Experimental prospects for indirect BSM searches in $e^+e^- \rightarrow q\bar{q}$ (q=b,c) processes at Higgs Factories.

ILD Meeting 17/01/2024 CERN

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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) (2309.01132) (arxiv:2301.07833)

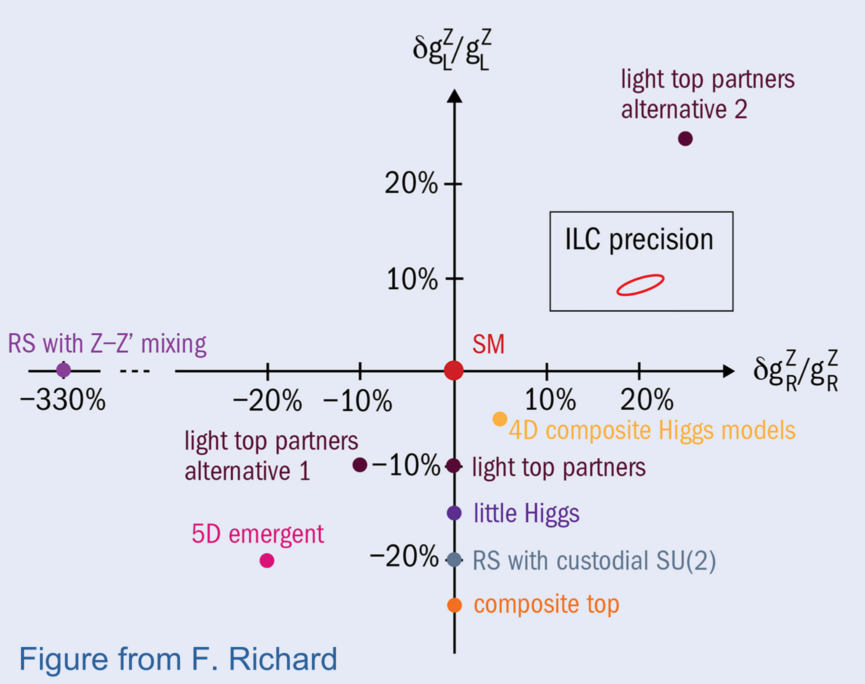


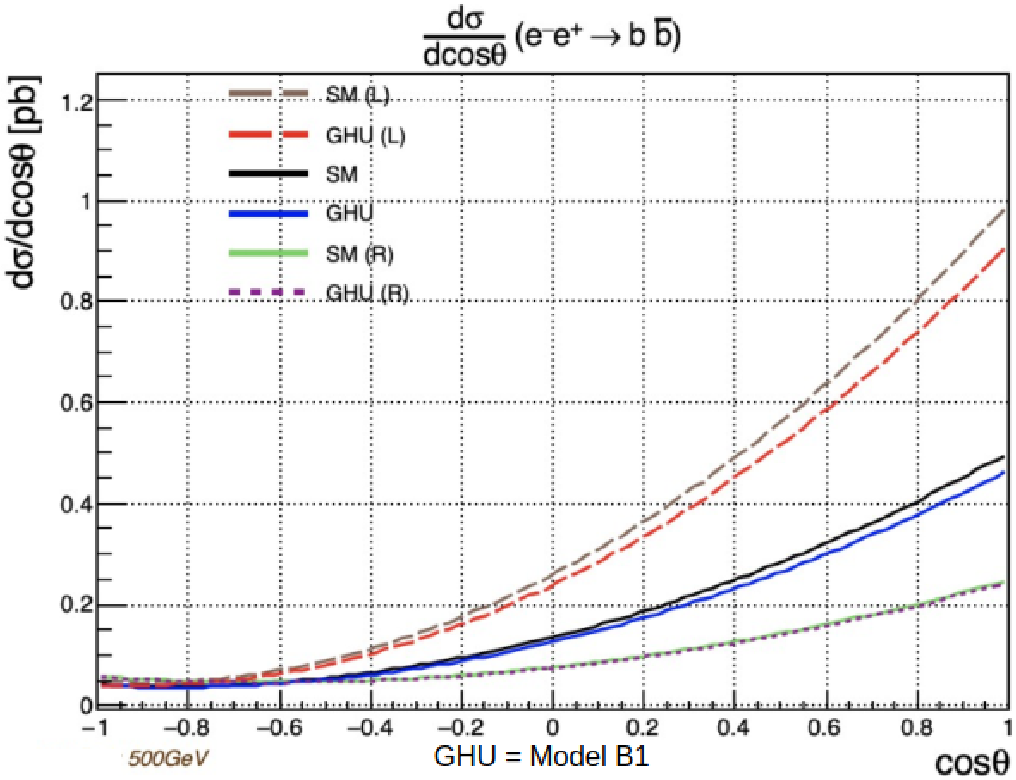
Figure from F. Richard

Probing such scenarios require at least per mil level for experimental precision

tt/**bb**/cc/ss/… **Can we do it?**

Gauge-Higgs Unification Models

- Randall-Sundrum metric (5D).
- The symmetry breaking pattern is different than in the SM and features the so-called Hosotani's mechanism.
- 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.

Gauge-Higgs Unification Models

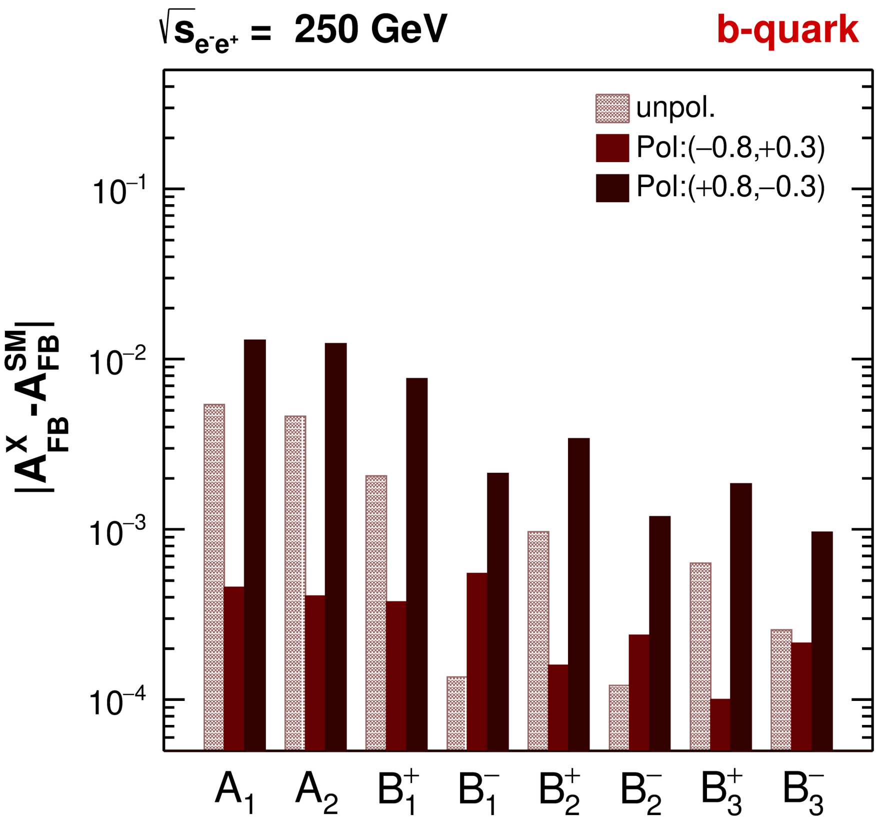
- A models: (arxiv:1705.05282)

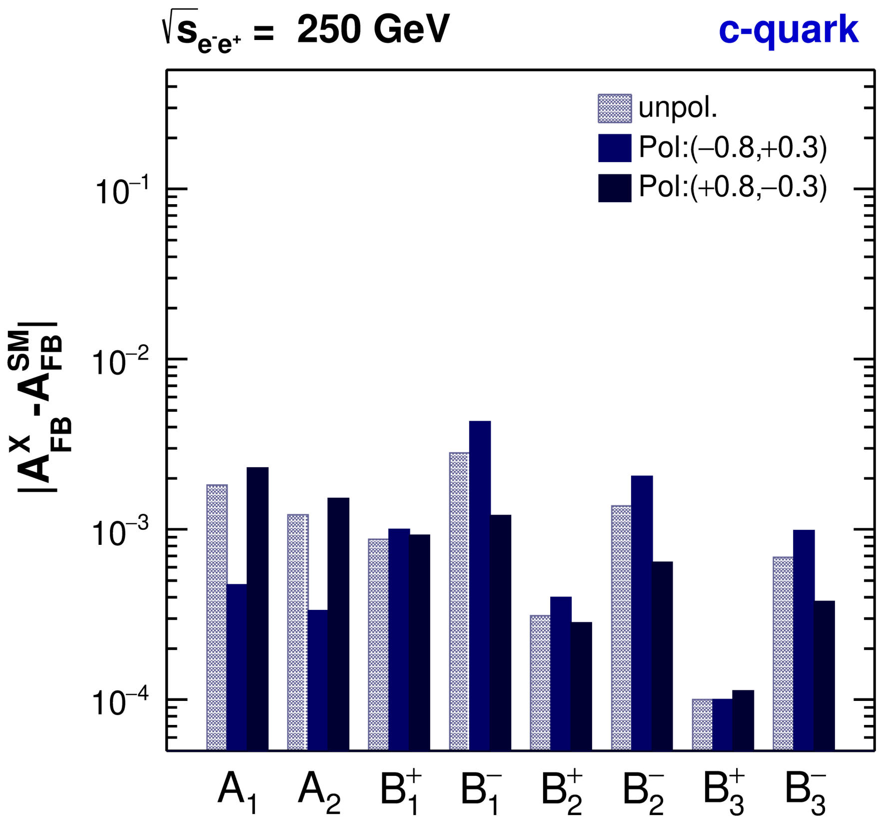
$$\begin{aligned} A_1 &: \theta_H = 0.0917, m_{KK} = 8.81\ \text{TeV} \rightarrow m_{Z'} = 7.19\ \text{TeV}; \\ A_2 &: \theta_H = 0.0737, m_{KK} = 10.3\ \text{TeV} \rightarrow m_{Z'} = 8.52\ \text{TeV}, \end{aligned}$$

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

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

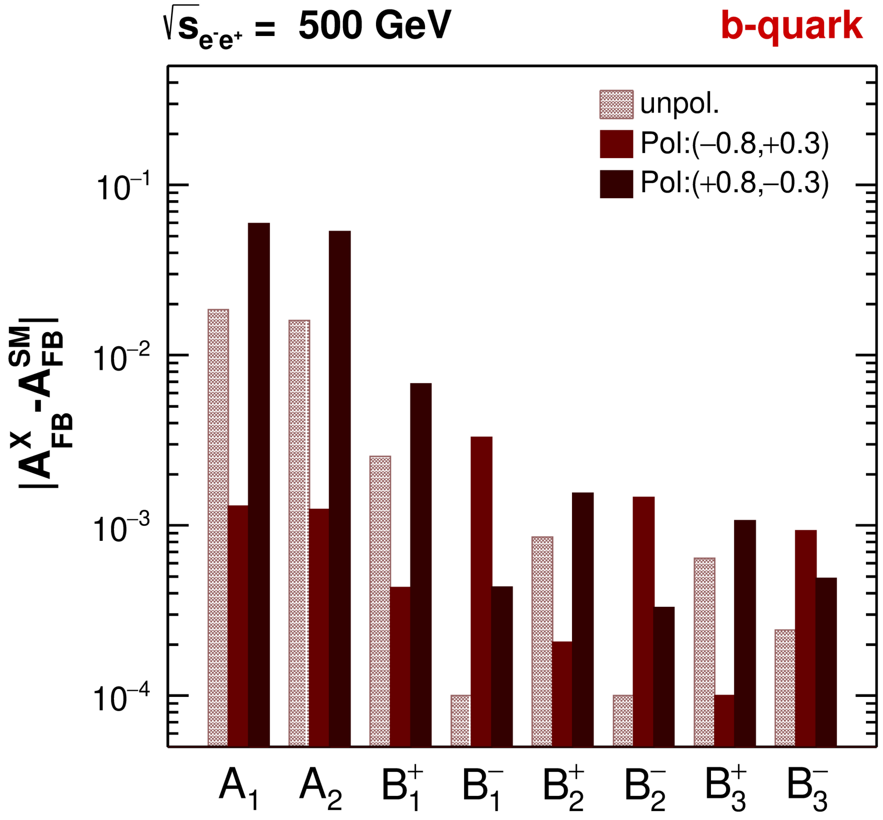
GHU vs SM (250 GeV)

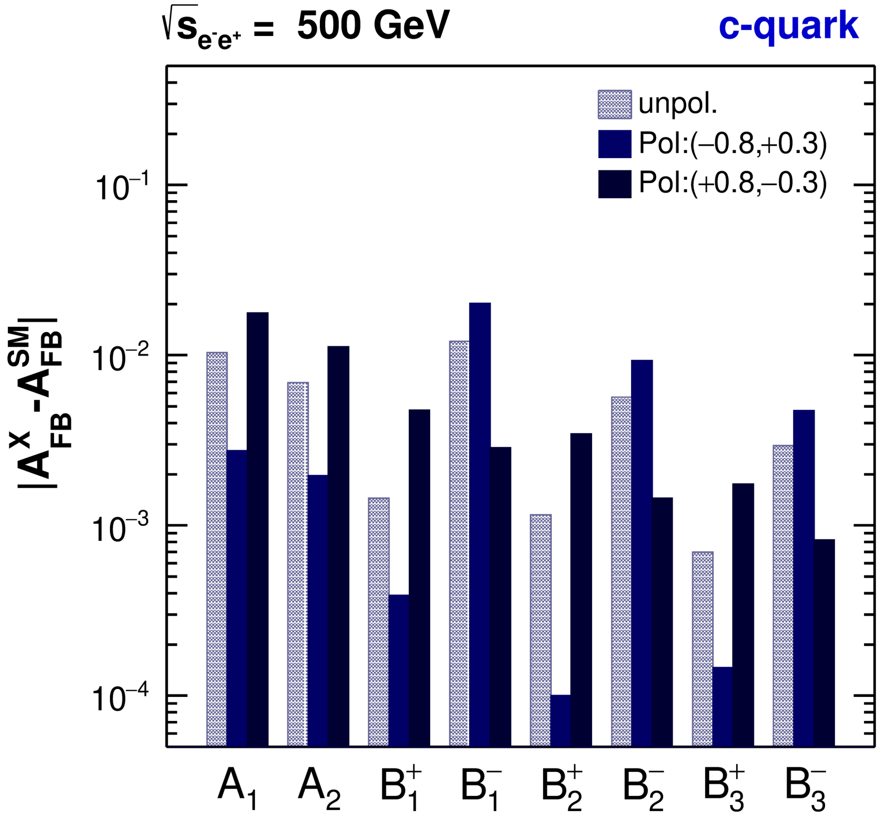




$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

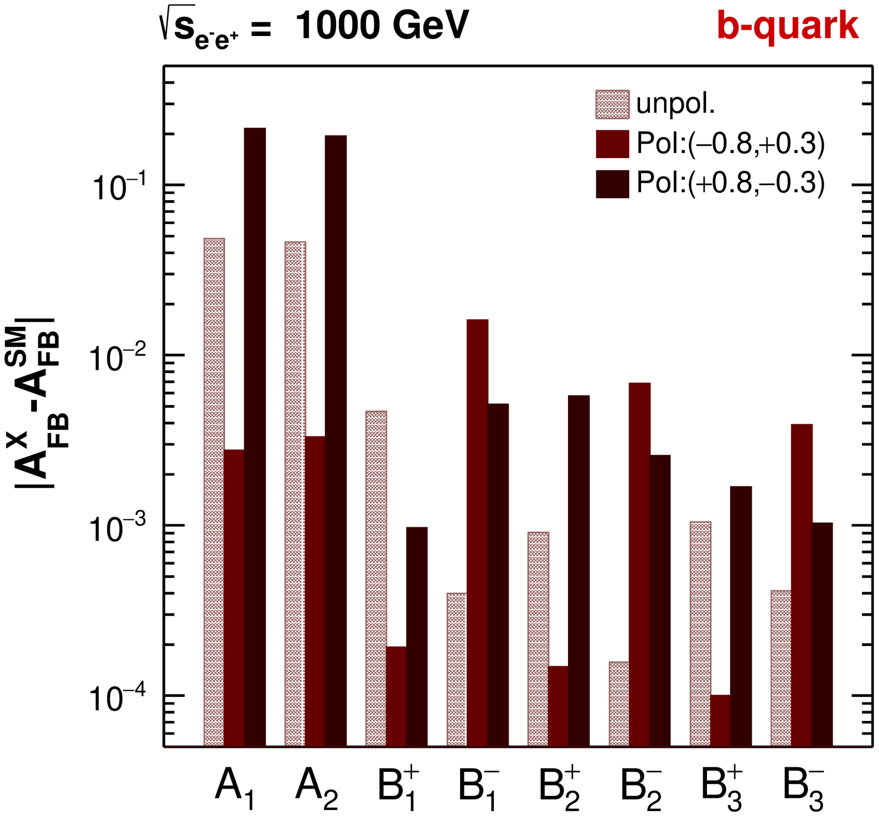
GHU vs SM (500 GeV)

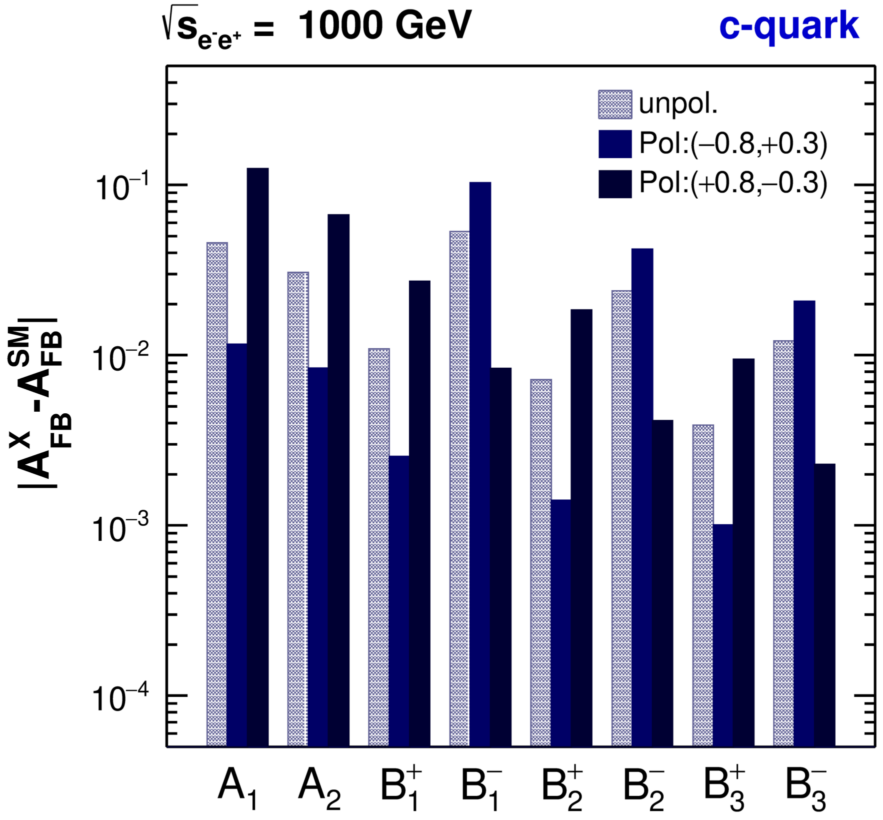




$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

GHU vs SM (1 TeV)





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

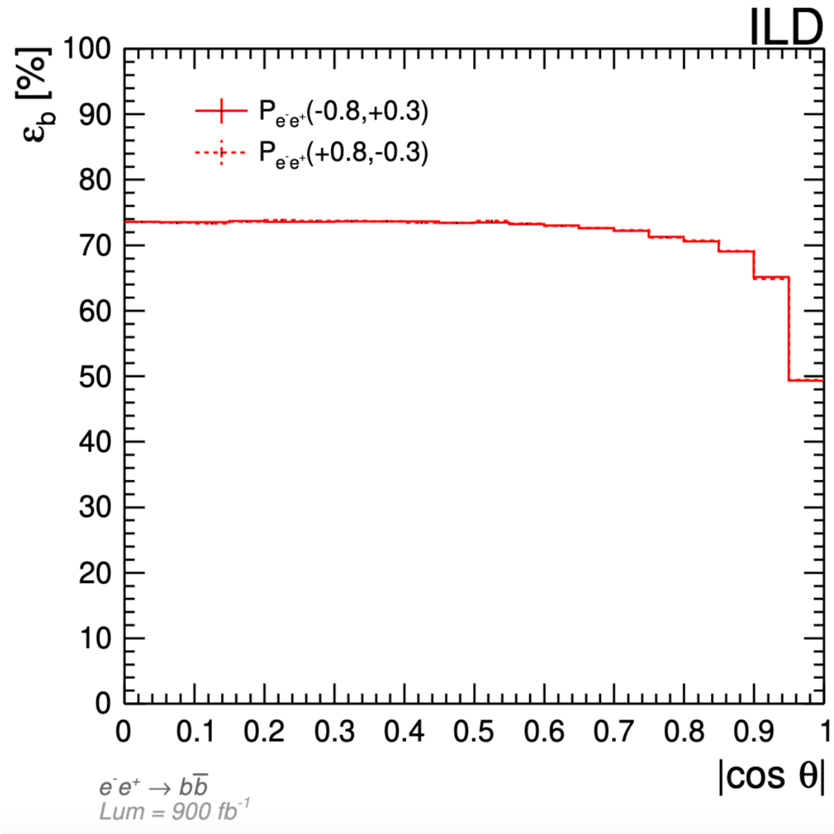
Experimental study with full simulation

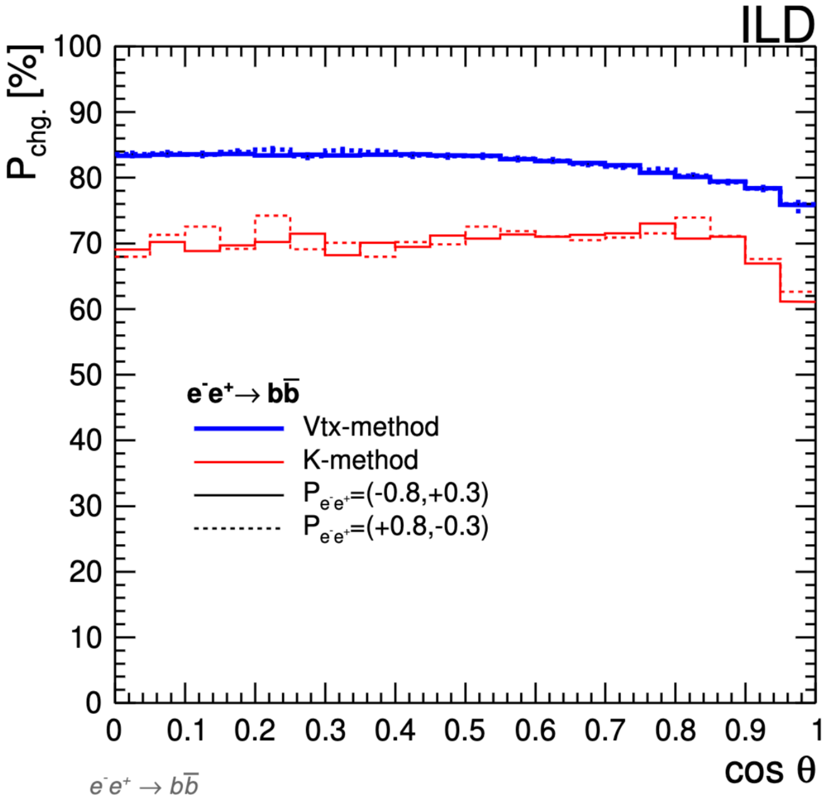
Study based on full simulation analysis

- ILD note and previous works https://inspirehep.net/literature/2669897
    - ILC250, b and c studies. (A. Irles, F. Richard, R. Poesch).
- Work presented in LCWS (J.P. Márquez):
    - Proceeding https://inspirehep.net/literature/2682331
    - Talk: https://indico.slac.stanford.edu/event/7467/contributions/5977/attachments/2862/8042/LCWS2023_JPMH.pdf
    - ILC250+ILC500 comparing scenarios with different PID (no PID, dEdx, dNdx).
        - Experimental cut-based analysis using “traditional” BDT algorithms for flavour tagging.
- Work presented in EPS-HEP (J.P. Márquez)
    - Proceeding: https://inspirehep.net/literature/2714494
    - Talk: https://indico.desy.de/event/34916/contributions/147224/
    - First theory prospects.
- Update presented at ECFA in Paestum (A. Irles).
    - Final theory prospects.
- Paper already being reviewed by ILD Editorial Board

Jet flavour tagging & charge measurement

- Double tagging & charge measurement methods
  - To maximally reduce the usage of MC tools (control of fragmentation, QCD correlations… uncertainties)

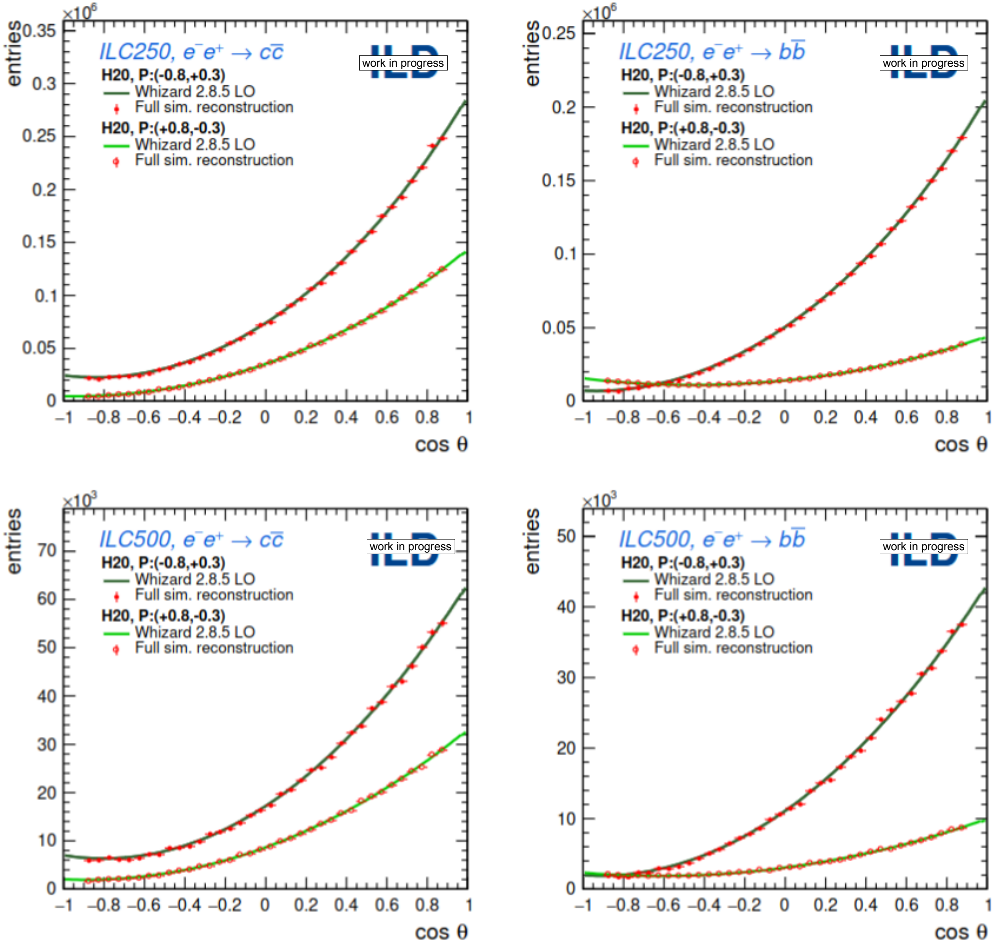




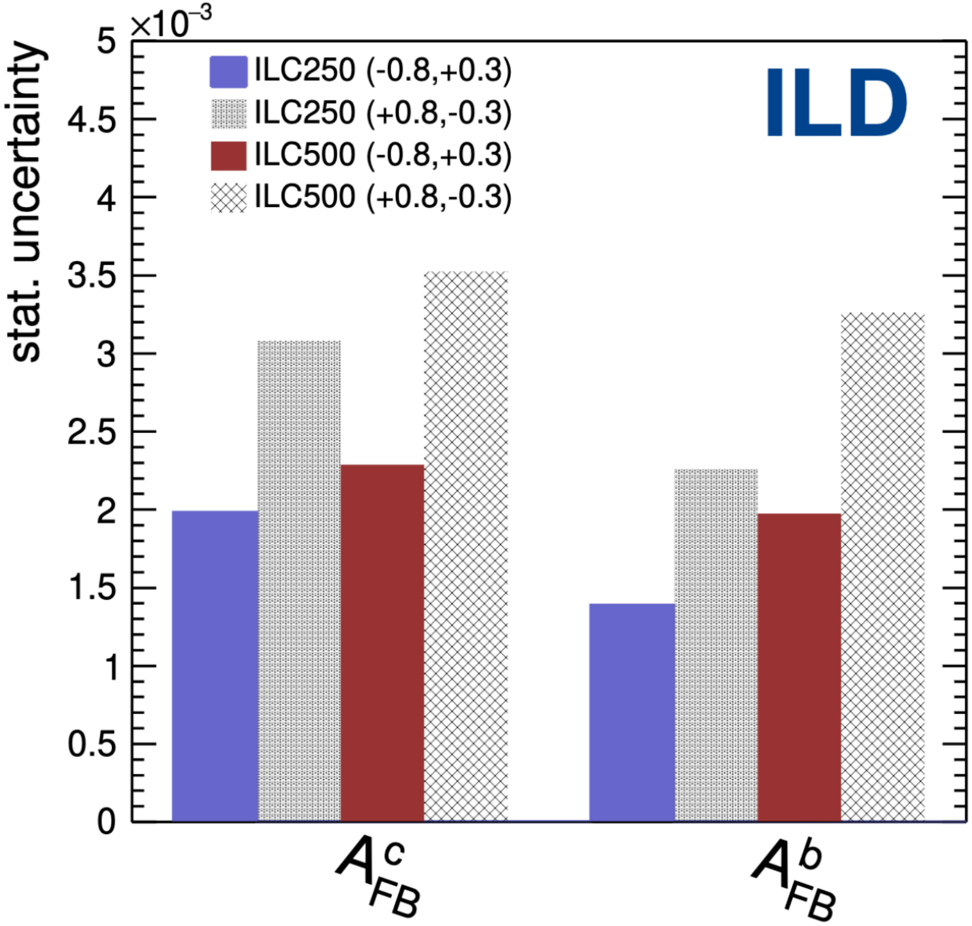
Result and fit

- **At least 4 observables for AFB 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**
  - Fragmentation, angular correlations, preselection efficiency...



Result ILC250 & ILC500



J. P. Márquez | ILD Meeting 17/01/2024

Discrimination power between GHU & SM

GHU vs SM: discrimination power

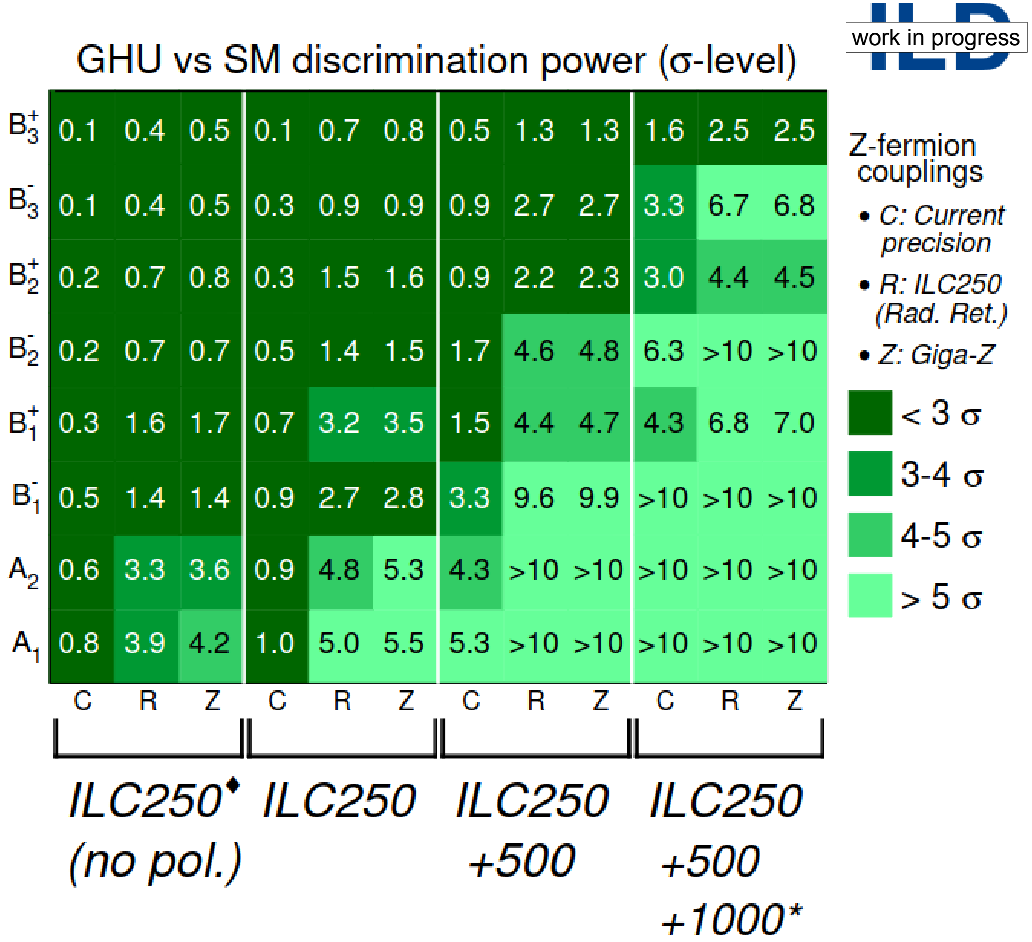
- Assumption: A measurement of one specific model is conducted.

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

$$d_\sigma = \frac{||\mathrm{AFB}_{\mathrm{test}} - \mathrm{AFB}_{\mathrm{ref}}||}{\Delta_{\mathrm{AFB}_{\mathrm{ref}}}}$$

- Combination of multiple measurements is done with a *multivariate gaussian*.
  - Assuming no correlations for AFB.

GHU vs SM: discrimination power plots



work in progress

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*

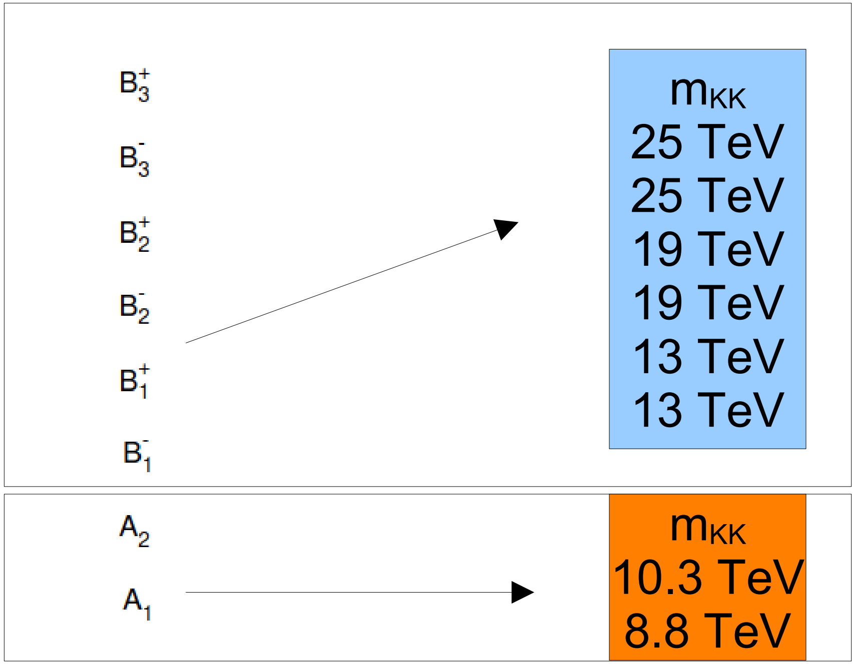
🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

GHU vs SM: 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

GHU vs SM: Beam scenarios

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

Full ILD simulation
assuming
no beam pol.

H20 nominal program

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

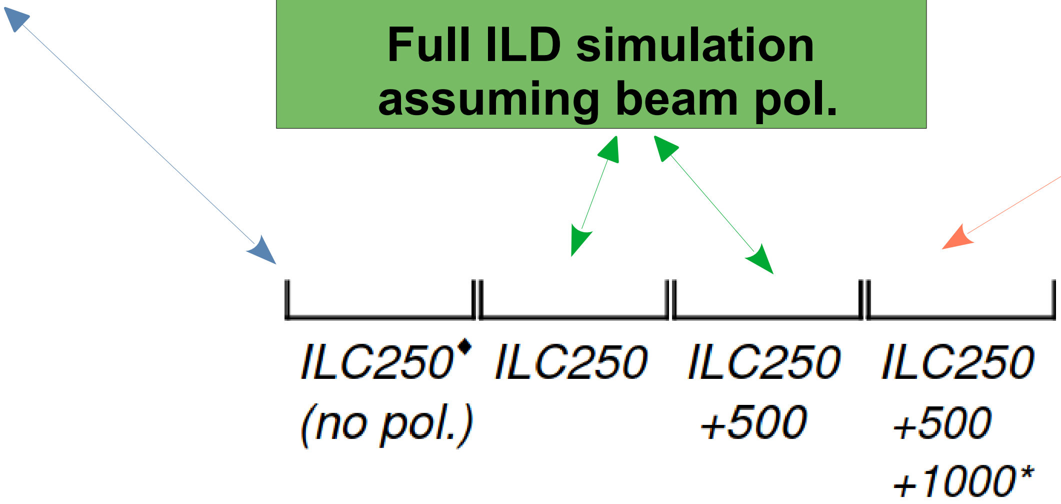
ILC500
(Pe-=0.8, Pe+=0.3)
$\int L = 4000$ fb^{-1}

Full ILD simulation
assuming beam pol.

H20 nominal program

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

Not full simulation studies
but extrapolations from ILC500



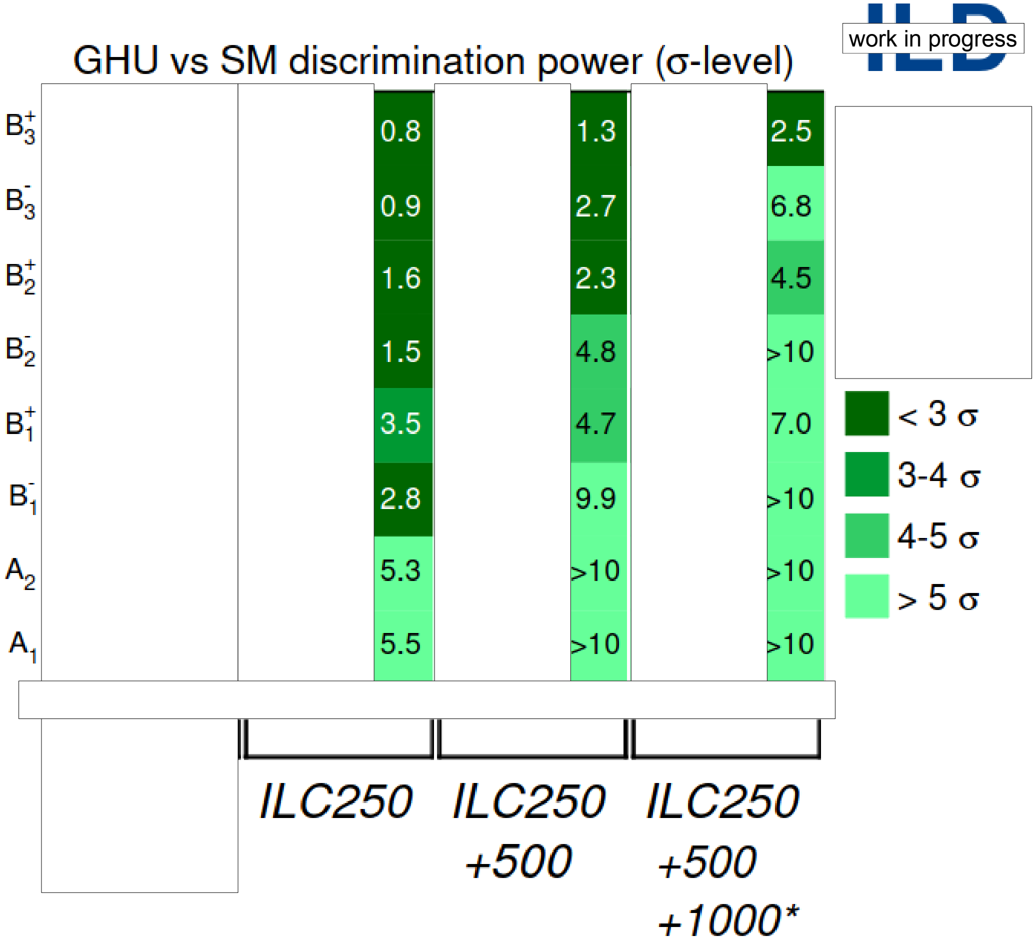
ILC250$^{\blacklozenge}$
(no pol.)

ILC250

ILC250
+500

ILC250
+500
*+1000**

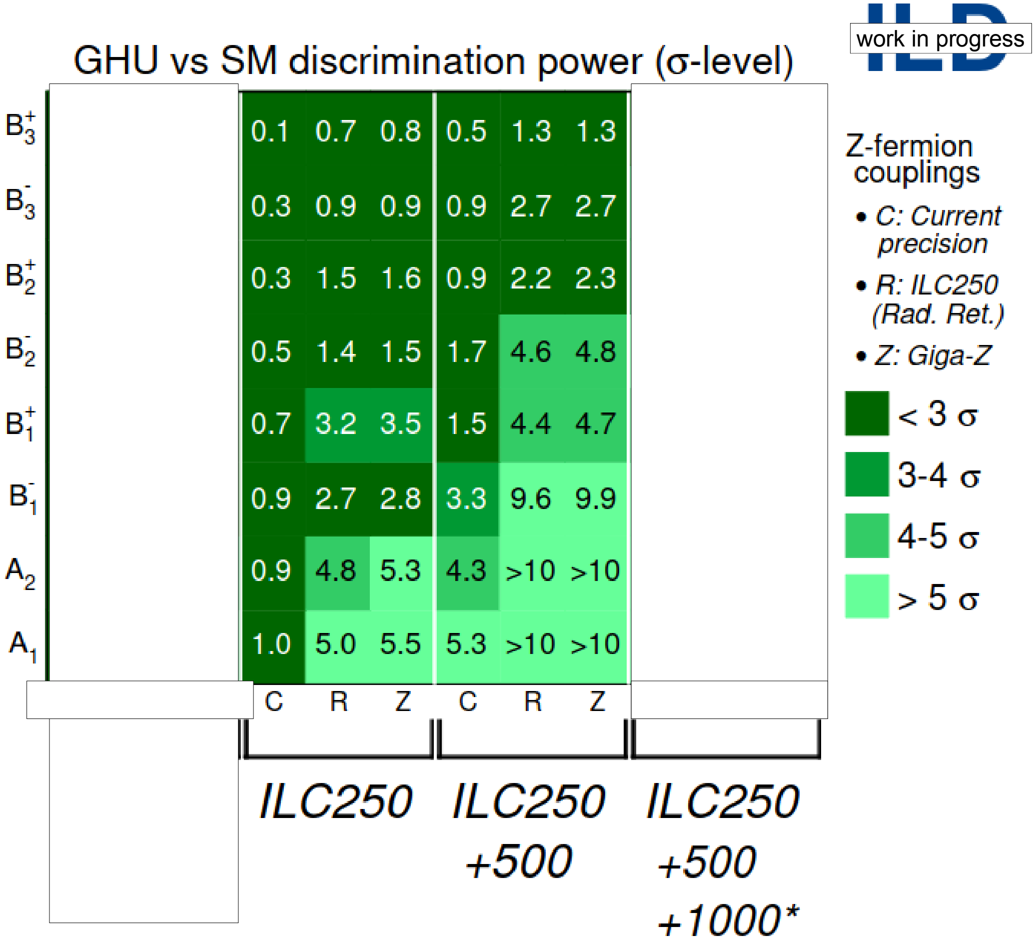
GHU vs SM: c. m. e.



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

GHU vs SM: Precision on Z-couplings



work in progress

GHU vs SM discrimination power (σ-level)

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

Z-fermion couplings

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

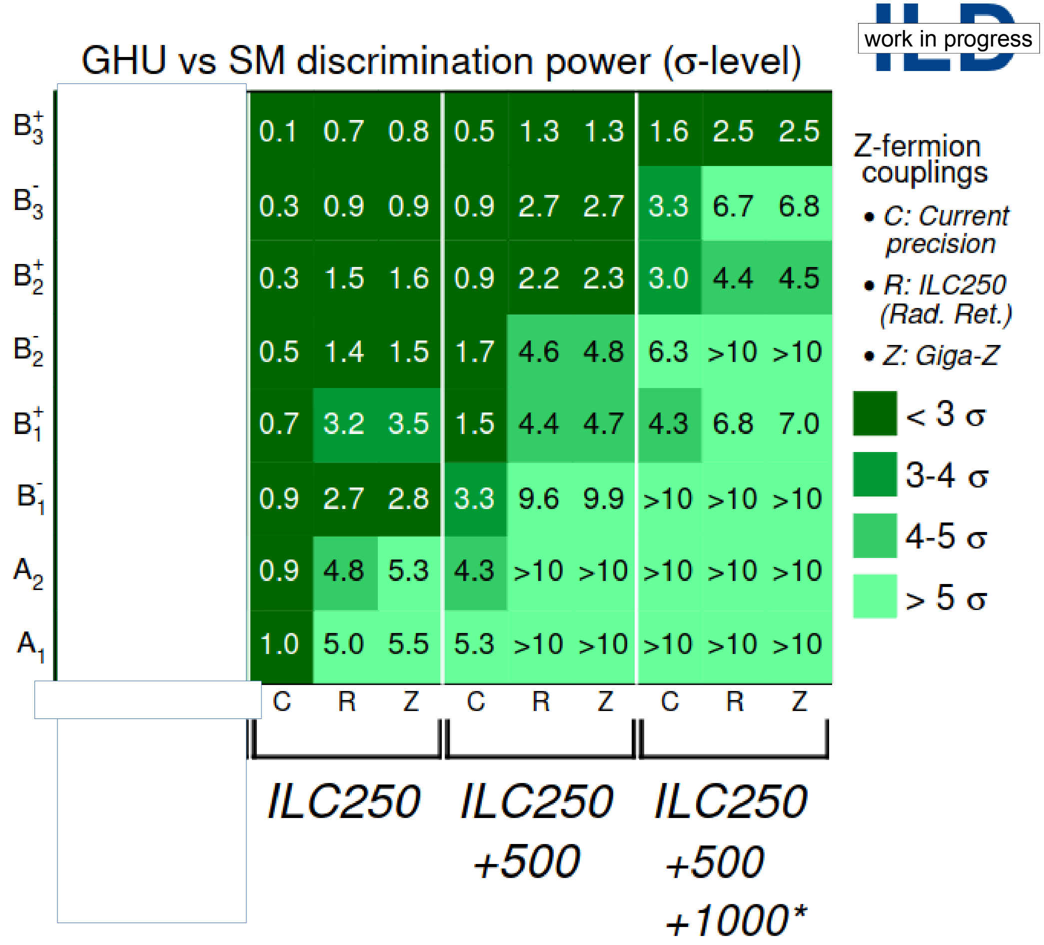
🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

GHU vs SM: Precision on Z-couplings



GHU vs SM discrimination power (σ-level)

	C	R	Z	C	R	Z	C	R	Z
	ILC250			ILC250 +500			ILC250 +500 +1000*		
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*

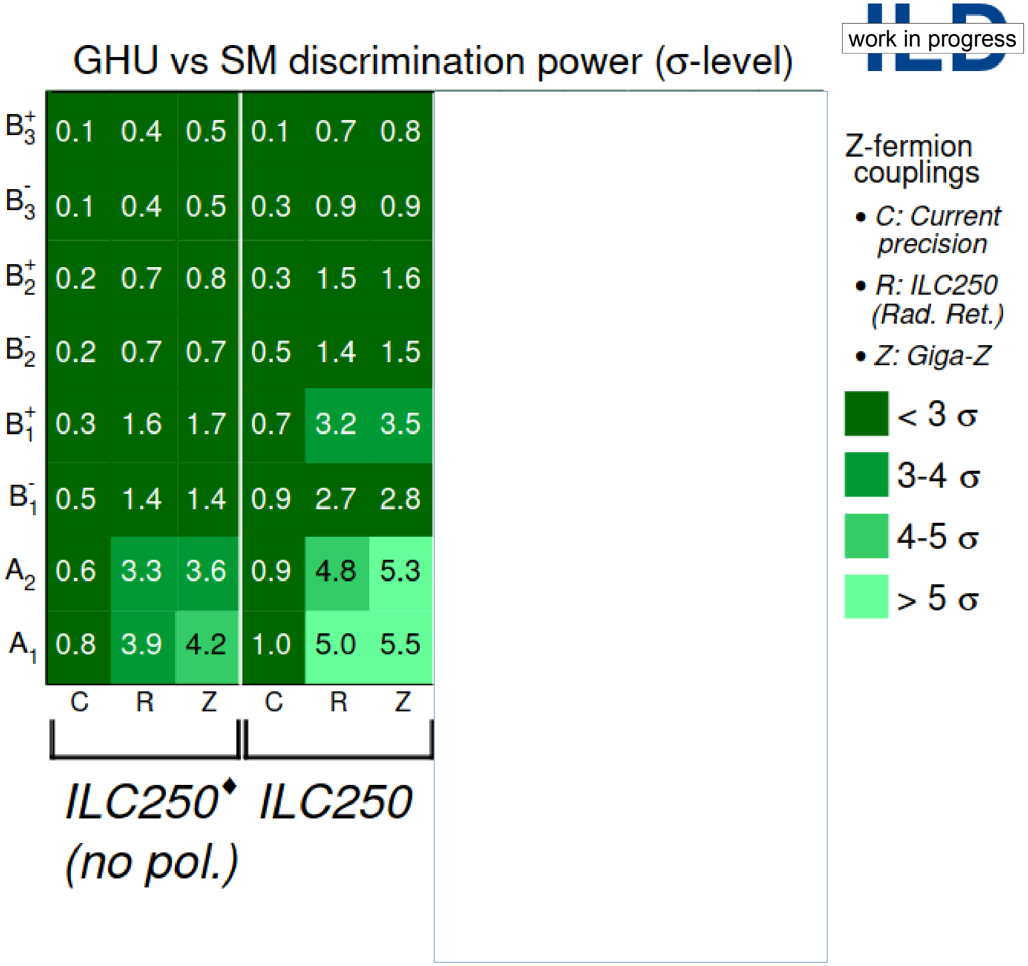
< 3 σ

3-4 σ

4-5 σ

> 5 σ

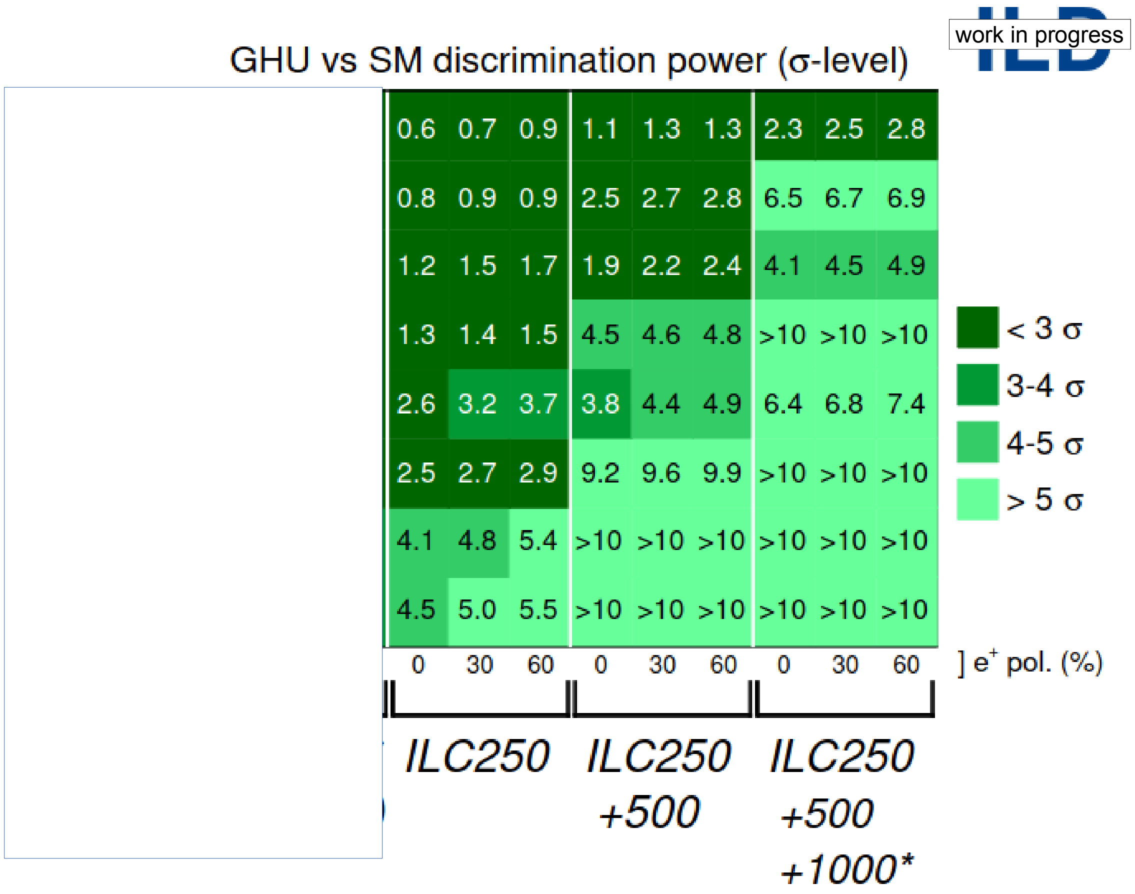
GHU vs SM: Beam(s) polarization



GHU vs SM discrimination power (σ-level)

	ILC250$^{\blacklozenge}$ (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

GHU vs SM: Positron beam polarization

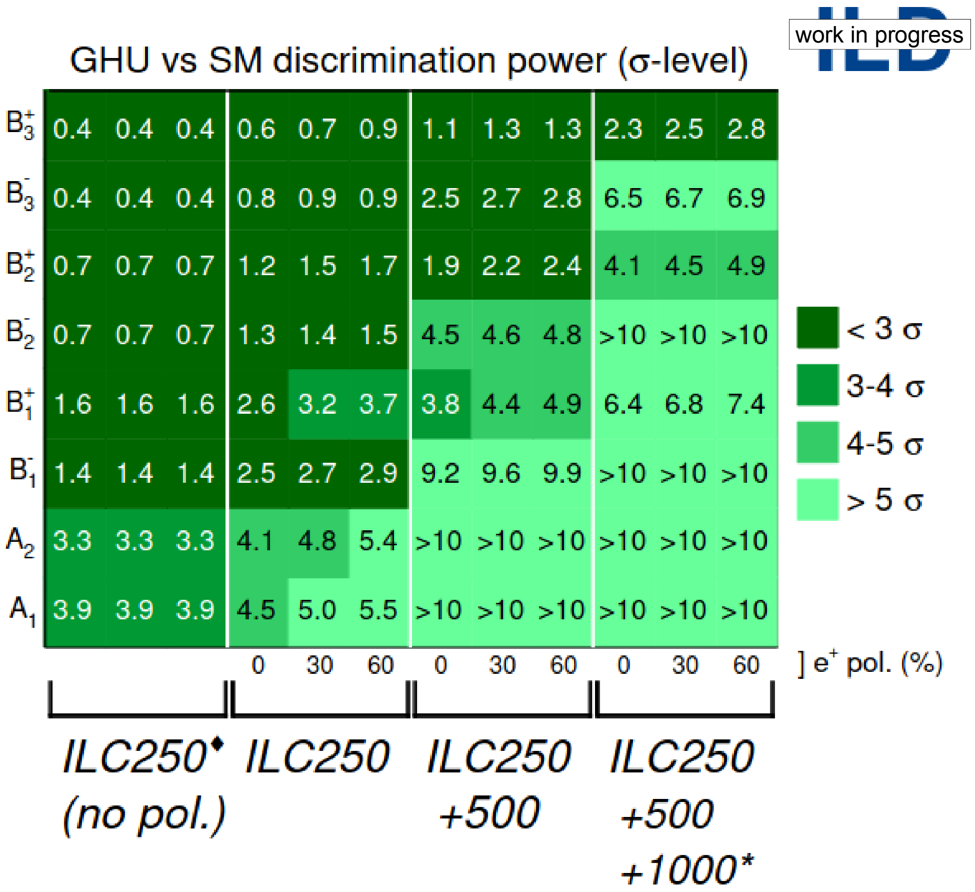


GHU vs SM discrimination power (σ-level)

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

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

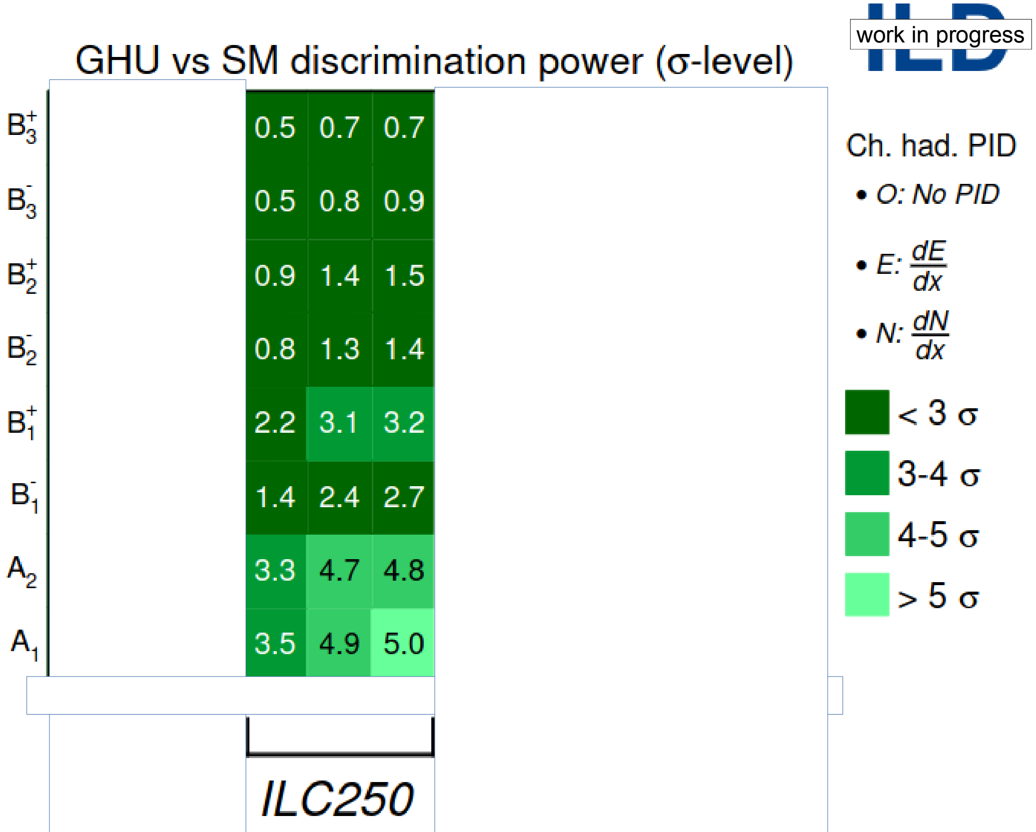
GHU vs SM: Positron beam polarization



GHU vs SM discrimination power (σ-level)

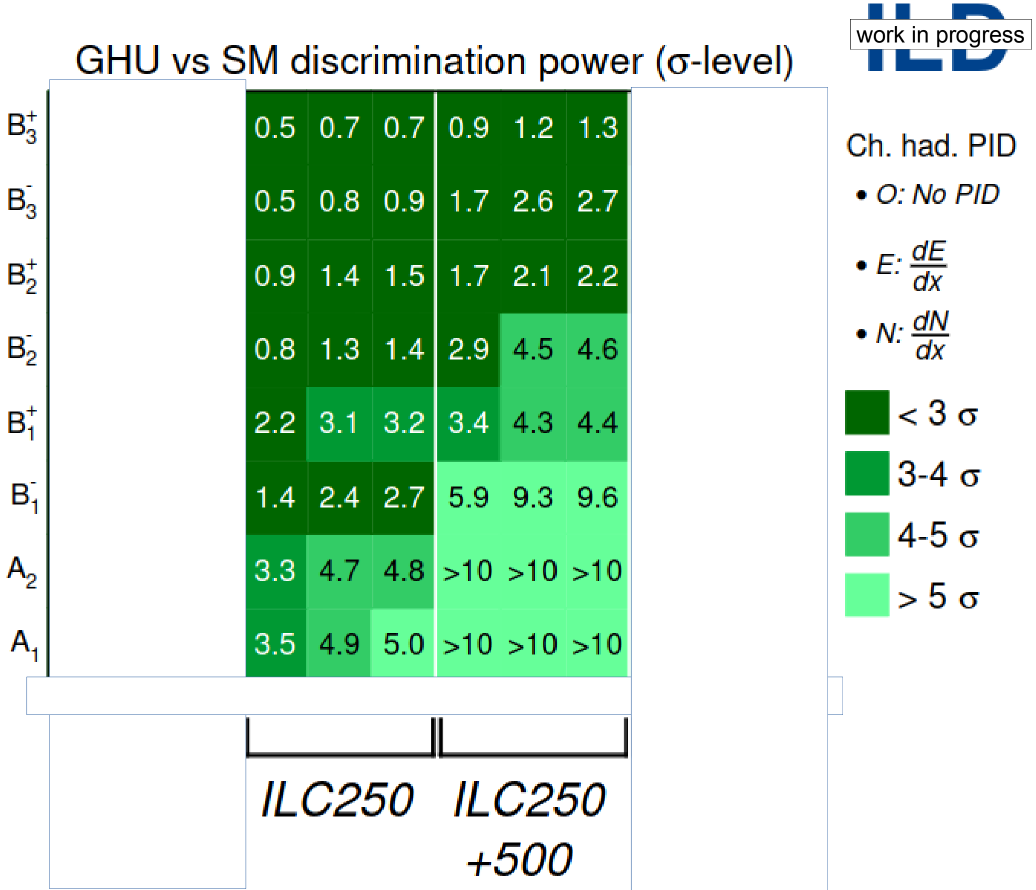
	ILC250◆ (no pol.)			ILC250			ILC250 +500			ILC250 +500 +1000*		
] e^+ pol. (%)				0	30	60	0	30	60	0	30	60
B_3^+	0.4	0.4	0.4	0.6	0.7	0.9	1.1	1.3	1.3	2.3	2.5	2.8
B_3^-	0.4	0.4	0.4	0.8	0.9	0.9	2.5	2.7	2.8	6.5	6.7	6.9
B_2^+	0.7	0.7	0.7	1.2	1.5	1.7	1.9	2.2	2.4	4.1	4.5	4.9
B_2^-	0.7	0.7	0.7	1.3	1.4	1.5	4.5	4.6	4.8	>10	>10	>10
B_1^+	1.6	1.6	1.6	2.6	3.2	3.7	3.8	4.4	4.9	6.4	6.8	7.4
B_1^-	1.4	1.4	1.4	2.5	2.7	2.9	9.2	9.6	9.9	>10	>10	>10
A_2	3.3	3.3	3.3	4.1	4.8	5.4	>10	>10	>10	>10	>10	>10
A_1	3.9	3.9	3.9	4.5	5.0	5.5	>10	>10	>10	>10	>10	>10

GHU vs SM: Particle ID dependence



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

GHU vs SM: Particle ID dependence



GHU vs SM discrimination power (σ-level)

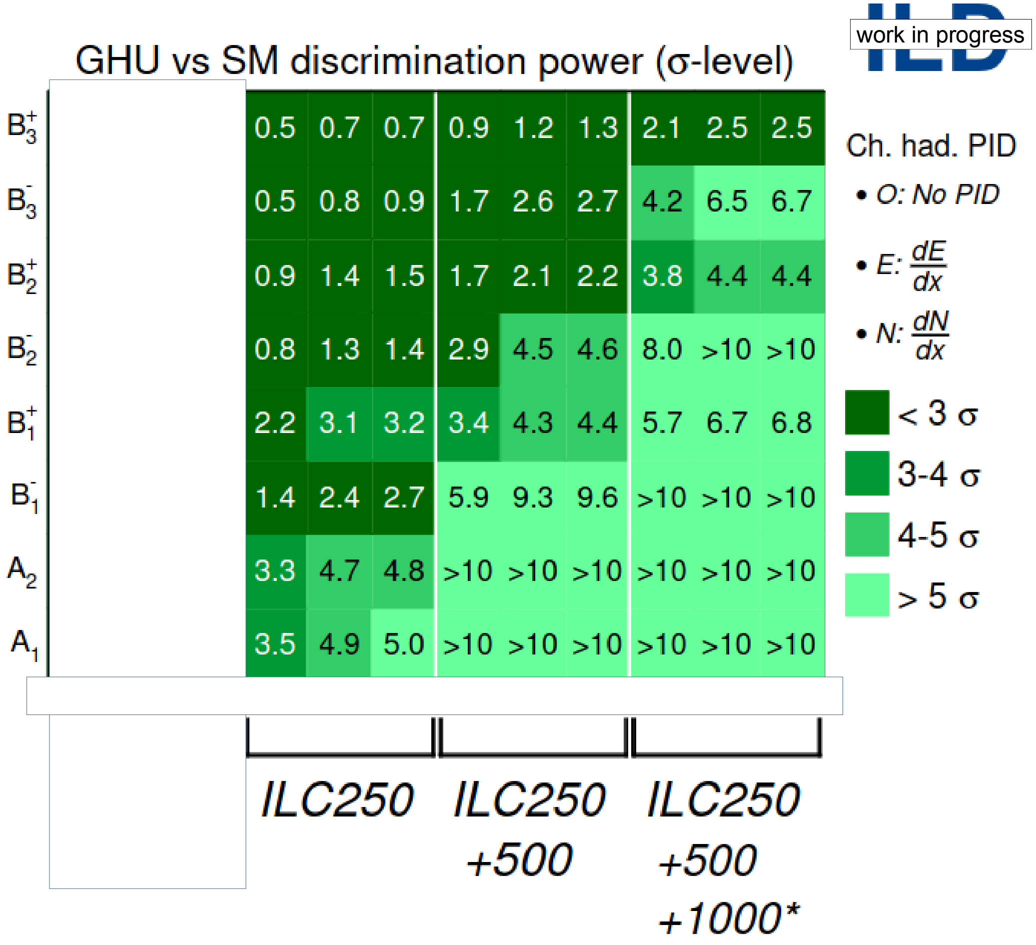
	ILC250			ILC250 +500		
B_3^+	0.5	0.7	0.7	0.9	1.2	1.3
B_3^-	0.5	0.8	0.9	1.7	2.6	2.7
B_2^+	0.9	1.4	1.5	1.7	2.1	2.2
B_2^-	0.8	1.3	1.4	2.9	4.5	4.6
B_1^+	2.2	3.1	3.2	3.4	4.3	4.4
B_1^-	1.4	2.4	2.7	5.9	9.3	9.6
A_2	3.3	4.7	4.8	>10	>10	>10
A_1	3.5	4.9	5.0	>10	>10	>10

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



work in progress

GHU vs SM discrimination power (σ-level)

	ILC250			ILC250 +500			ILC250 +500 +1000*		
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: $\frac{dN}{dx}$*

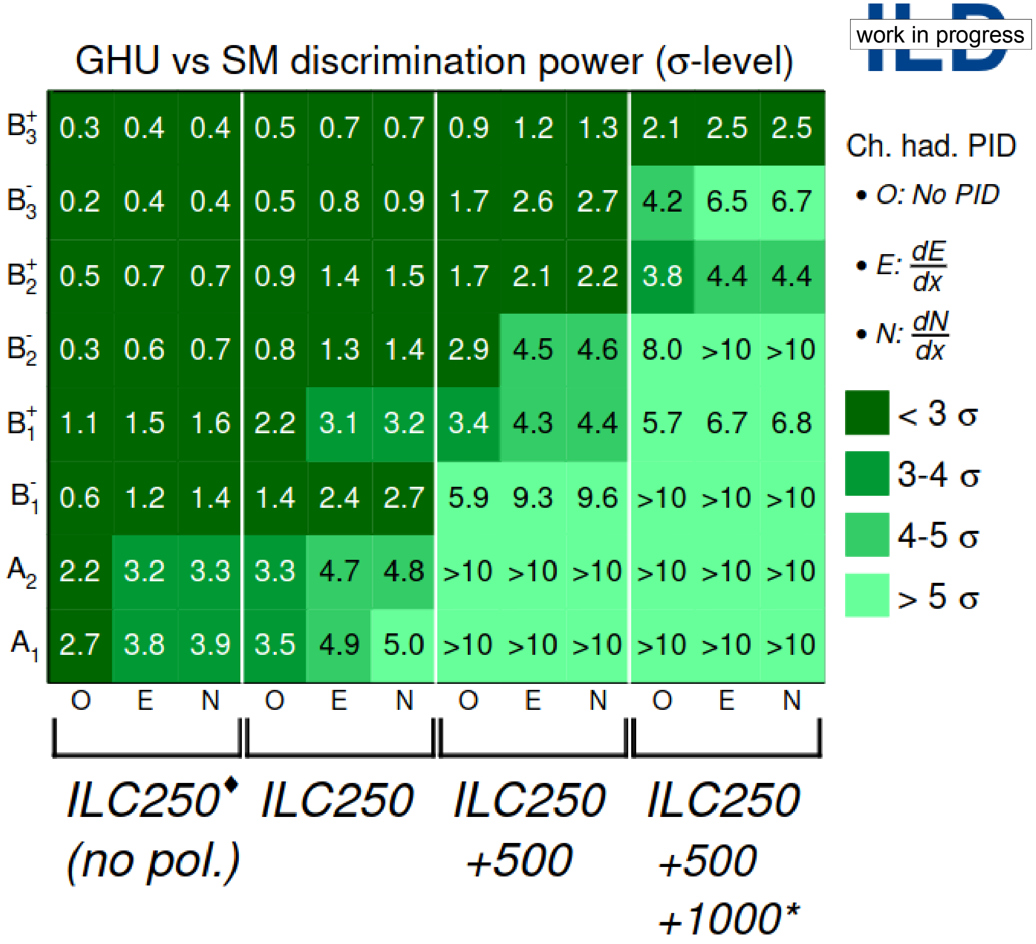
🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

GHU vs SM: Particle ID dependence



GHU vs SM discrimination power (σ-level)

work in progress

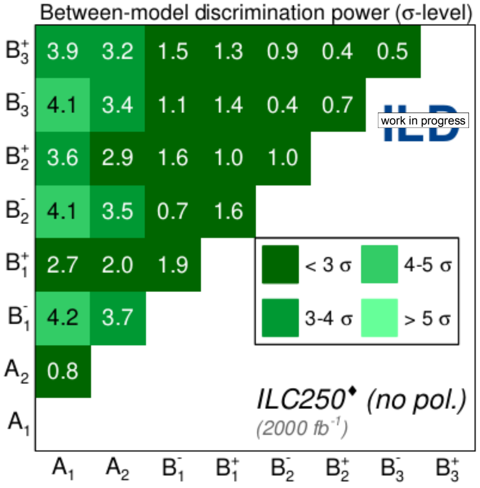
	ILC250◆ (no pol.)			ILC250			ILC250 +500			ILC250 +500 +1000*		
	O	E	N	O	E	N	O	E	N	O	E	N
B_3^+	0.3	0.4	0.4	0.5	0.7	0.7	0.9	1.2	1.3	2.1	2.5	2.5
B_3^-	0.2	0.4	0.4	0.5	0.8	0.9	1.7	2.6	2.7	4.2	6.5	6.7
B_2^+	0.5	0.7	0.7	0.9	1.4	1.5	1.7	2.1	2.2	3.8	4.4	4.4
B_2^-	0.3	0.6	0.7	0.8	1.3	1.4	2.9	4.5	4.6	8.0	>10	>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:* $\frac{dN}{dx}$

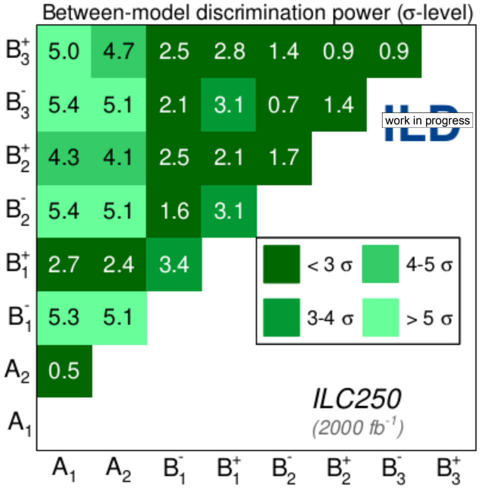
🟩 < 3 σ
🟩 3-4 σ
🟩 4-5 σ
🟩 > 5 σ

GHU between model discrimination


Between-model discrimination power (σ-level)

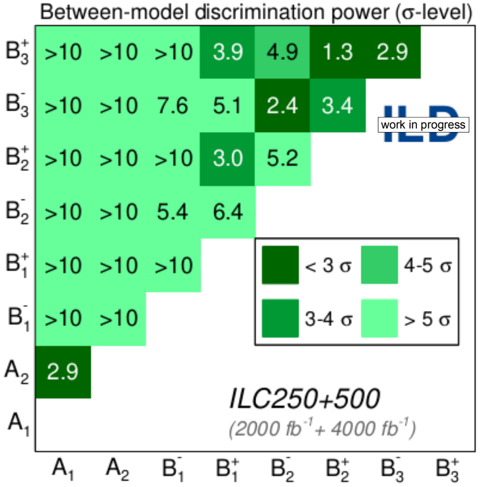
ILC250$^\blacklozenge$ (no pol.)
(2000 fb^{-1})

	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)

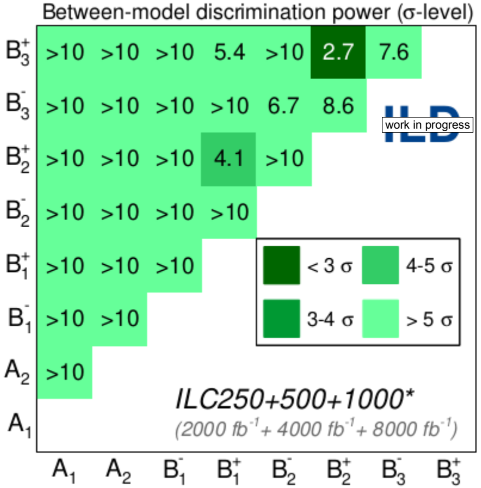
ILC250
(2000 fb^{-1})

	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								

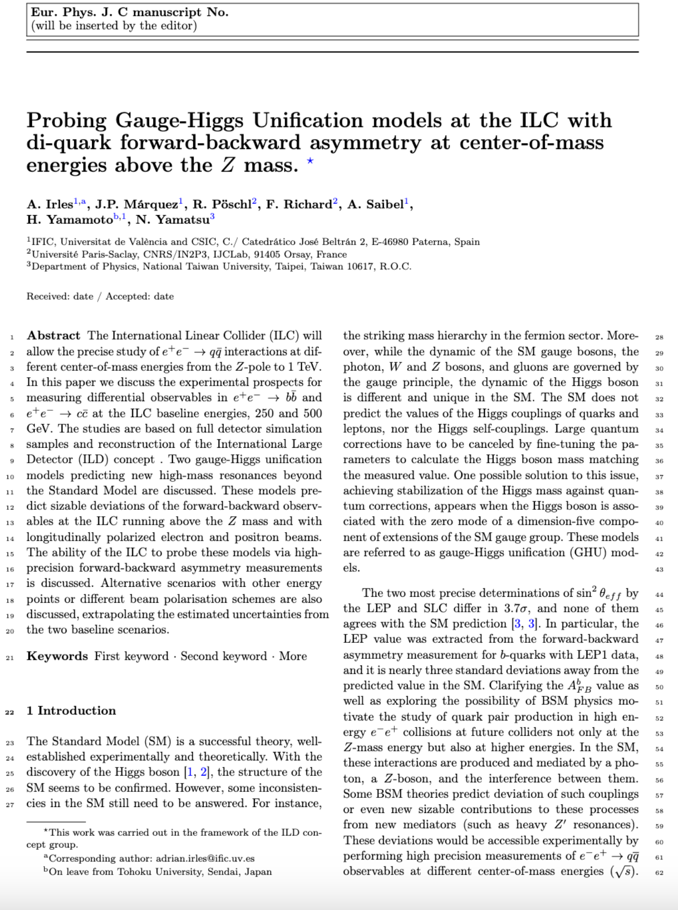
Conclusion/ summary

Conclusions and summary

- 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).
- AFB studies for c and b-quark above the Z-pole.
  - Flavour tagging and jet charge determination with kaon ID are key.
- 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 for measurements with different BSM sensitivity (for control of systematics)
- (ILD) PID capabilities (kaon)

Paper being prepared

- A paper is being prepared exploring
  - First draft for EPJ-C.
- ILD editorial board:
  - Review by Mikael Berggren and Daniel Jeans.
  - Already finished a first iteration of corrections.
- It’s going to be finished really soon!



Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

Probing Gauge-Higgs Unification models at the ILC with di-quark forward-backward asymmetry at center-of-mass energies above the Z mass. [*]

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Received: date / Accepted: date

Abstract The International Linear Collider (ILC) will allow the precise study of $e^+e^- \to q\bar{q}$ 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 $e^+e^- \to b\bar{b}$ and $e^+e^- \to c\bar{c}$ at the ILC baseline energies, 250 and 500 GeV. The studies are based on full detector simulation samples 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 forward-backward asymmetry measurements is discussed. Alternative scenarios with other energy points or different beam polarisation schemes are also discussed, extrapolating the estimated uncertainties from the two baseline scenarios.

Keywords First keyword · Second keyword · More

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, some inconsistencies in the SM still need to be answered. For instance, the striking mass hierarchy in the fermion sector. Moreover, while the dynamic of the SM gauge bosons, the photon, W and Z bosons, and gluons are governed by the gauge principle, the dynamic of the Higgs boson is different and unique in the SM. The SM does not predict the values of the Higgs couplings of quarks and leptons, nor the Higgs self-couplings. Large quantum corrections have to be canceled by fine-tuning the parameters to calculate the Higgs boson mass matching the measured value. One possible solution to this issue, achieving stabilization of the Higgs mass against quantum corrections, appears when the Higgs boson is associated with the zero 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 $\sin^2\theta_{eff}$ by the LEP and SLC differ in 3.7σ, and none of them agrees with the SM prediction [3, 3]. In particular, the LEP value was extracted from the forward-backward asymmetry measurement for b-quarks with LEP1 data, and it is nearly three standard deviations away from the predicted value in the SM. Clarifying the A^b_{FB} value as well as exploring the possibility of BSM physics motivate the study of quark pair production in high energy e^-e^+ collisions at future colliders not only at the Z-mass energy but also at higher energies. In the SM, these interactions are produced and mediated by a photon, a Z-boson, and the interference between them. Some BSM theories predict deviation of such couplings or even new sizable contributions to these processes from new mediators (such as heavy Z' resonances). These deviations would be accessible experimentally by performing high precision measurements of $e^-e^+ \to q\bar{q}$ observables at different center-of-mass energies ($\sqrt{s}$).

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[*] This work was carried out in the framework of the ILD concept group.

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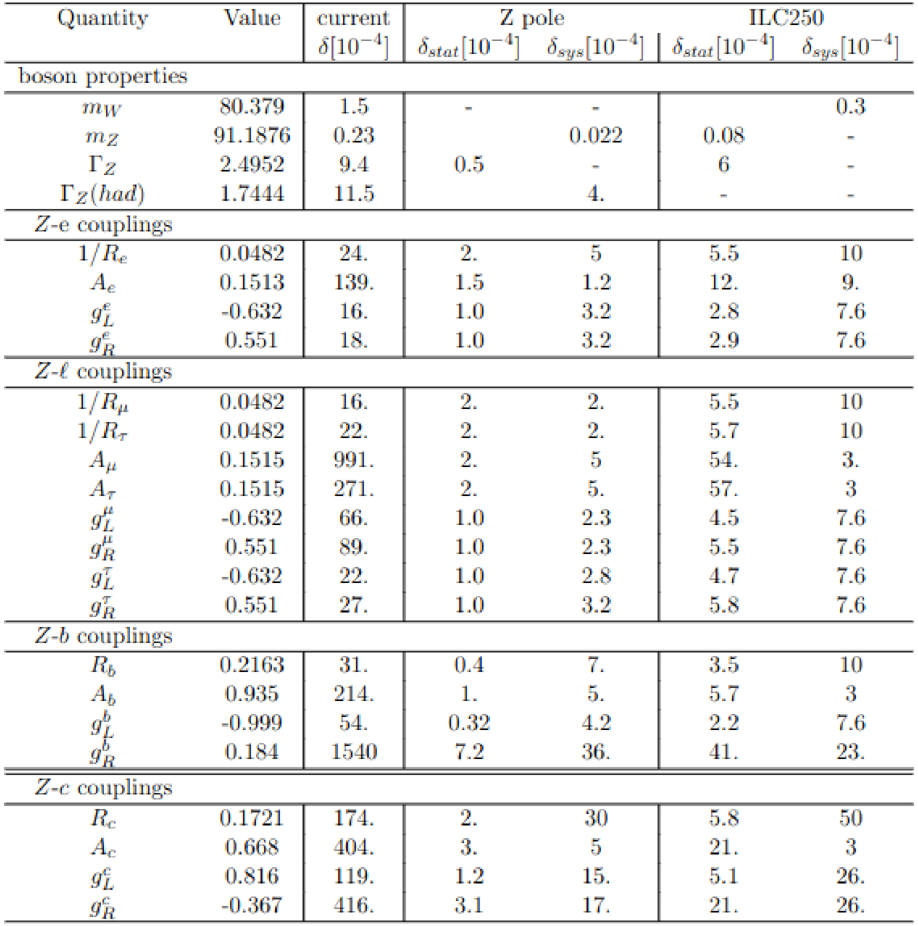
[b] On leave from Tohoku University, Sendai, Japan

Thanks for your attention!

back-up

Z-couplings

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

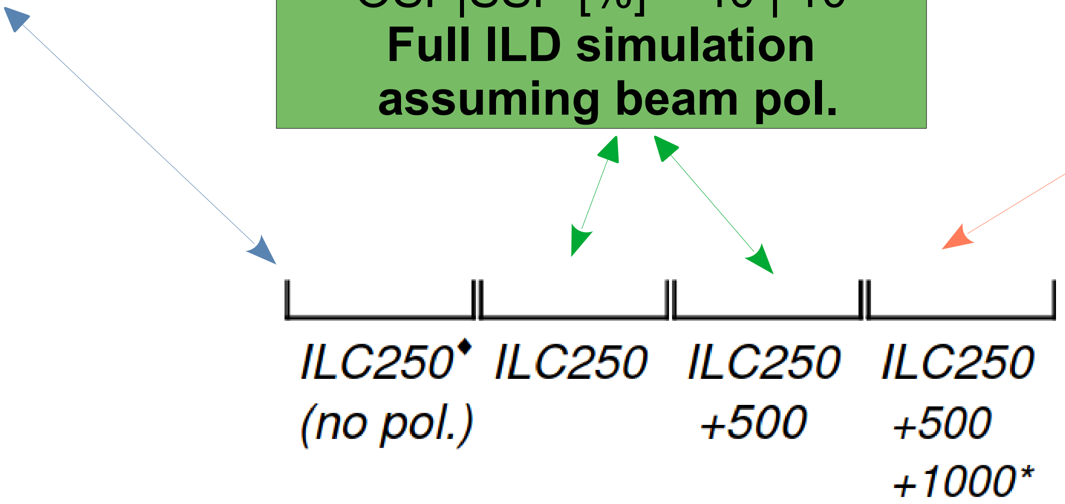
H20 nominal program

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

H20 nominal program

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

Not full simulation studies but extrapolations from ILC500



ILC250♦ (no pol.)

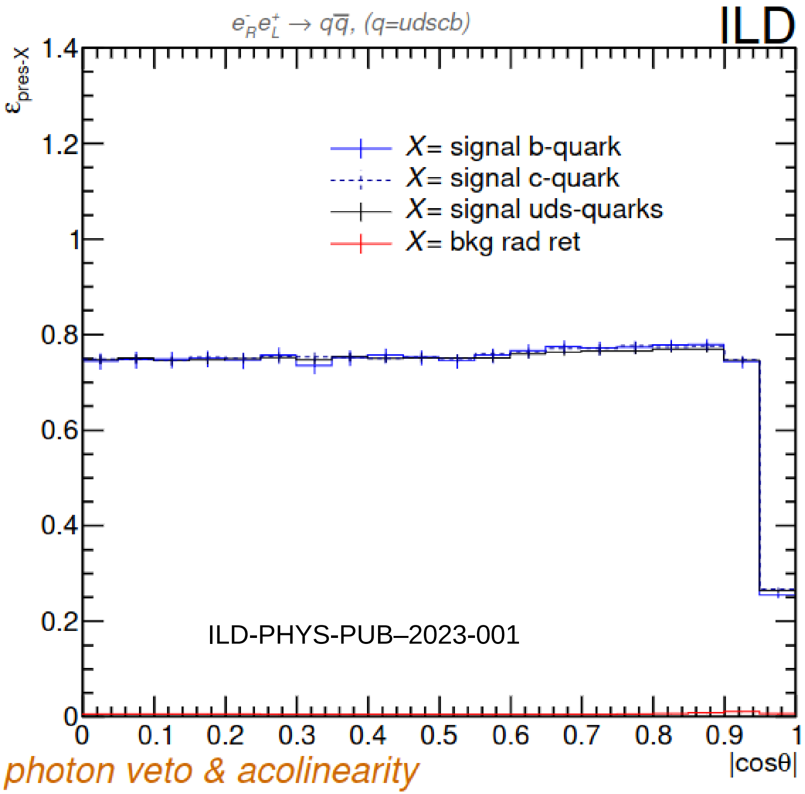
ILC250

ILC250 +500

*ILC250 +500 +1000**

Preselection

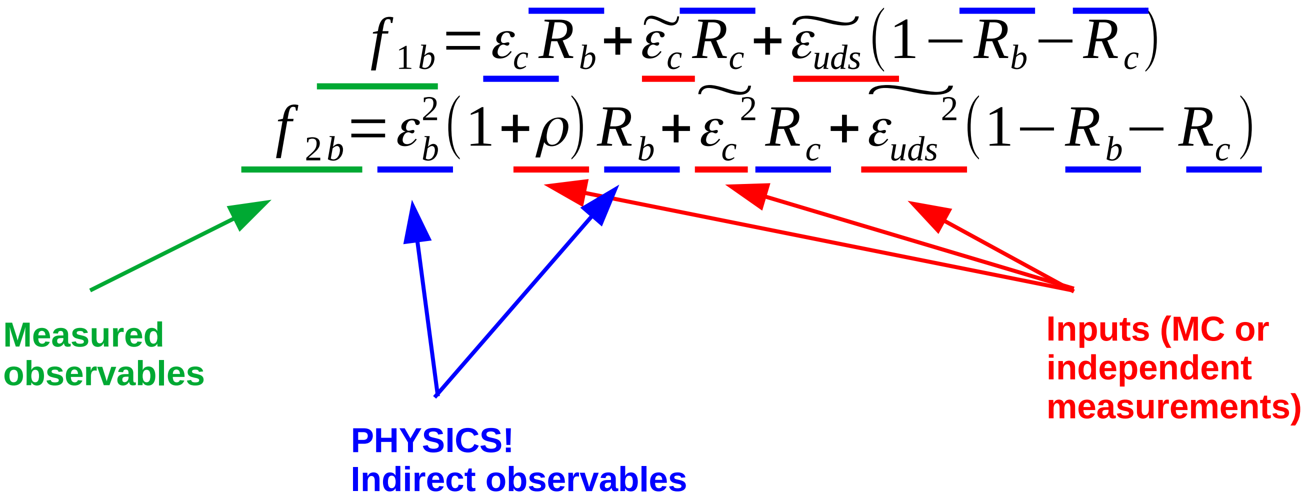
- **Topology: 2 back-to-back jets (pencil-like topology)**
- **Preselection aiming for high background rejection and high efficiency.**
- Main bkg ee→ Zγ(radiative return through ISR)
  - ~x10 larger than signal
  - **~90% of such ISR photons are lost in the beam pipe** → events filtered by energy &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

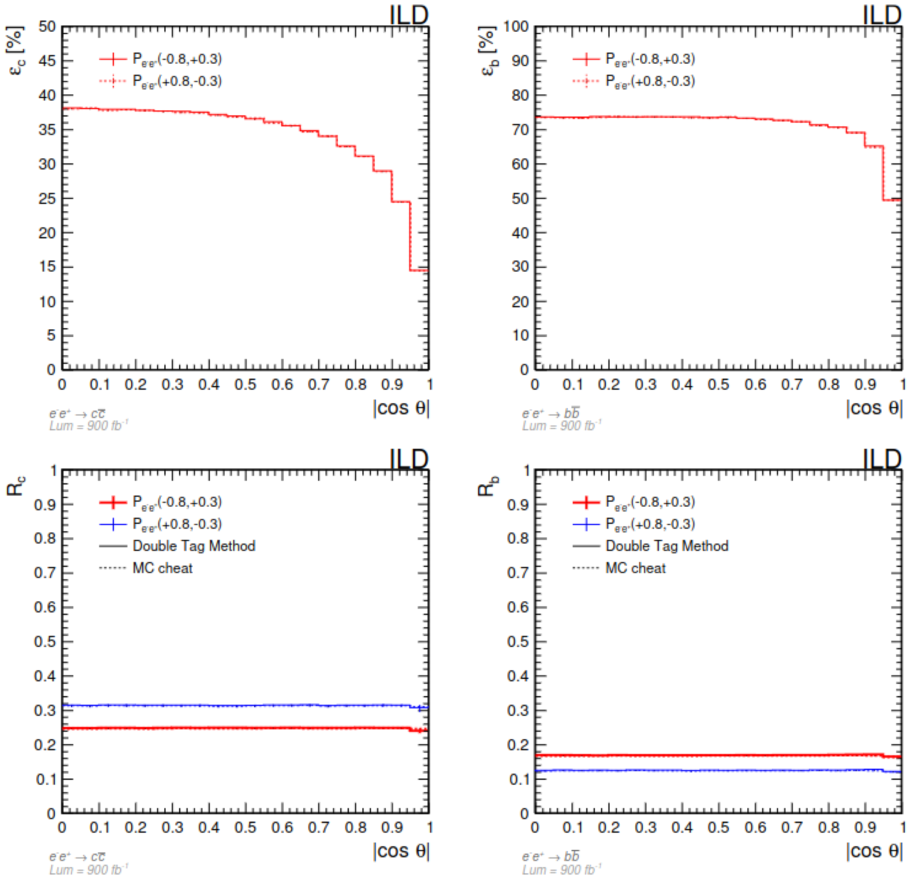
PHYSICS!
Indirect observables

Inputs (MC or independent measurements)

Similar set of equations for the c-quark
solved simultaneously

Double flavour tagging – control of systematics

- **Flavour tagging efficiency will be measured (double tagging)**
  - **Not estimated with MC**
  - **Per mil level reachable** because the contamination from lighter quarks is minimal and the tight IP constraint
- **Fully differential analysis !!**
- **Rb and Rc measured at the same time**
  - **than the tagging efficiencies**
  - No assumption needed in Ruds
- **Per mil level stat. Uncertainty**
- **Comparable/lower exp syst. uncertainty**
  - Dominated by flavour tagging and followed by angular correlations



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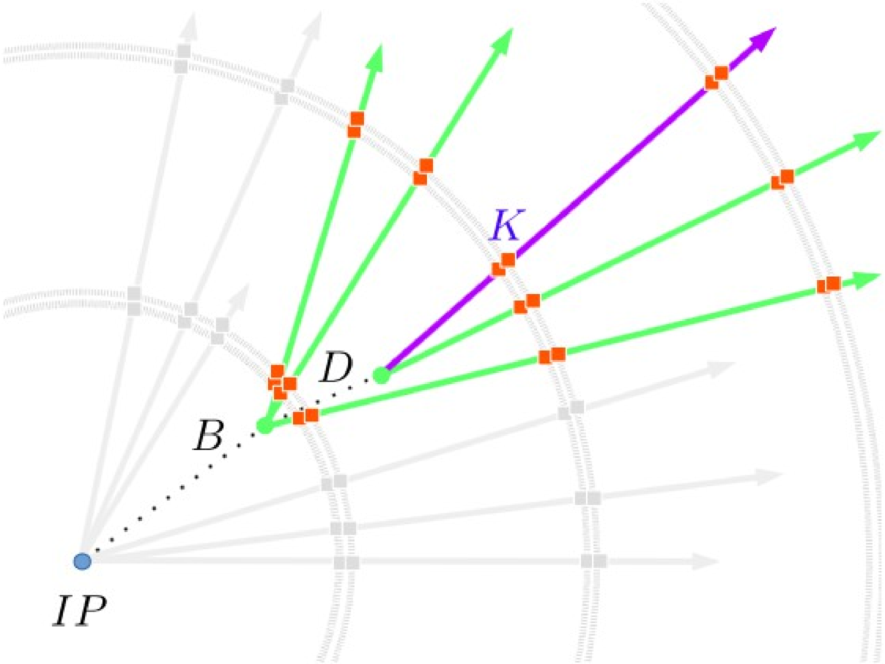
Jet charge

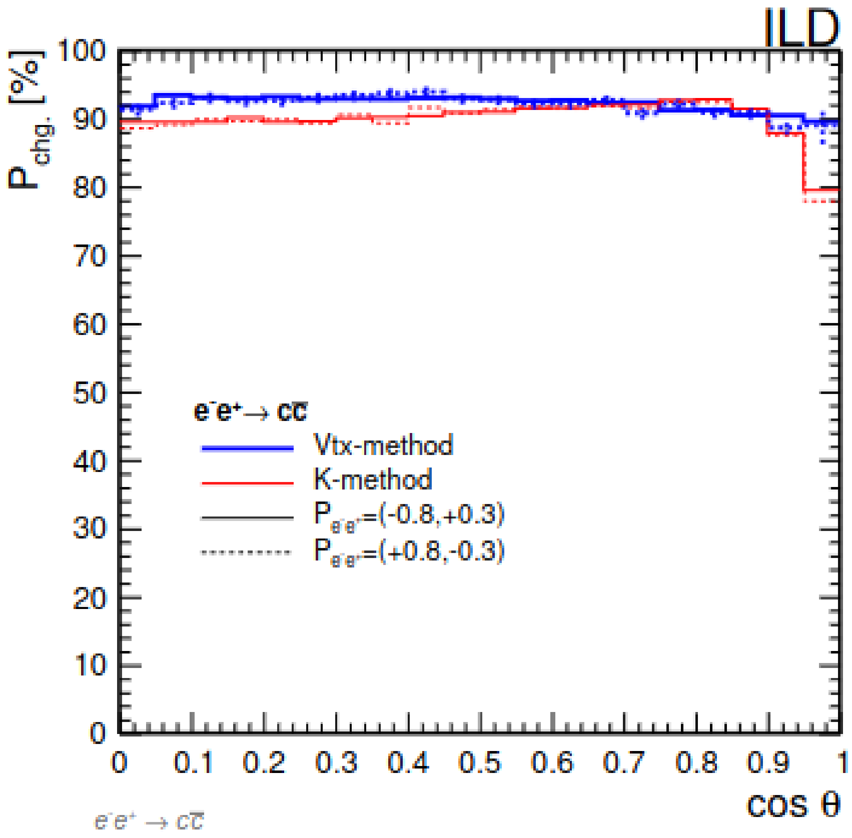
- ▶ We start from a very pure & background-free **double tagged** sample

- ▶ 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)

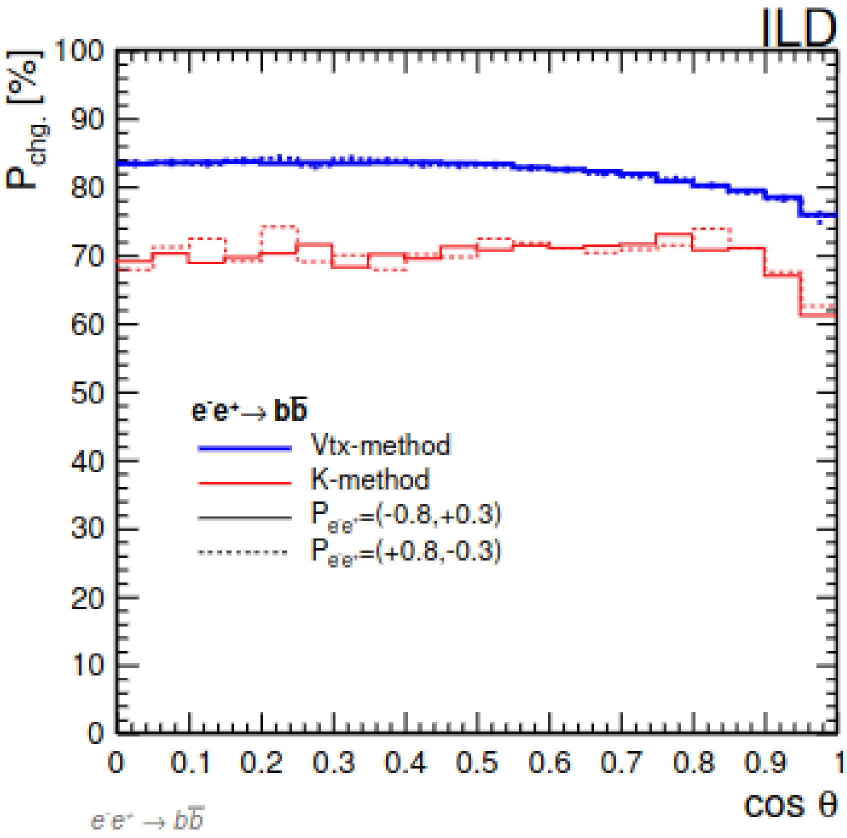
- ▶ We use the **double charge** measurements
  - To control / reduce the systematic uncertainties



Jet charge



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



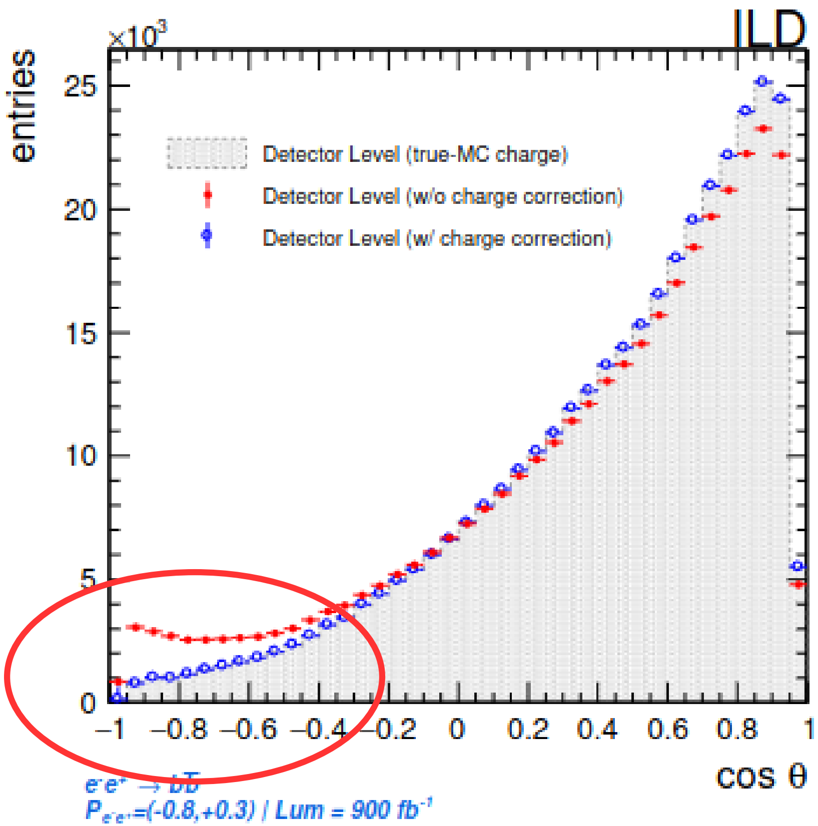
$e^-e^+ \rightarrow b\bar{b}$

ILD-PHYS-PUB–2023-001

Double charge method

- **Double Tag + Double Charge**
  - Both jets need to have a charge measurement compatible with the 2 quarks back to back scenario
- Double mistakes are unlikely but still not negligible and lead to “sign flip” → migrations

BSM or simple migrations?



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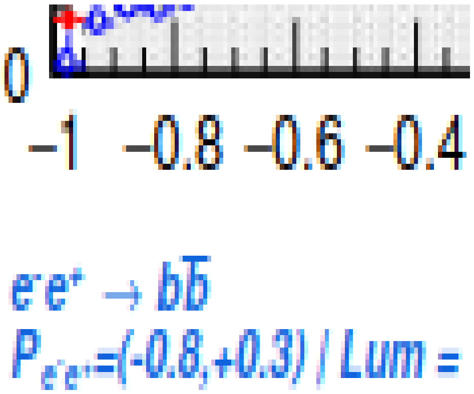
Red shows the distribution withtout sign correction.

Gray is the parton level distribution

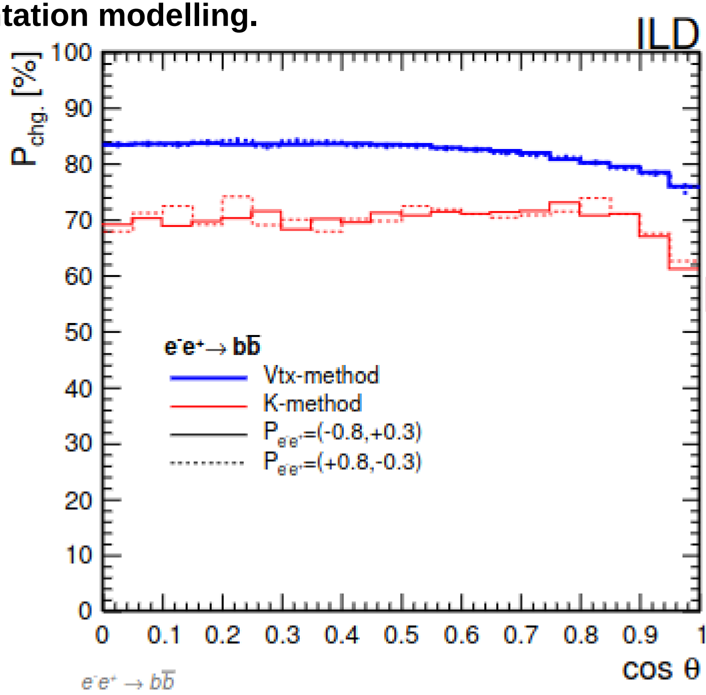
Migration correction

- Migrations look as “new physics” → we need to correct them
  - **Using data: double charge measurements** with same and opposite charges (see back-up slides)
  - We measure the probability to reconstruct correctly the charge (P_B) and use it for correction
  - **DATA DRIVEN METHOD → non sensitive to fragmentation modelling.**



blue shows the distribution after sign correction.

Gray is the parton level distribution



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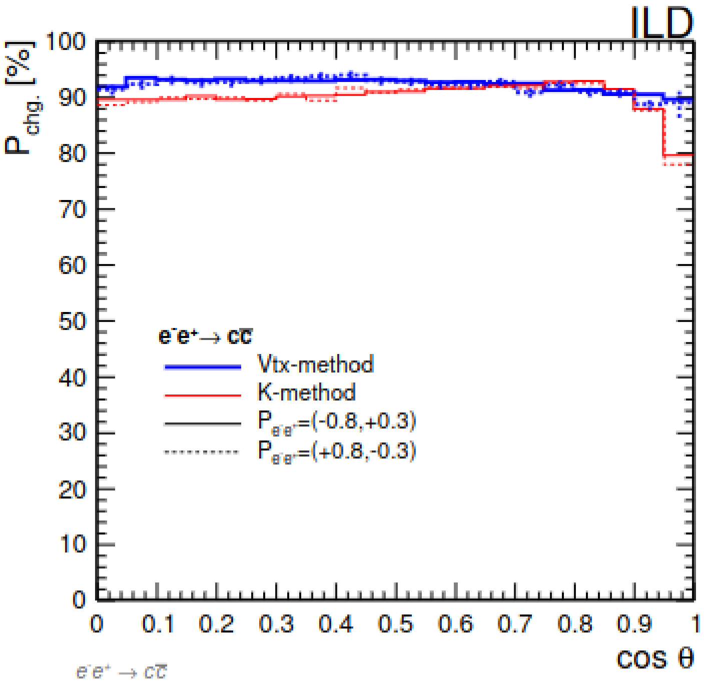
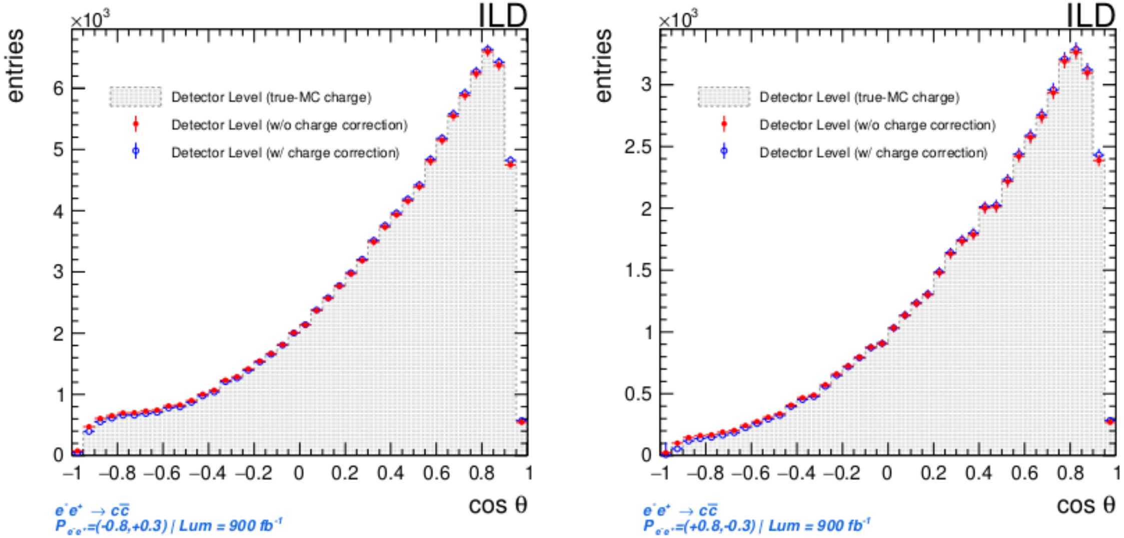
- **Pchg limited by vertex reconstruction efficiency, Particle ID efficiency and B0 oscillations** (b-quark case)**.**

Migration correction – c quark case

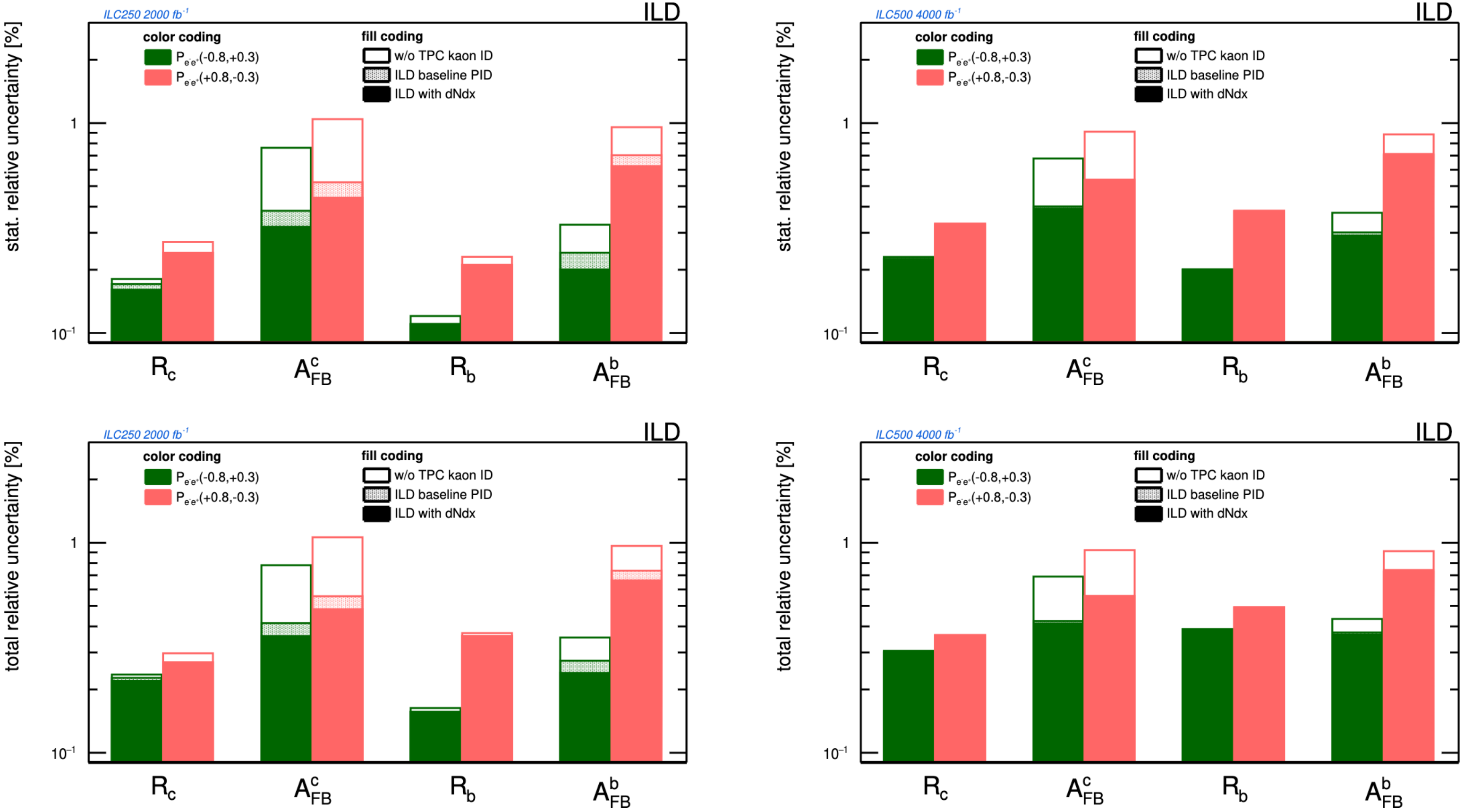




Minimal migration effects (and corrections!)

ILD-PHYS-PUB–2023-001

Total uncertainties



Statistical uncertainties dominate over systematic uncertainties