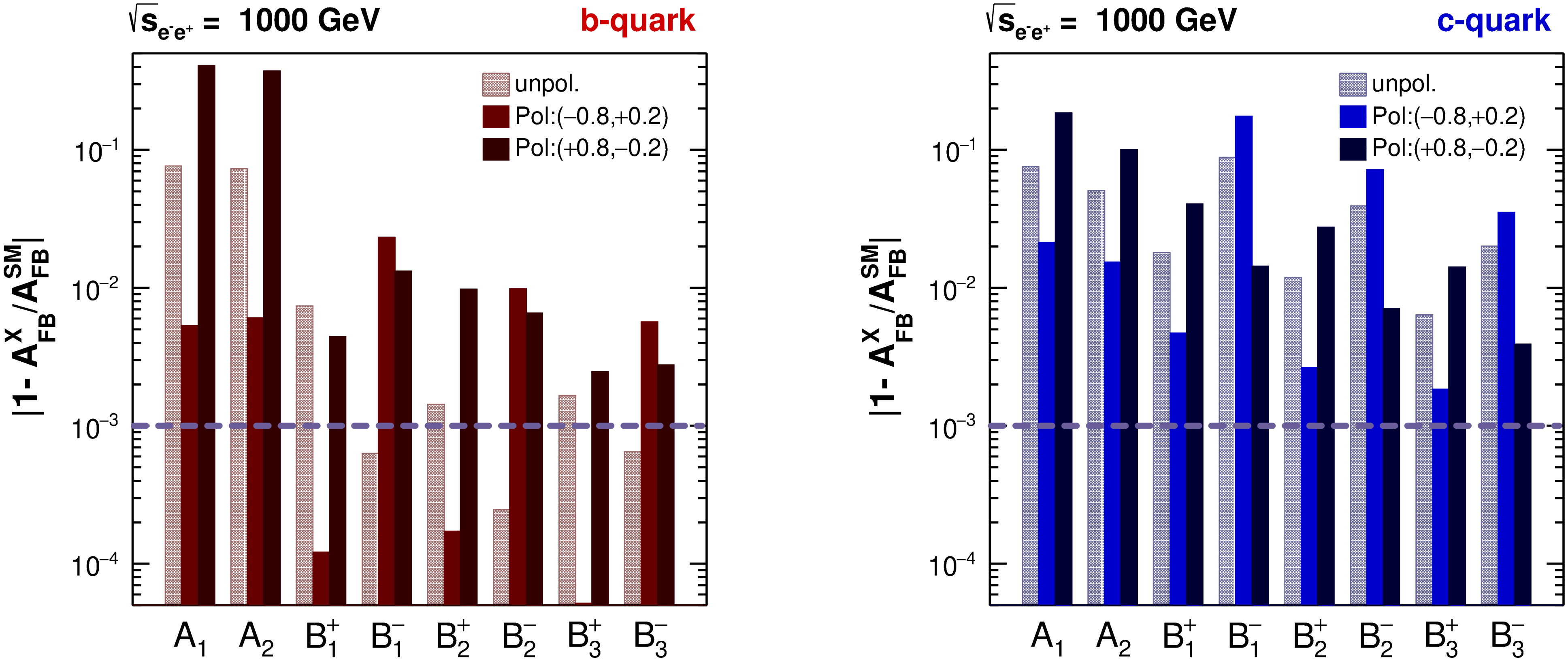
GHU vs SM (500 GeV)



Deviations at the per mil level

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

GHU vs SM (1 TeV)

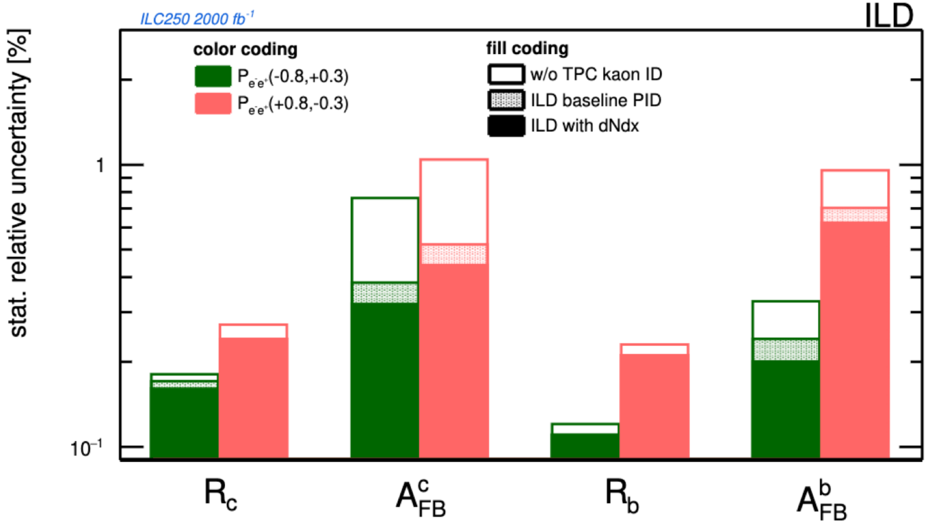


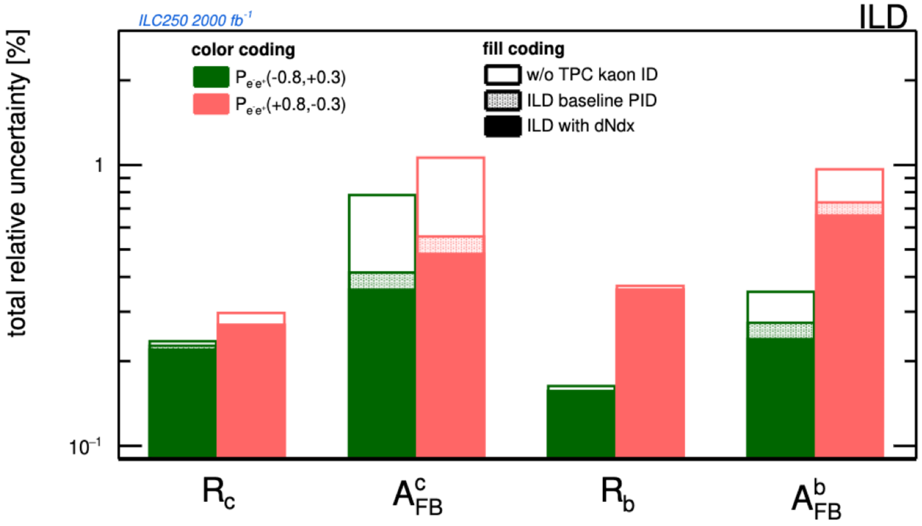
Deviations at the per mil level

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

Uncertainties ILC250

- Presented in LCWS (2023) 2307.14888

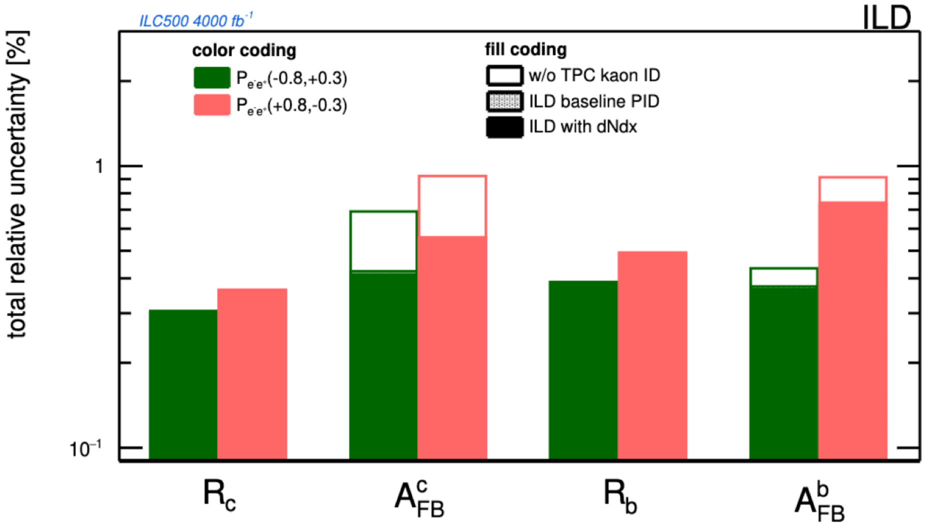


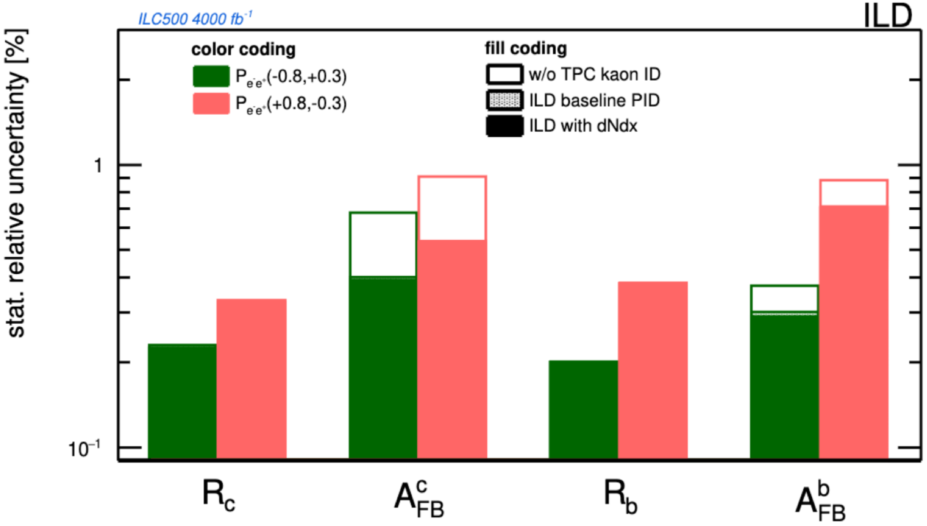


Statistical uncertainties dominate over systematic uncertainties

Uncertainties ILC500

- Presented in LCWS (2023) 2307.14888
  - Less benefit from the use of PID, but the A_{FB} uncertainties are in the same level.

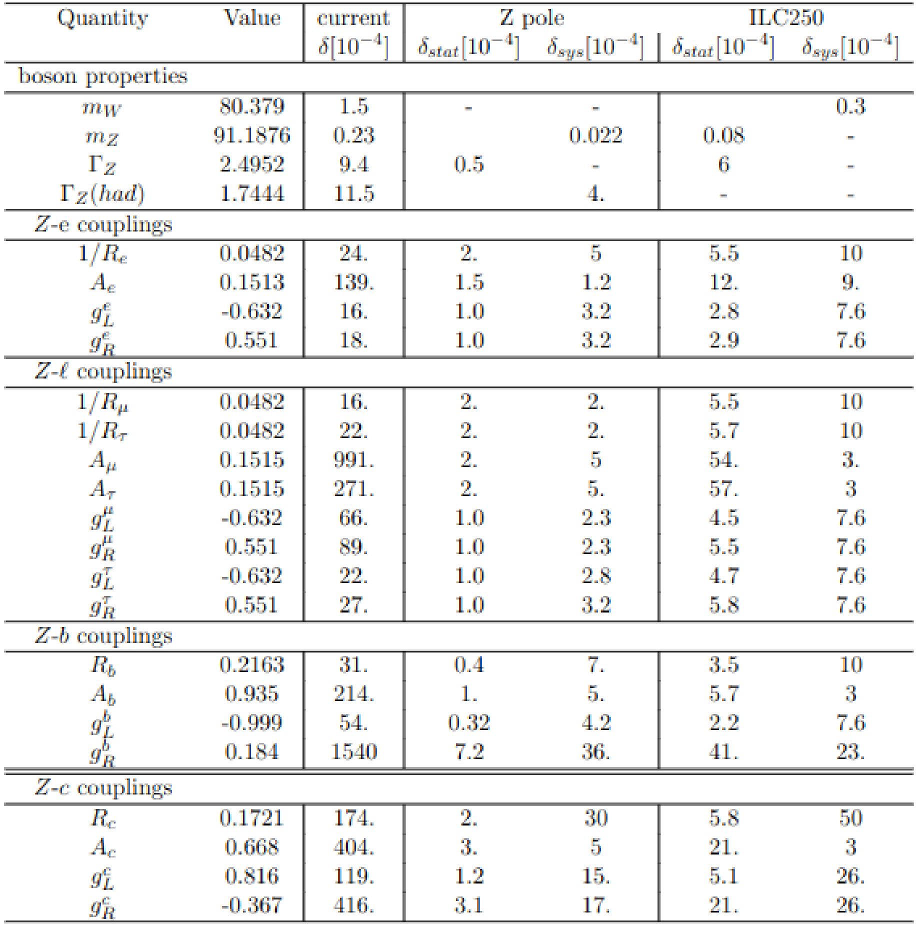




Statistical uncertainties dominate over systematic uncertainties

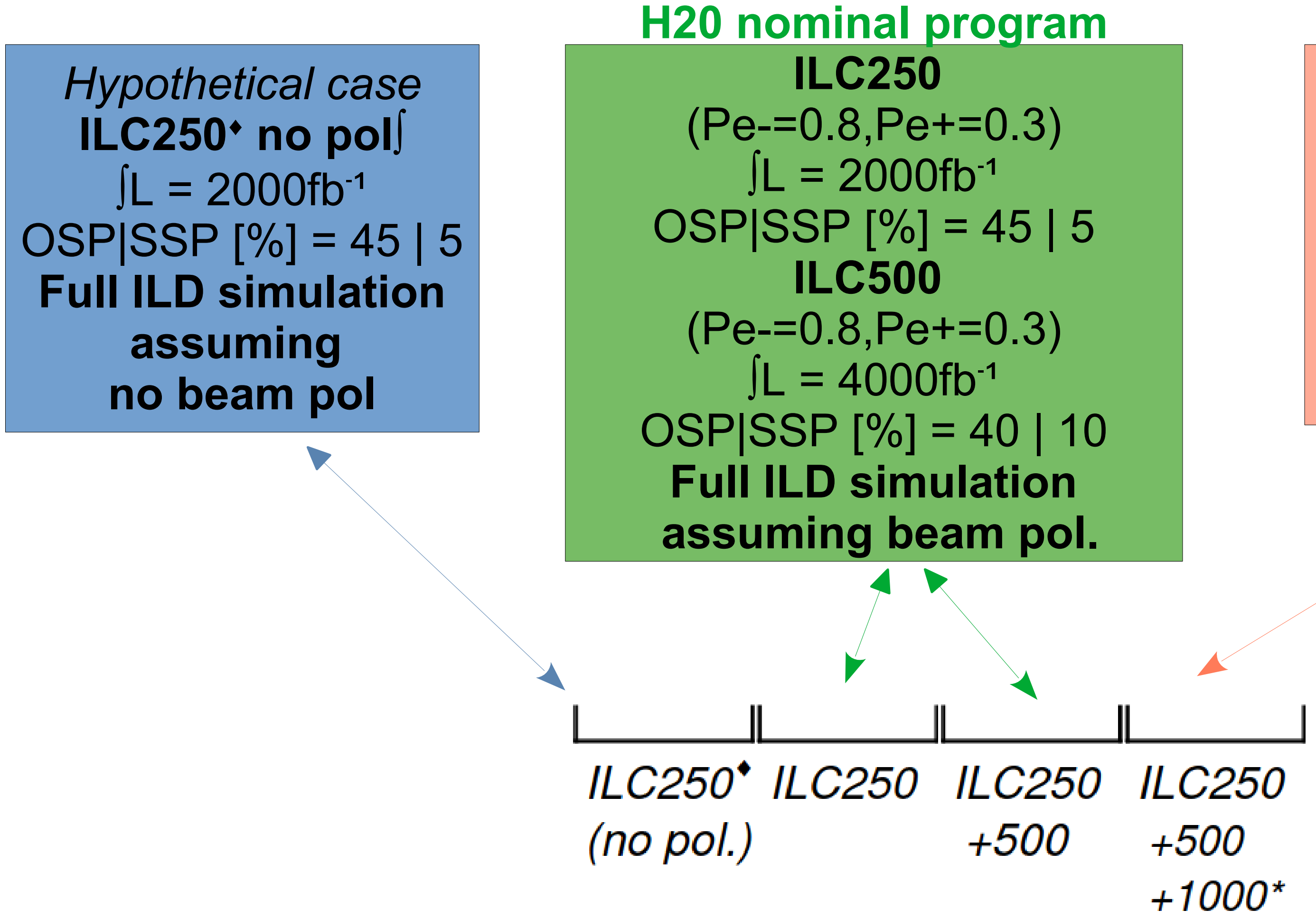
Z-couplings

- https://arxiv.org/pdf/2203.07622.pdf



Quantity	Value	current $\delta[10^{-4}]$	Z pole $\delta_{stat}[10^{-4}]$	Z pole $\delta_{sys}[10^{-4}]$	ILC250 $\delta_{stat}[10^{-4}]$	ILC250 $\delta_{sys}[10^{-4}]$
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∫
$\int L = 2000fb^{-1}$
OSP|SSP [%] = 45 | 5
Full ILD simulation assuming no beam pol

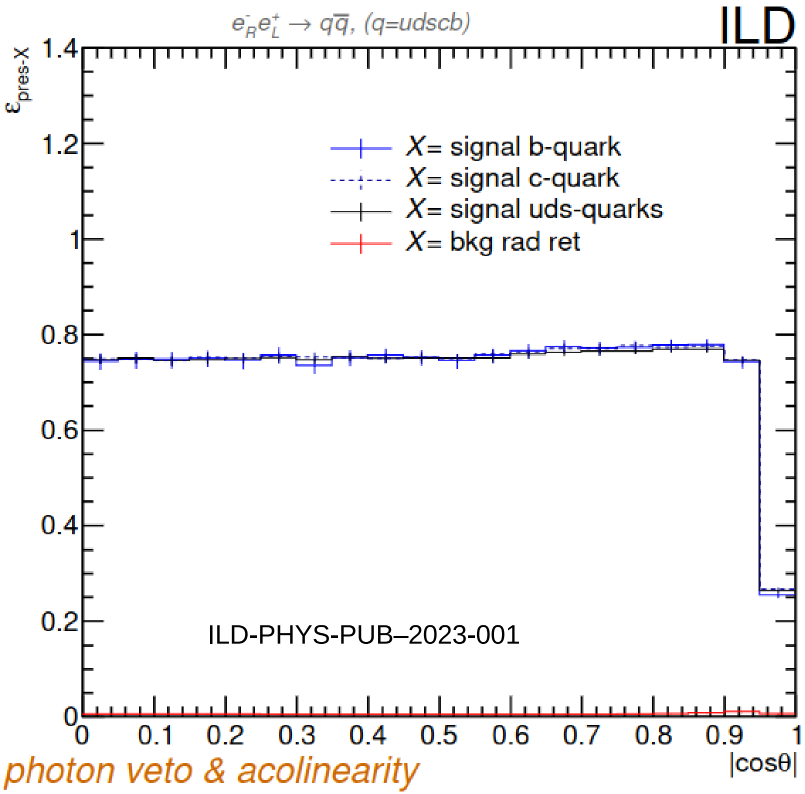
H20 nominal program
ILC250
(Pe-=0.8,Pe+=0.3)
$\int L = 2000fb^{-1}$
OSP|SSP [%] = 45 | 5
ILC500
(Pe-=0.8,Pe+=0.3)
$\int L = 4000fb^{-1}$
OSP|SSP [%] = 40 | 10
Full ILD simulation assuming beam pol.

H20 nominal program
ILC1000
(Pe-=0.8,Pe+=0.2)
$\int L = 8000fb^{-1}$
OSP|SSP [%] = 40 | 10

Not full simulation studies but extrapolations from ILC500

Preselection

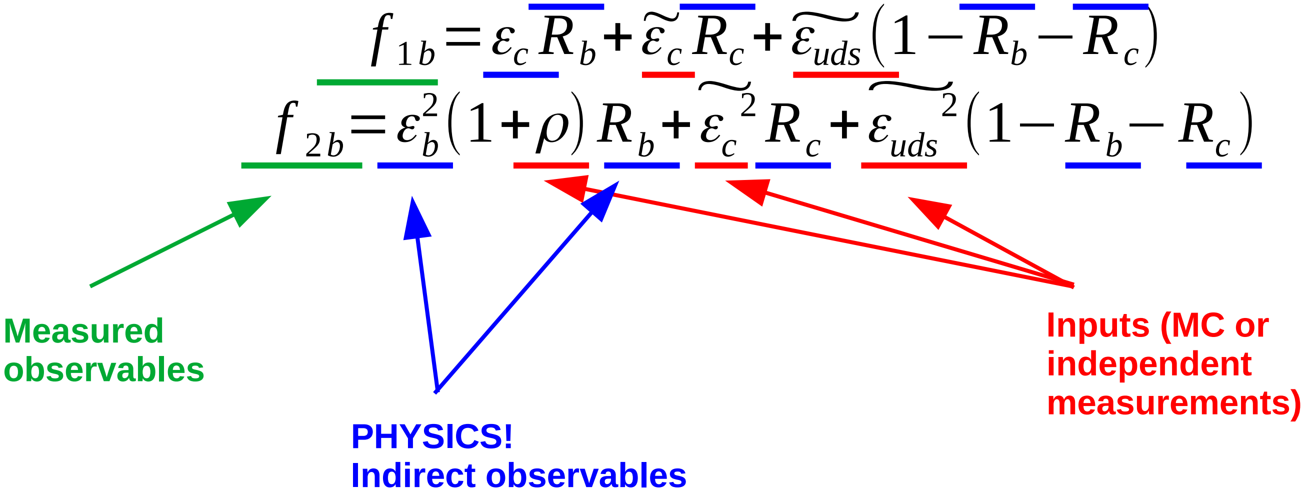
- **Topology: 2 back-to-back jets (pencil-like topology)**
- **Preselection aiming for high background rejection and high efficiency.**
- Main bkg ee→ Zγ(radiative return through ISR)
  - ~x10 larger than signal
  - **~90% of such ISR photons are lost in the beam pipe** → events filtered by energy & angular mom. conservation arguments
  - The **remaining ~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 toplogical cuts.



photon veto & acolinearity & m_{jj} & y_{23} cuts

Double-Tag method

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



$$f_{1b} = \varepsilon_c R_b + \widetilde{\varepsilon_c} R_c + \widetilde{\varepsilon_{uds}} (1 - R_b - R_c)$$

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

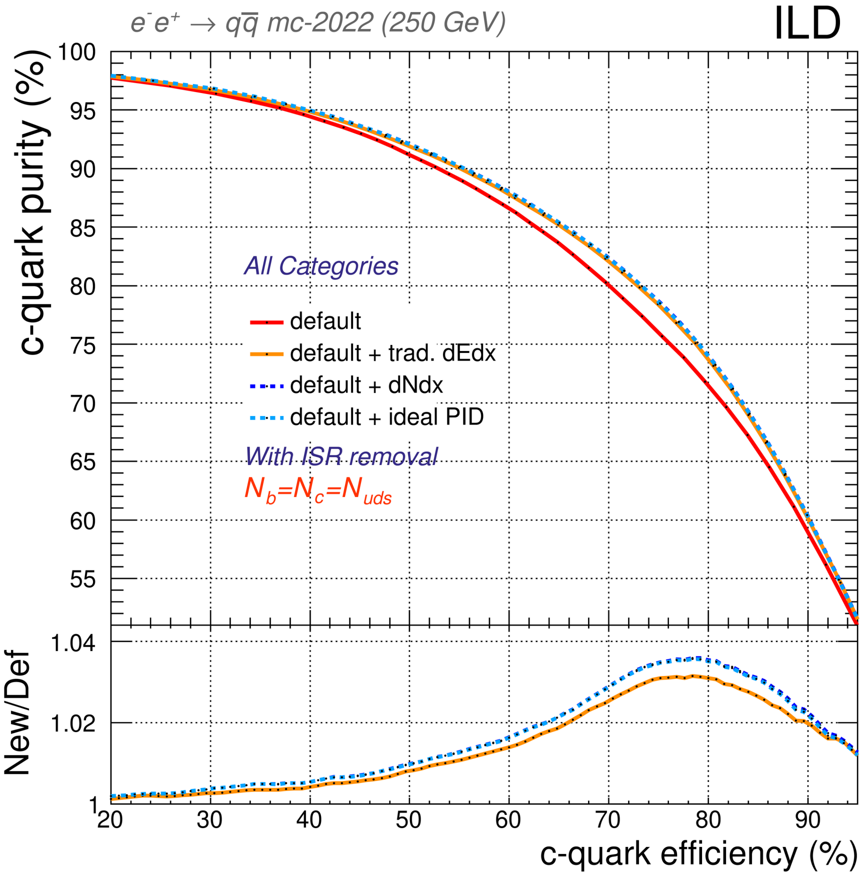
Measured observables

PHYSICS!
Indirect observables

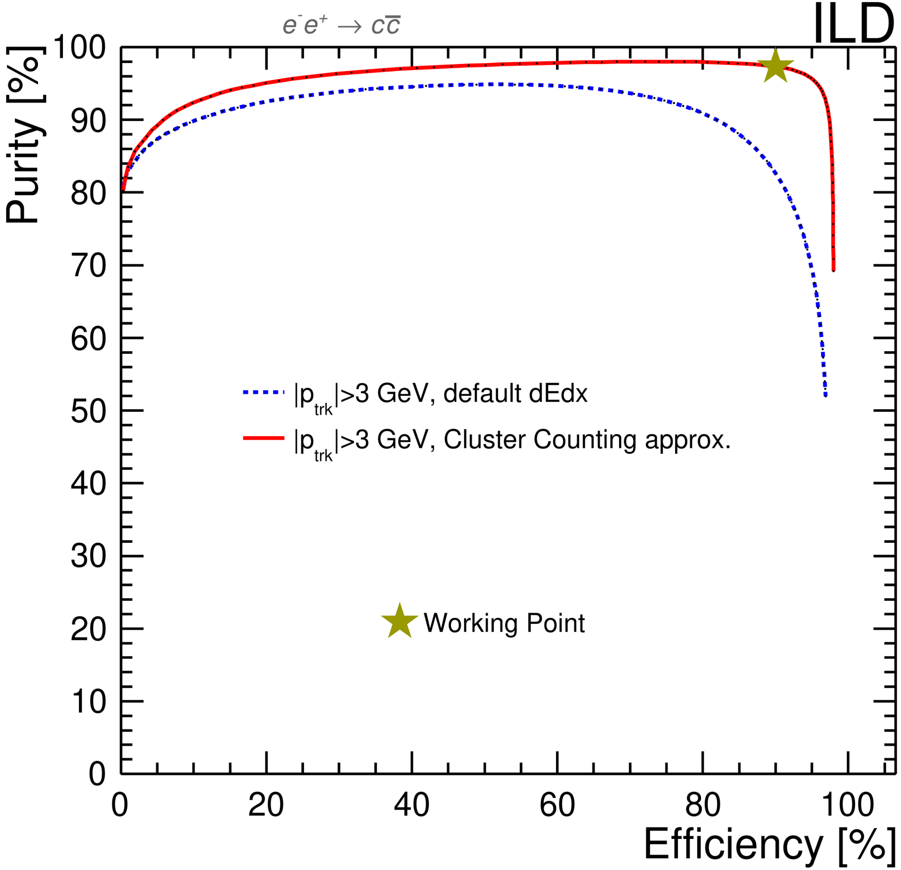
Inputs (MC or independent measurements)

Similar set of equations for the c-quark
solved simultaneously

PID: From dEdx to dNdx



Effects in **Flavour Tagging**



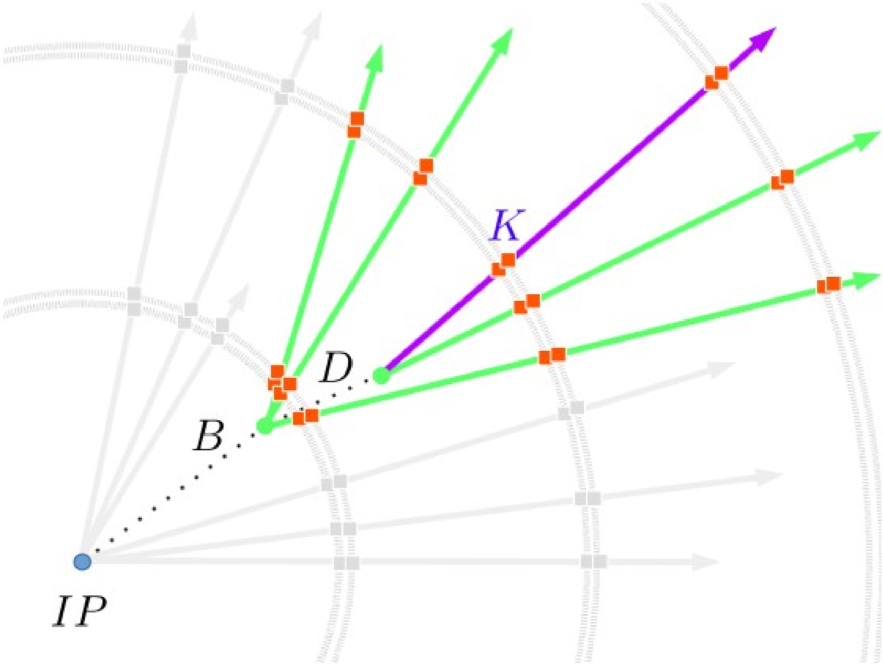
Effects in **Kaon ID** for charge reco.

Jet charge

- We start from a very pure & background-free **double tagged** sample

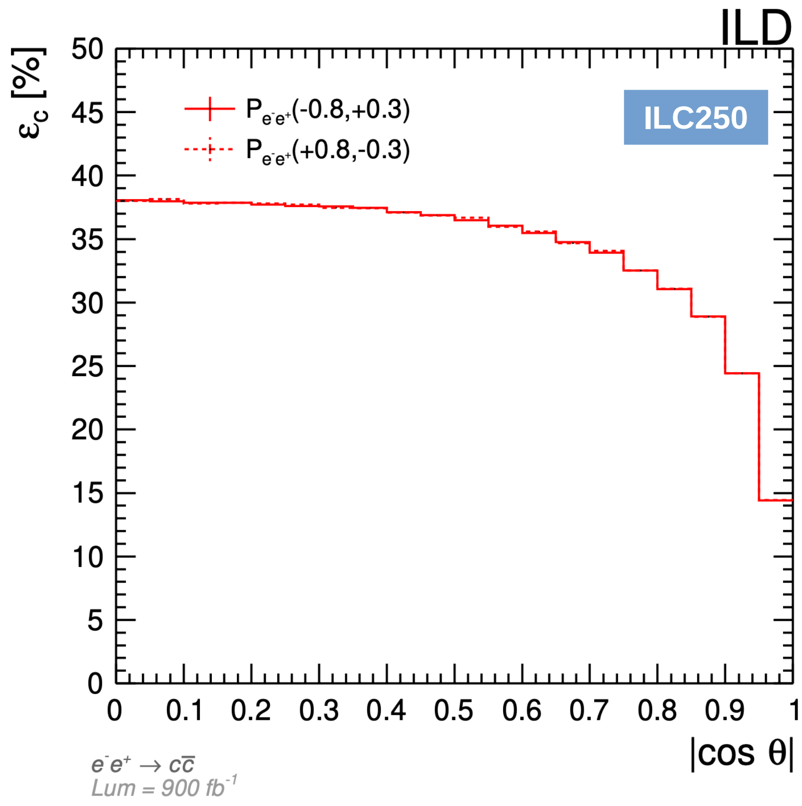
- We are required to **measure the jet charge**
  - Using K-ID and/or full Vtx charge measurement
  - K-ID is better suited for the C-quark (Vtx is better suited for b-quark)

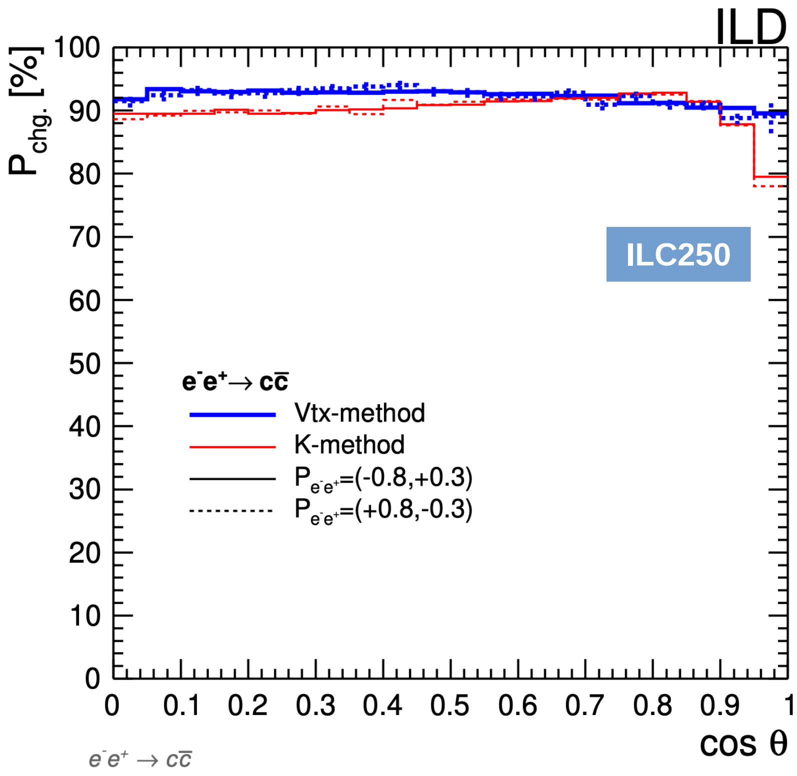
- We use the **double charge** measurements
  - To control / reduce the systematic uncertainties



Jet flavour tagging & charge measurement

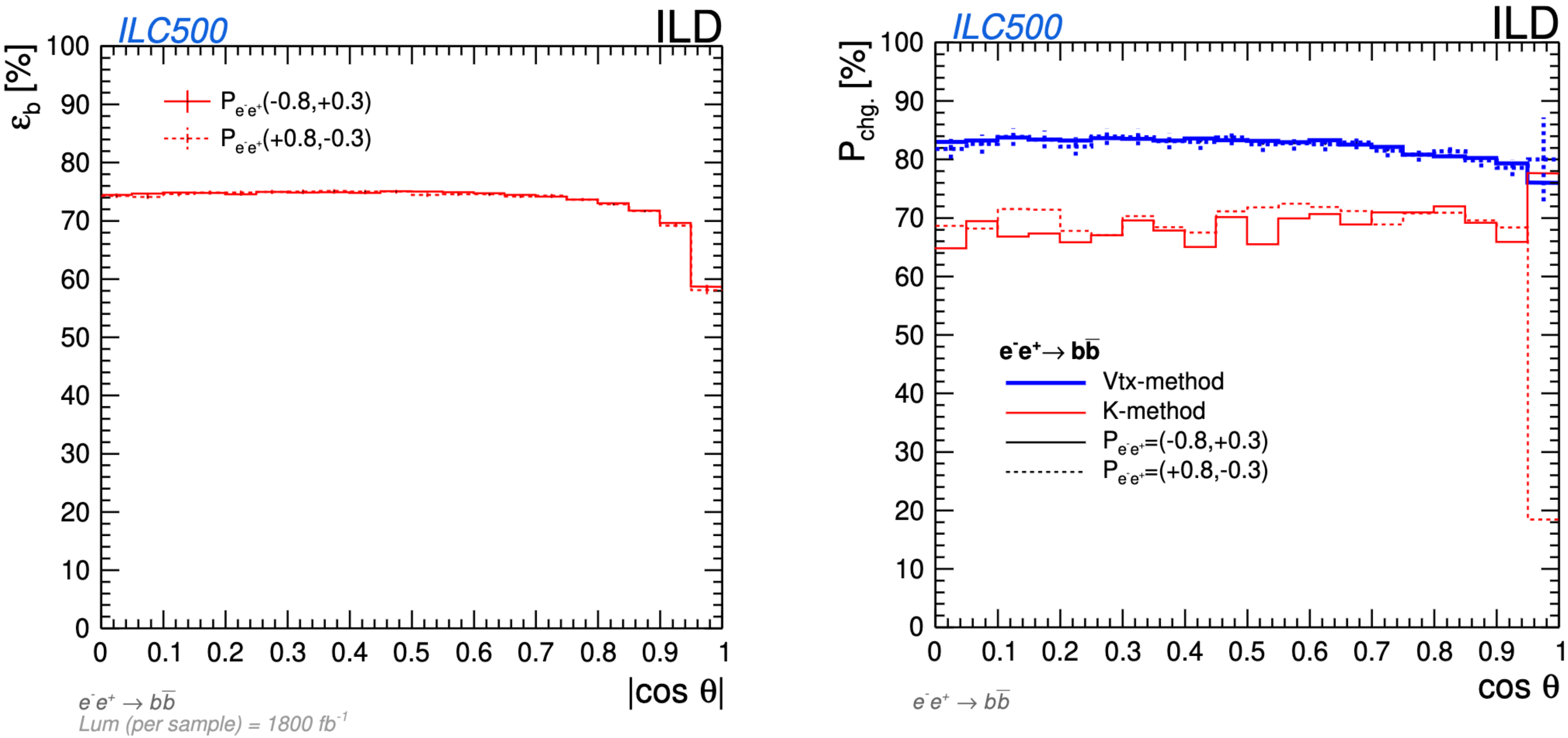
- Double tagging & double charge measurement methods. (described in previous ILD Note 2306.11413 (2022))
  - To maximally reduce the usage of MC tools (control of fragmentation, QCD correlations… uncertainties)





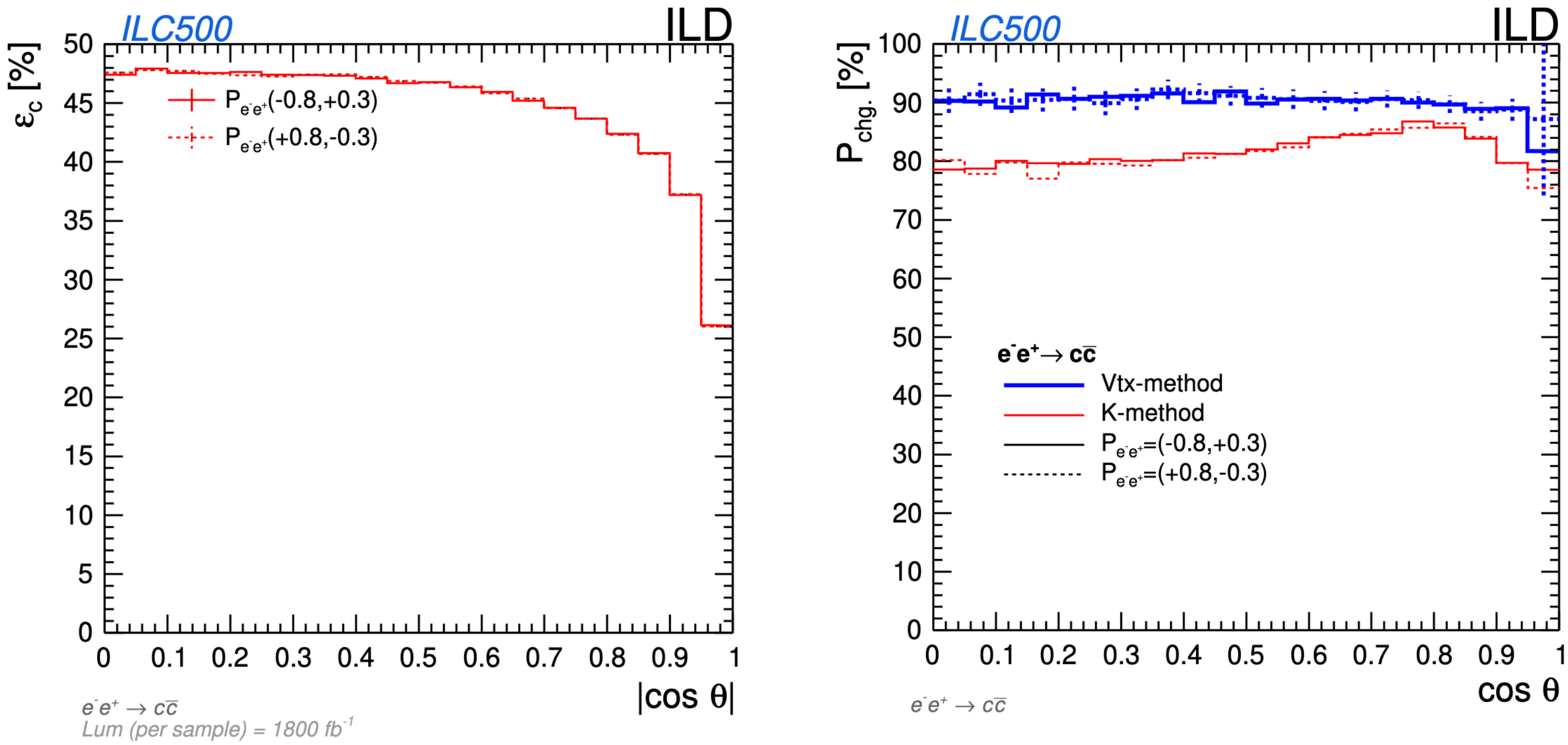
Jet flavour tagging & charge measurement

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



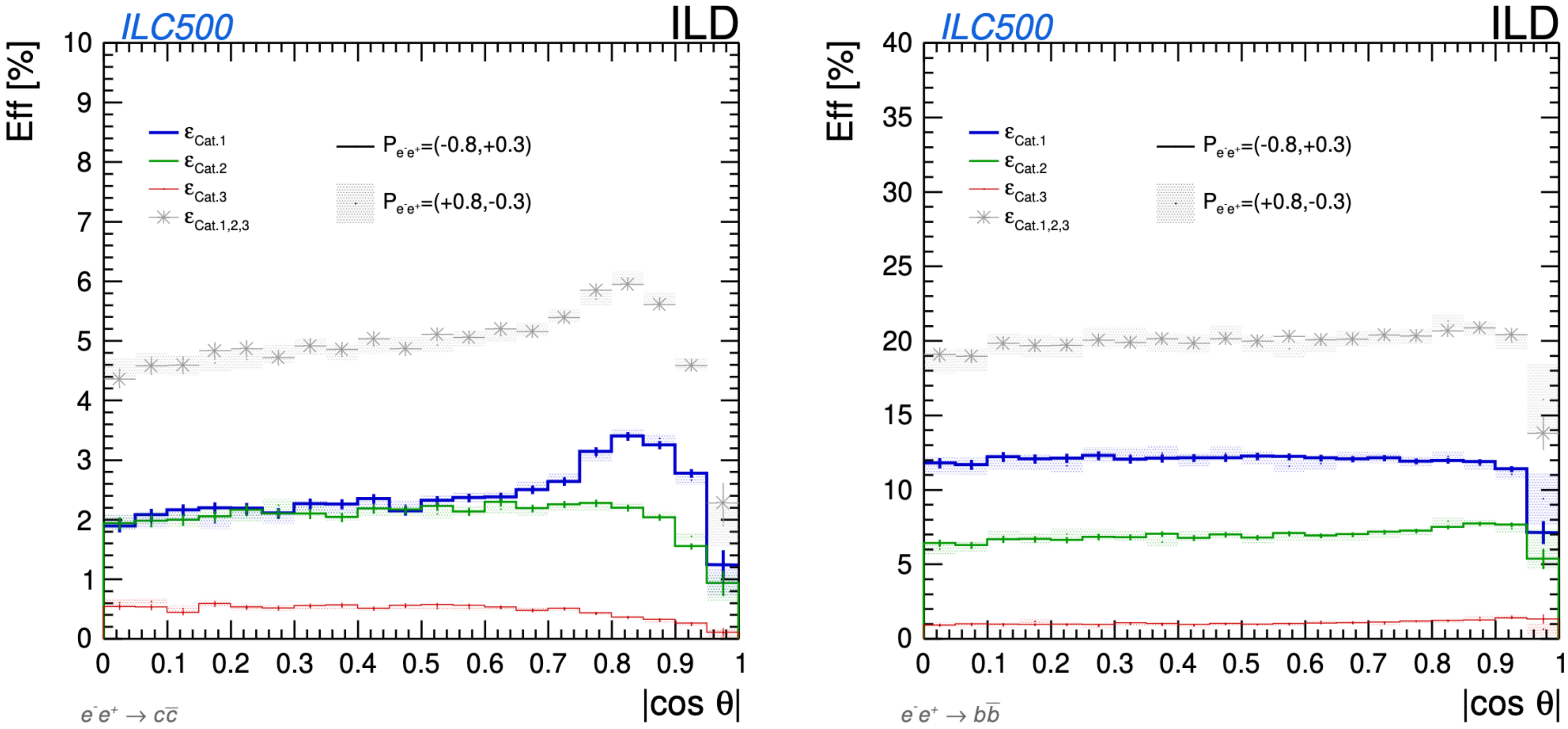
Jet flavour tagging & charge measurement

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



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_Lp_R, e_Rp_L).

- **Per mil level statistical uncertainties** reachable for the nominal **ILC program**
  - **Smaller exp syst. Uncertainties.**
    - Fragmentation, angular correlations, preselection efficiency, mistag, etc.