AITANA ANNUAL MEETING 2023/24

IFIC (CSIC/UV)

Jesús P. Márquez Hernández

02 / 02 / 24

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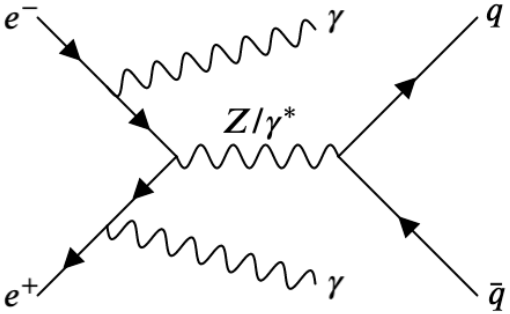
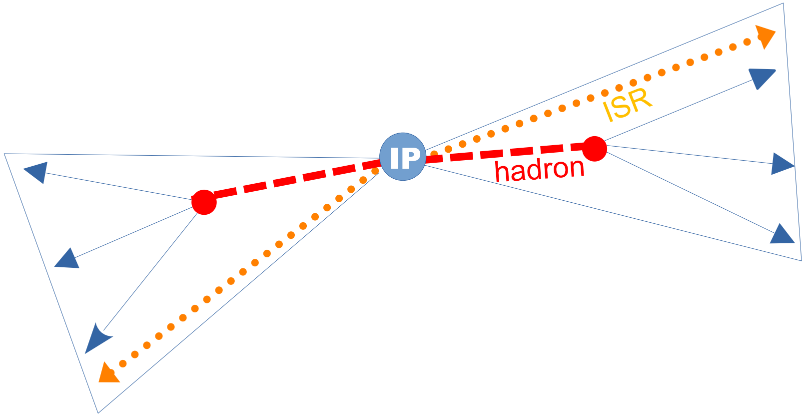
Plan de Recuperación, Transformación y Resiliencia
CALICE
ILD
AITANA

From heavy quarks to GHU Models

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:
  - Remove backgrounds → Selection of $q\bar{q}$ events.
  - Flavor tagging → Selection of $b\bar{b}$ & $c\bar{c}$ events.
    - Double tagging.
  - Charge measurement → Quark-Antiquark identification.
    - Double charge.





High-purity & independent samples for each quark flavour.

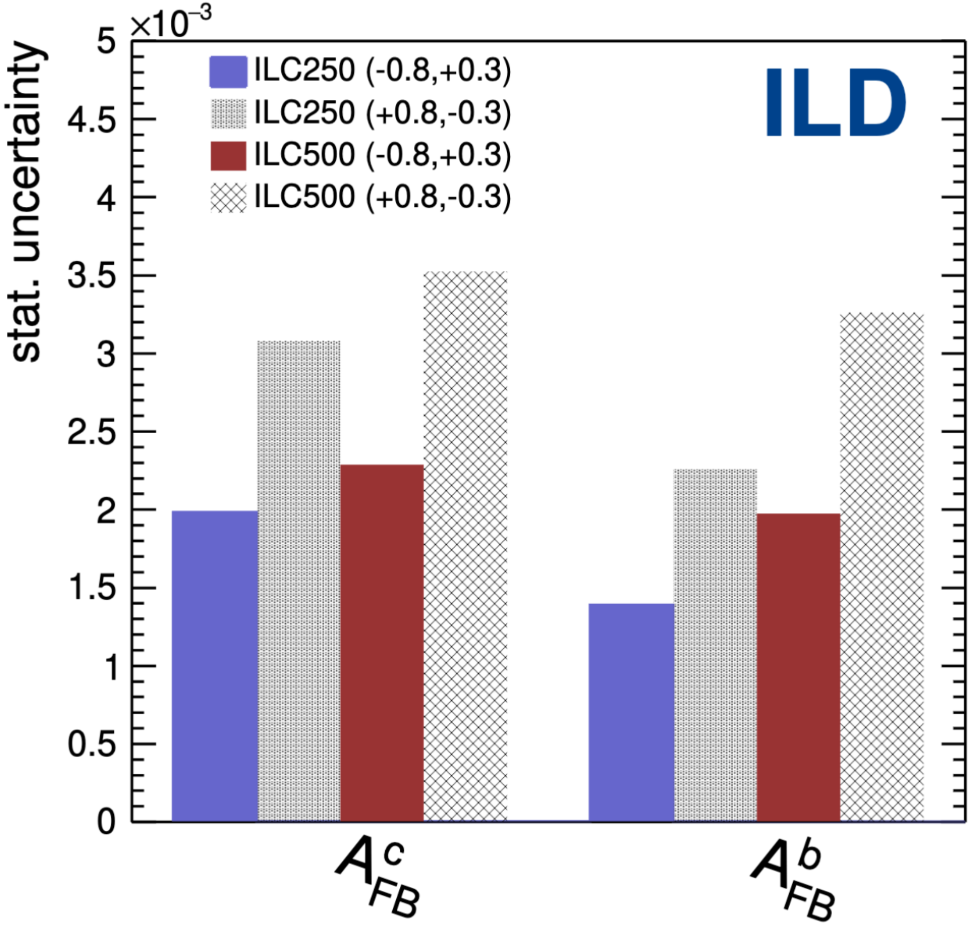
Results

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

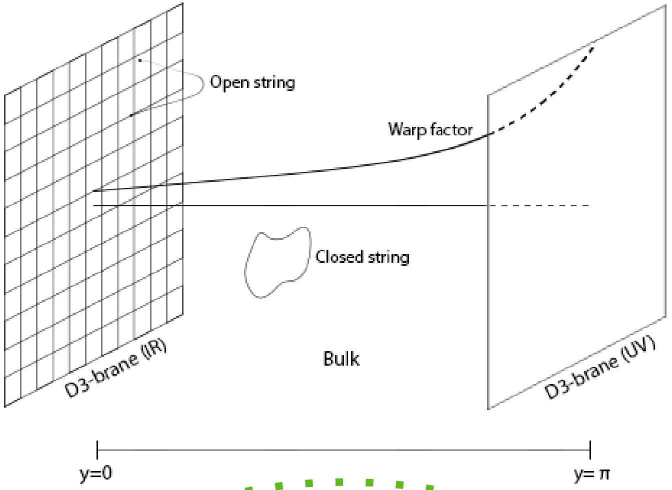
- **Per mil level statistical uncertainties** reachable for the nominal **ILC program**
  - **Smaller exp. syst. Uncertainties**

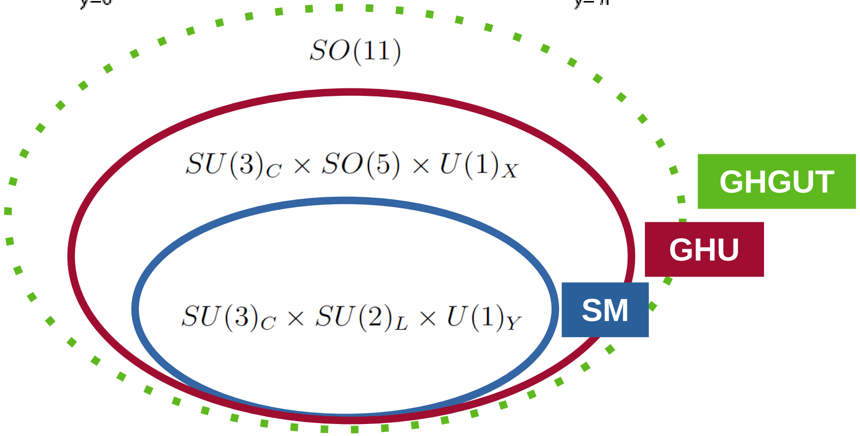


Gauge-Higgs Unification models

- Randall-Sundrum metric (5D).
- Higgs boson appears as any other gauge boson but using a symmetry group in 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.*

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





$SO(11)$

$SU(3)_C \times SO(5) \times U(1)_X$

$SU(3)_C \times SU(2)_L \times U(1)_Y$

GHGUT

GHU

SM

Gauge-Higgs Unification models

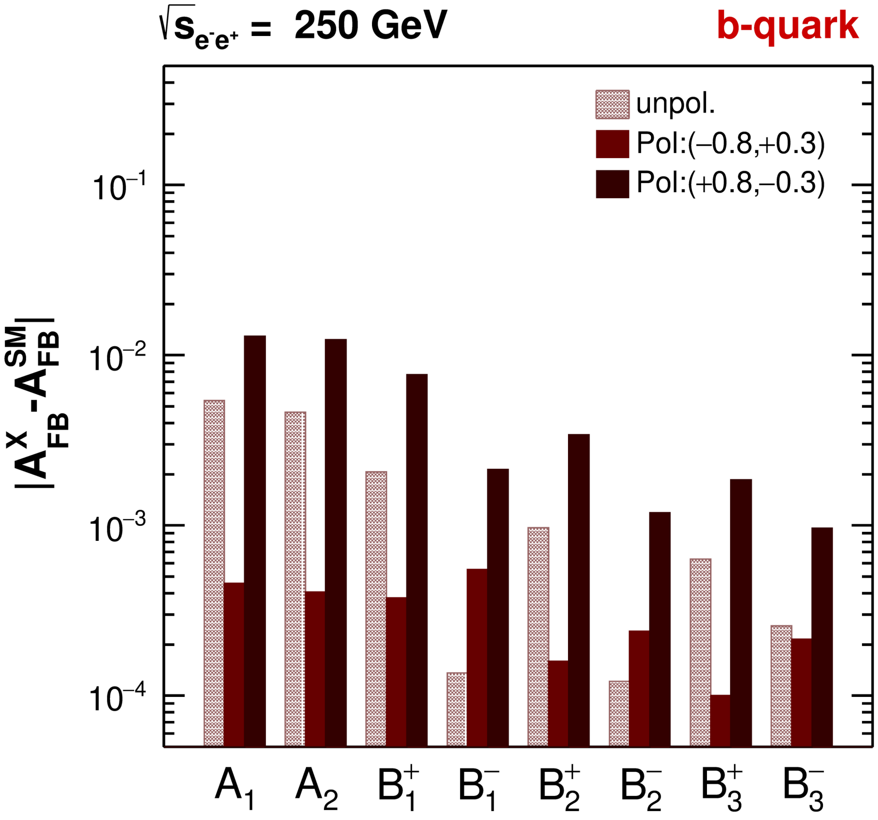
- A models: (arxiv:1705.05282)

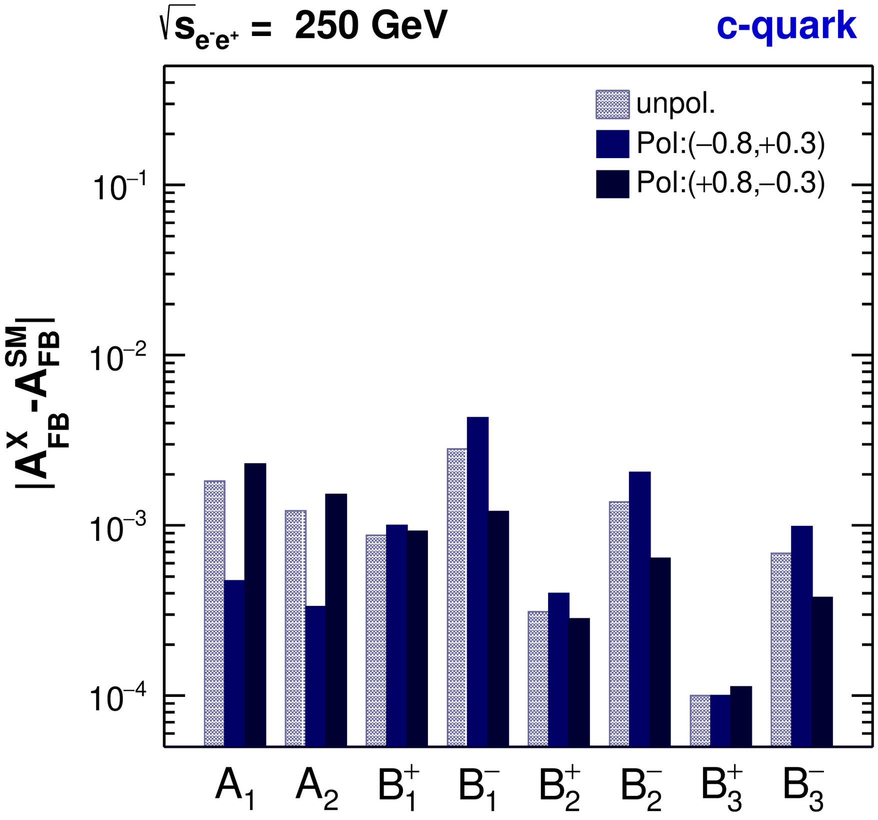
$$A_1 : \theta_H = 0.0917, m_{KK} = 8.81 \text{ TeV} \rightarrow m_{Z'} = 7.19 \text{ TeV};$$
$$A_2 : \theta_H = 0.0737, m_{KK} = 10.3 \text{ TeV} \rightarrow m_{Z'} = 8.52 \text{ TeV},$$

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

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

GHU vs SM (deviations at 250 GeV)





Higher deviations for ILC500 and ILC1000!

GHU vs SM: Discrimination power

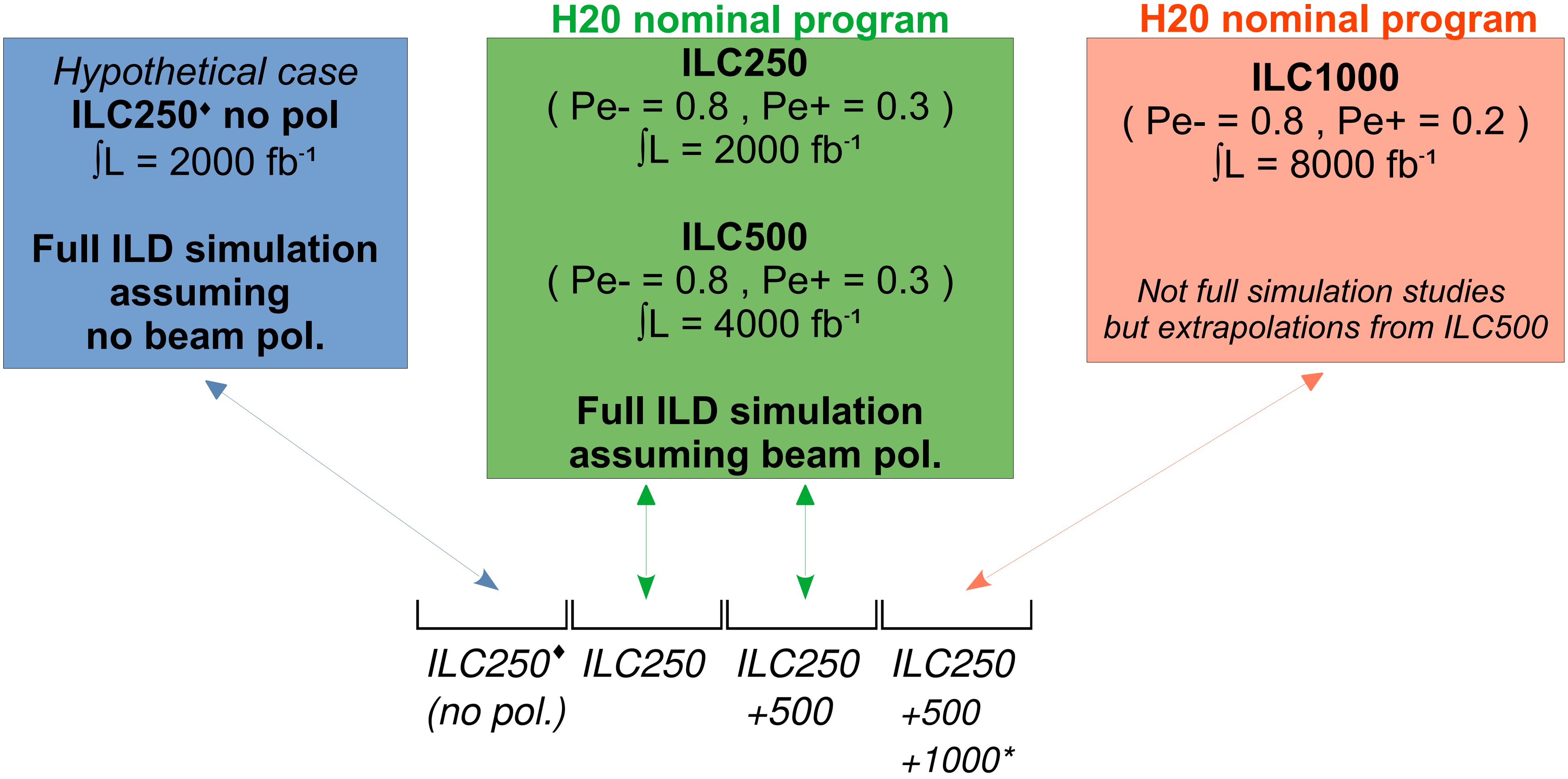
- Assumption: A measurement of one specific model is conducted.

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

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

- Combination of multiple measurements is done with a **multivariate gaussian**.
  - Assuming *no correlations* for A_{FB}.

GHU vs SM: Beam scenarios



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

Full ILD simulation assuming no beam pol.

H20 nominal program

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

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

Full ILD simulation assuming beam pol.

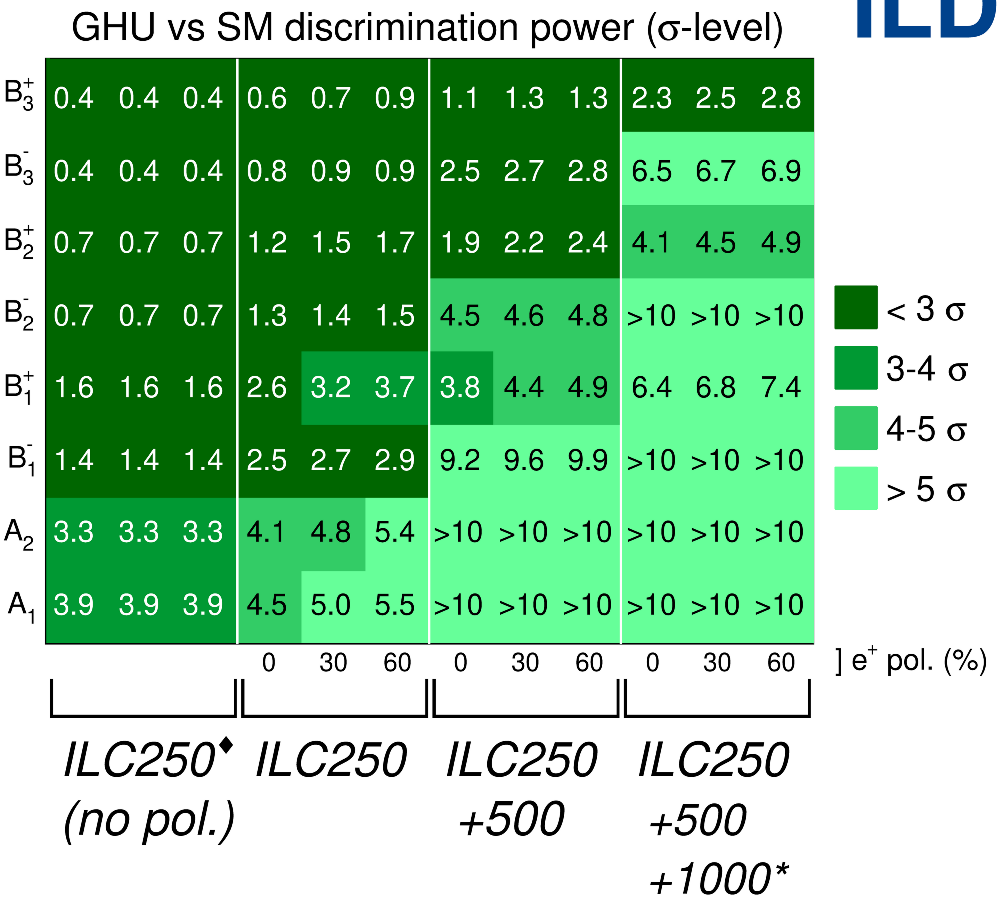
H20 nominal program

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

Not full simulation studies but extrapolations from ILC500

GHU vs SM: Positron beam polarization

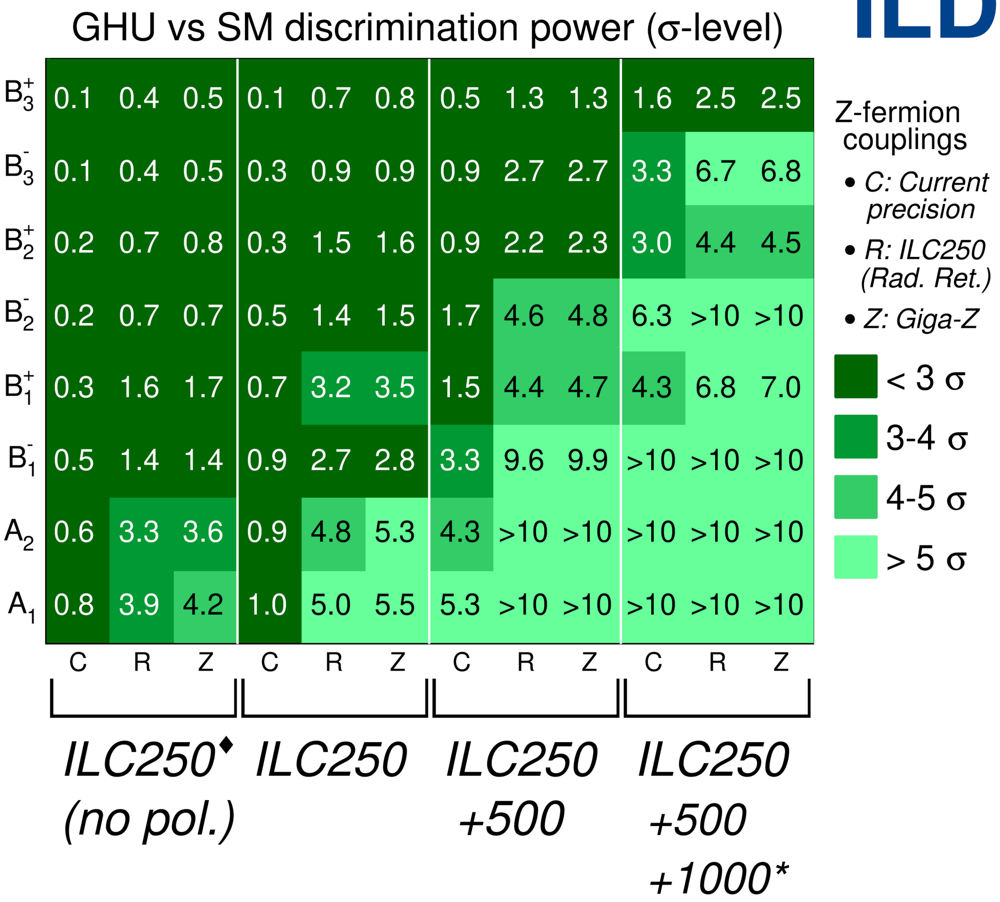
ILD


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: Precision on Z-couplings

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

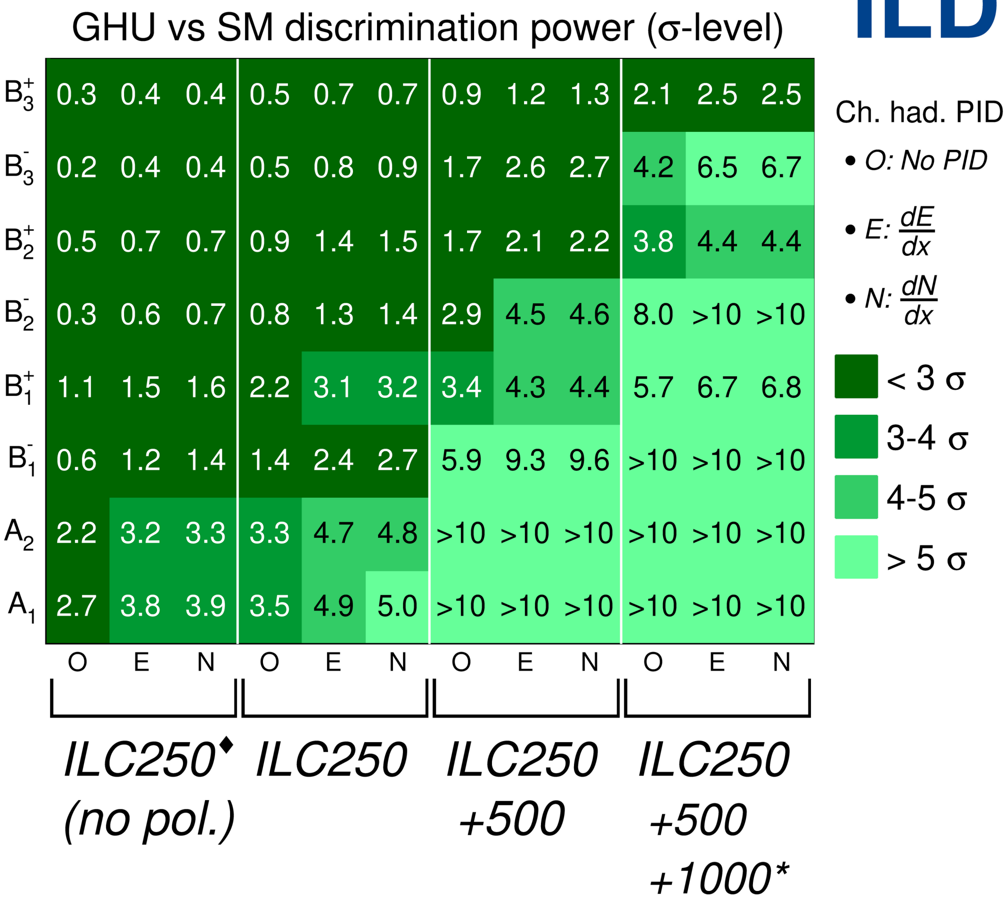
🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

GHU vs SM: Particle ID

ILD



GHU vs SM discrimination power (σ-level)

	ILC250$^{\blacklozenge}$ (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

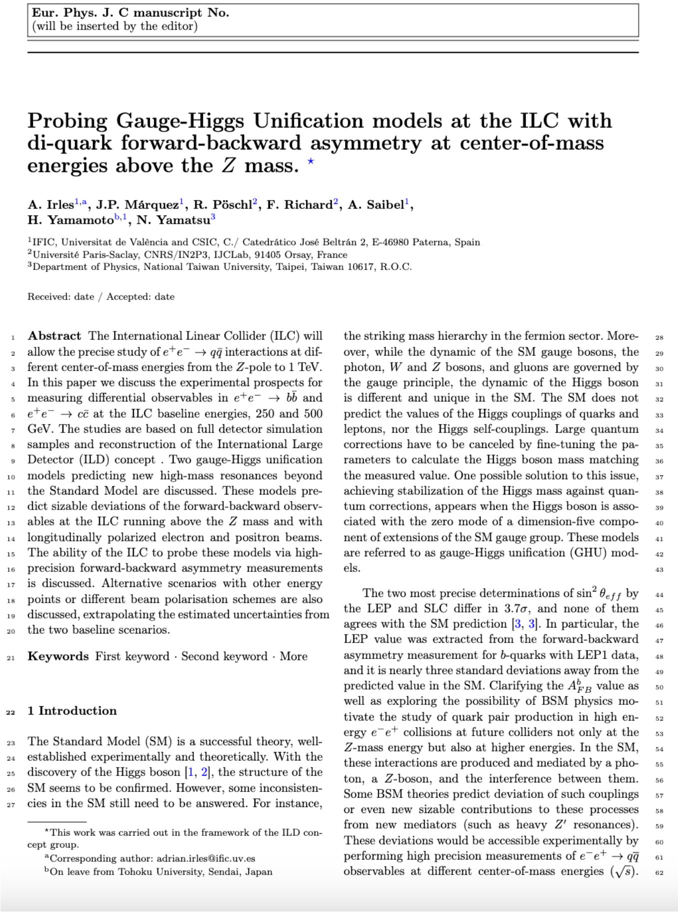
🟩 > 5 σ

This study is (mostly) finished

- Results already presented in 2 conferences.
  - With 2 proceedings published covering different parts of the study (some focus on technical details).

- A paper is being prepared.
  - First draft for EPJ-C.
  - ILD editorial board reviewing it.
    - Second iteration of corrections ongoing.

- It’s almost ready!



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_{FB}^b 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.

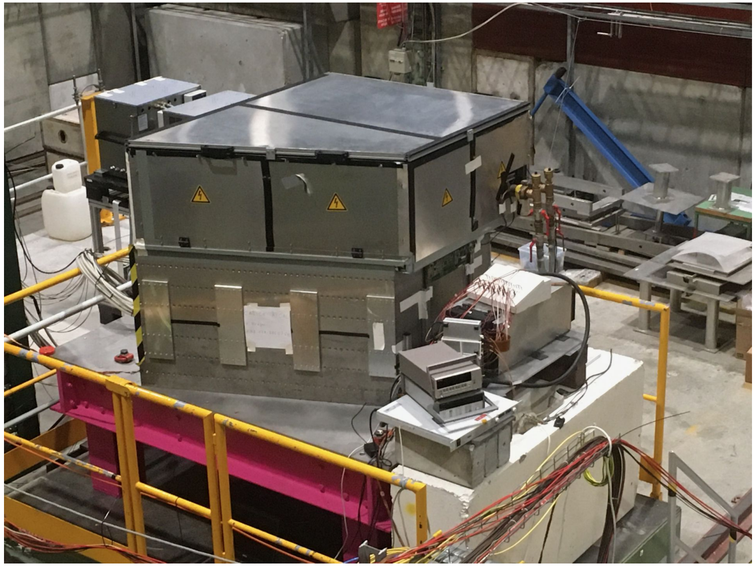
[a] Corresponding author: adrian.irles@ific.uv.es

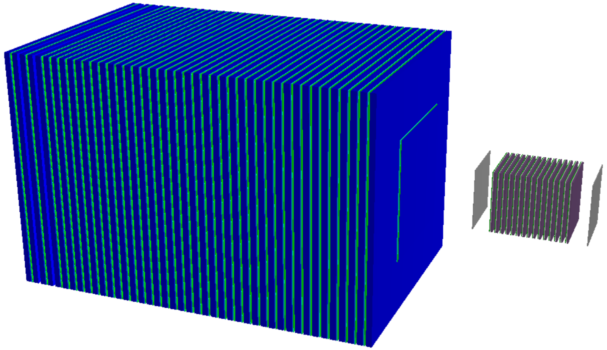
[b] On leave from Tohoku University, Sendai, Japan

Calorimetry studies from June 2022 CALICE's Test Beam

SiWECAL + AHCAL Simulation

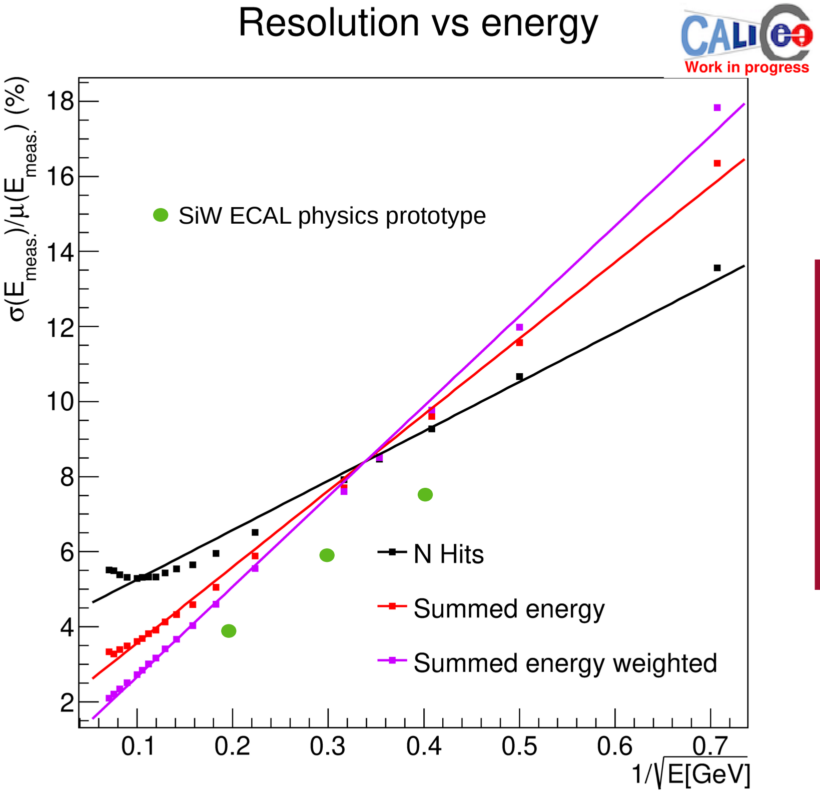
- Worked at DESY with the AHCAL stuff and prepared all the simulation process while staying there.
  - Software: dd4hep (GEANT4).
- Setup and simulation geometry:





SiW ECAL Simulation Analysis

- First plot: resolution for different methods.
  - Note: SiW ECAL physics prototype had 30 layers, this one only 15.



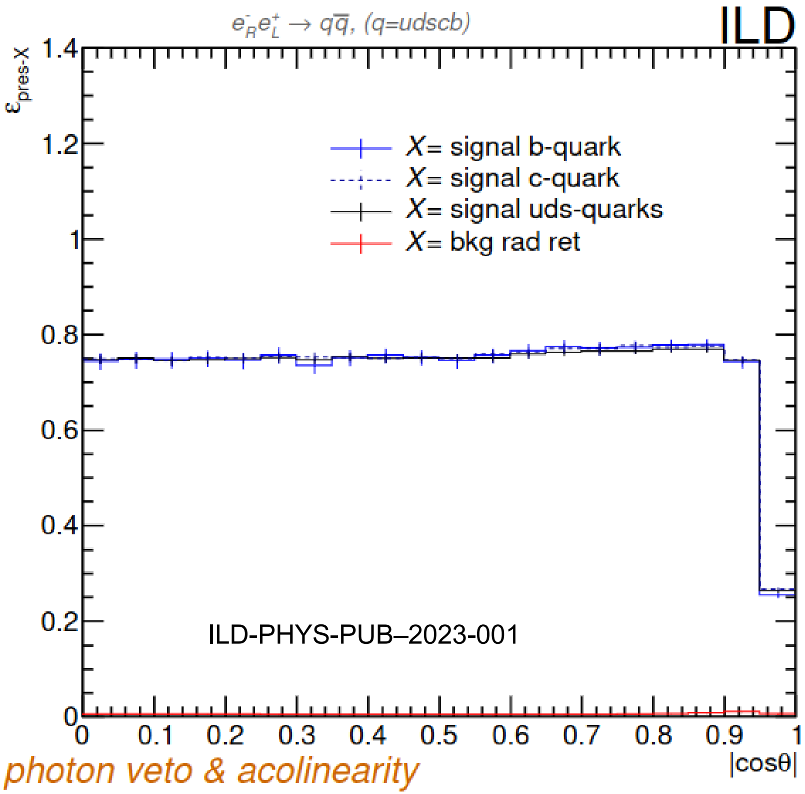
TO-DO list:
- **Molière radius.**
- **Shower profile.**
- **AHCAL+SiW ECAL comb.**
- **ML PID study.**
- **ILD model study.**
- **Add digitization effects.**

Thanks for your attention!

AITANA

Preselection

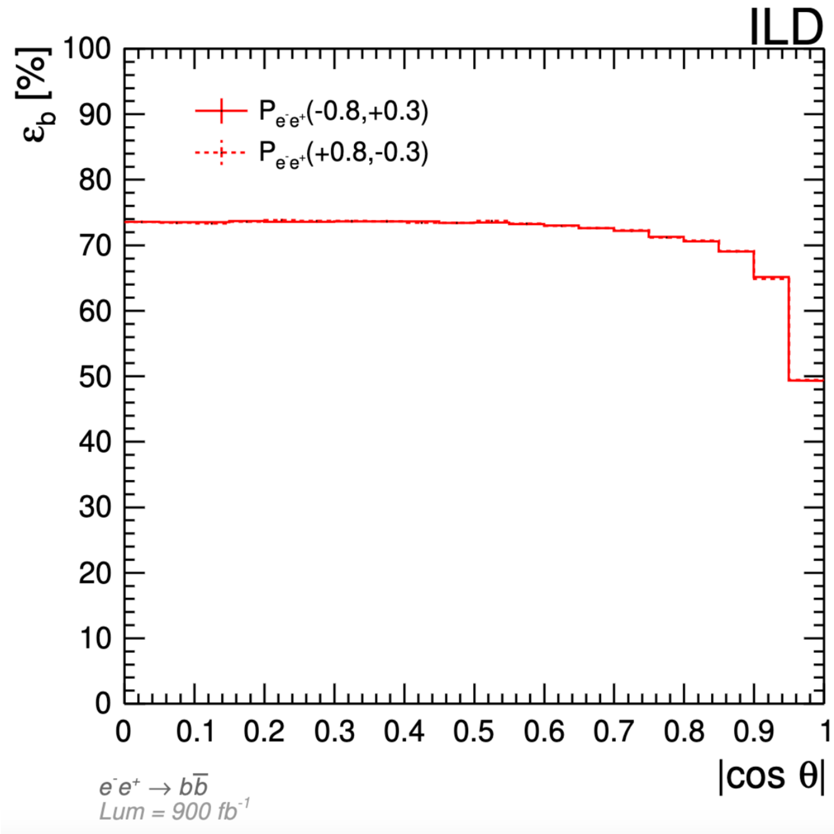
- **Topology: 2 back-to-back jets (pencil-like topology)**
- **Preselection aiming for high background rejection and high efficiency.**
- Main bkg ee→ Zγ(radiative return through ISR)
  - ~x10 larger than signal
  - **~90% of such ISR photons are lost in the beam pipe** → events filtered by energy &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

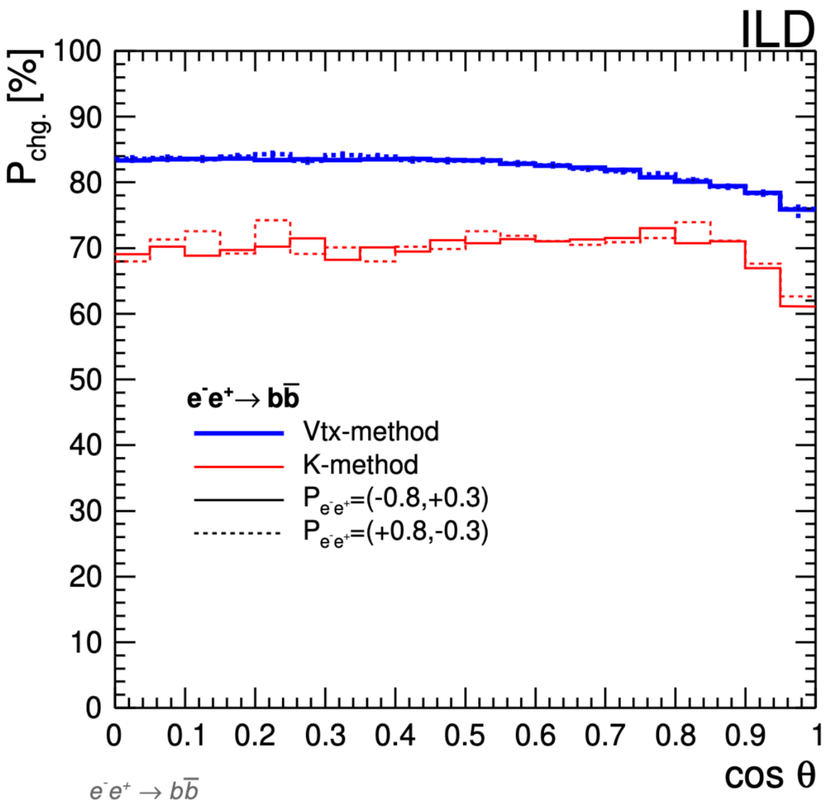


photon veto & acolinearity & m_{jj} & y_{23} cuts

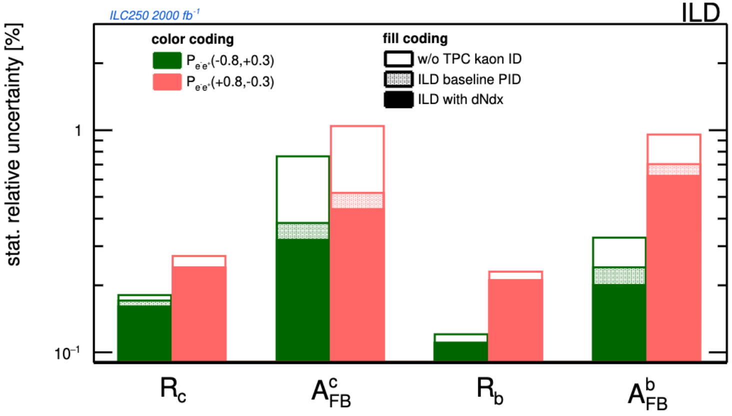
Jet flavour tagging & charge measurement

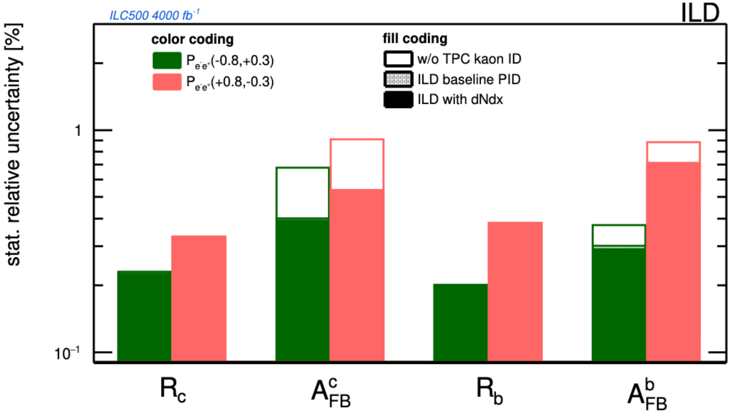
- Double tagging & charge measurement methods
  - To maximally reduce the usage of MC tools (control of fragmentation, QCD correlations… uncertainties)

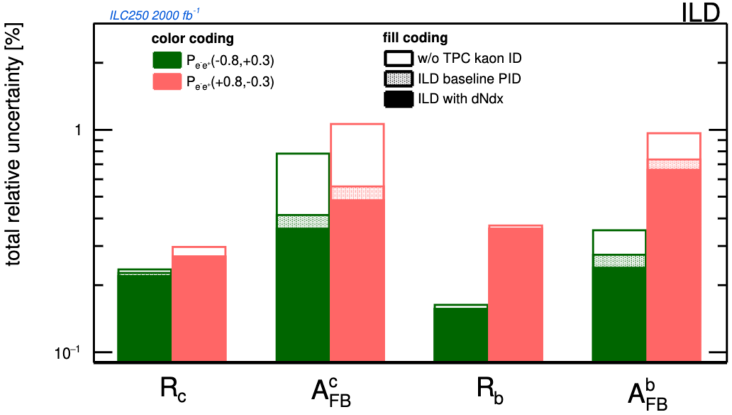


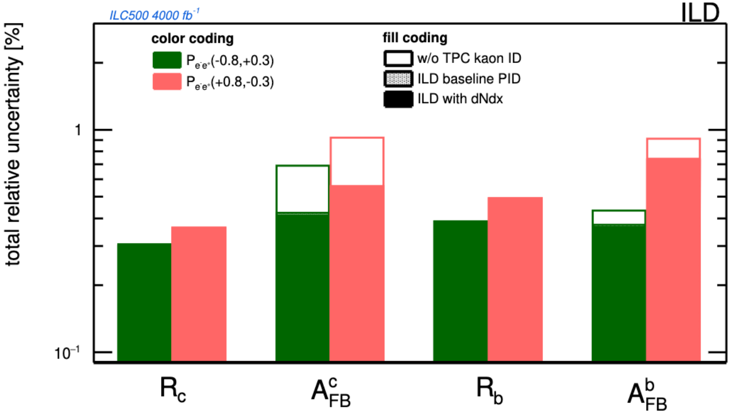


Total uncertainties



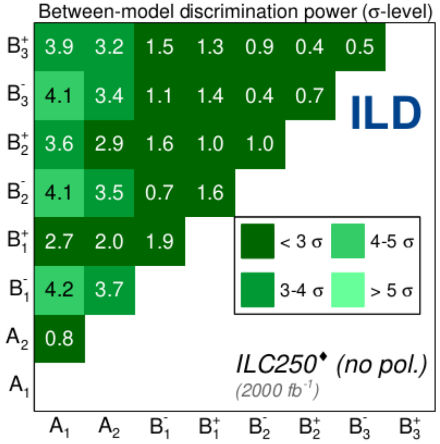






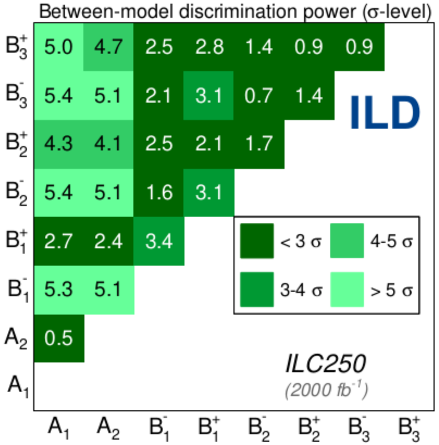
Statistical uncertainties dominate over systematic uncertainties

GHU between model discrimination



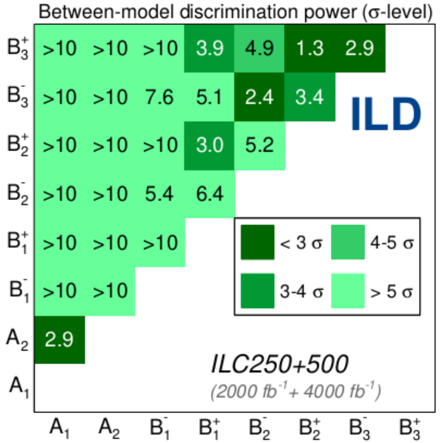
Between-model discrimination power (σ-level)

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								
	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+



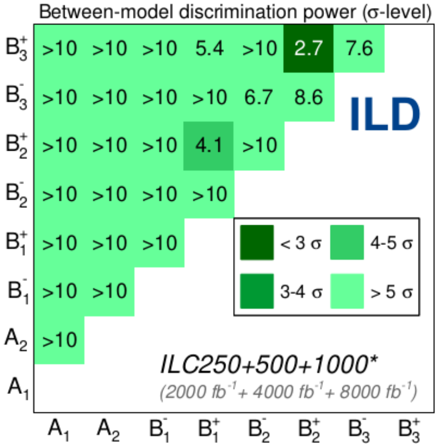
Between-model discrimination power (σ-level)

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								
	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+



Between-model discrimination power (σ-level)

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								
	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+



Between-model discrimination power (σ-level)

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								
	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+

Linearity and resolution studies (I)

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