FUTURE COLLIDERS

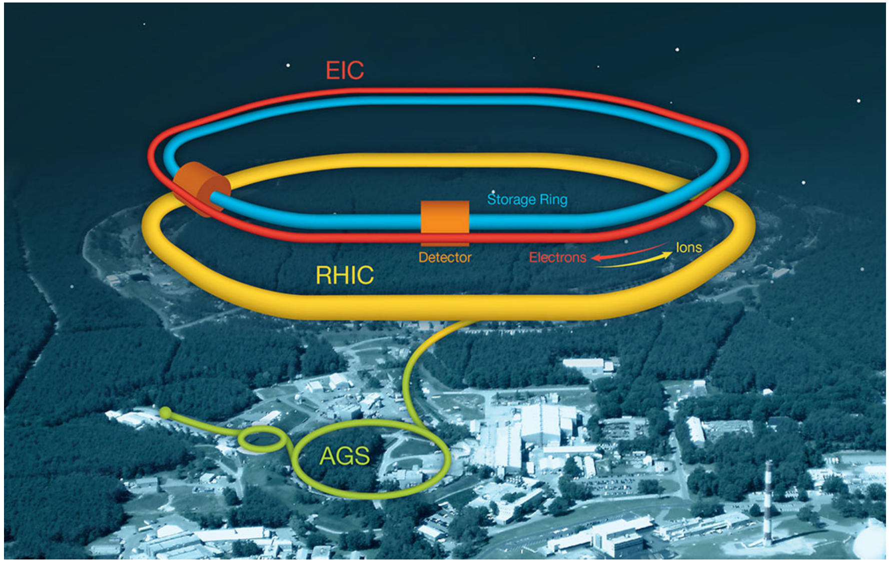
(...AND MY PHD ABOUT IT)

Student Seminar - 05/12/2024

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

Near future: The electron-ion collider (EIC)

- The only *future collider* that is 100% happening.
  - Approved in 2020.
  - Construction starts in ~2026.
  - Operation starts in ~2030.
- Characteristics:
  - Electron accelerator on top of the RHIC.
  - **Not going further than LHC**: c.m.e. 20-140 GeV.
    - Electrons with between 5 and 18 GeV.
    - Protons up to 275 GeV.
    - Heavy ions up to 100 GeV per nucleon.
  - It is a DIS experiment to study QCD effects.
- Studying Higgs physics, top physics and BSM physics will require a e^-e^+ (or pp) collisions at higher energies!



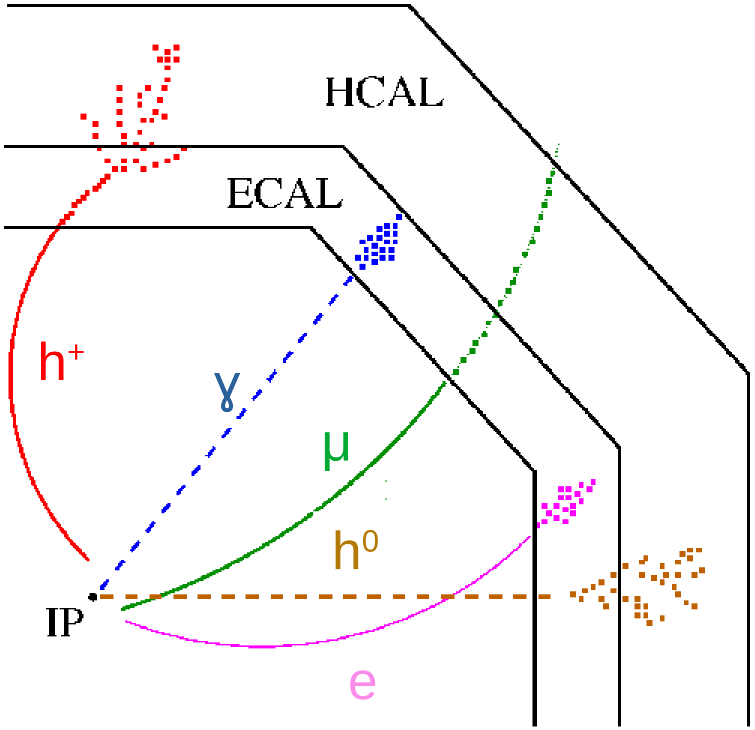
← **Higgs factories**

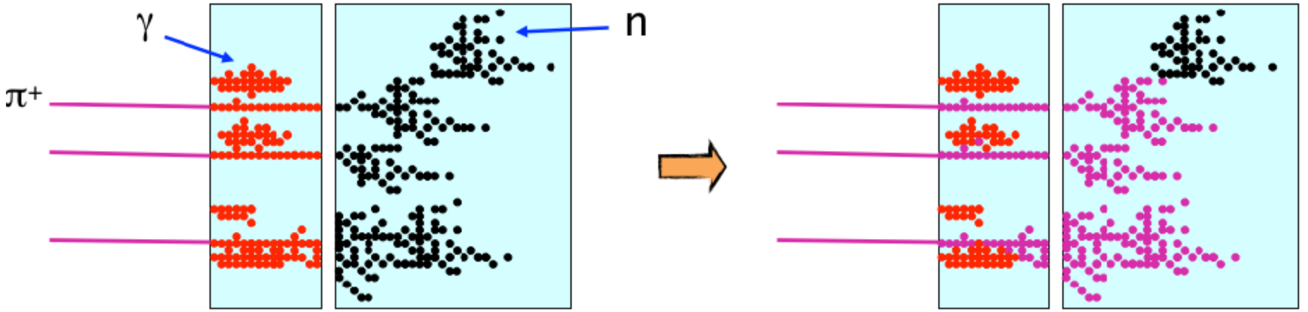
Working on future colliders

- **Parallel working**
  - Many people work in more than one project!
    - Current + Future colliders: ATLAS+FCC, CMS+CLIC, CMS+ILC, etc.
    - Several future colliders: ILC+HALHF, ILC+CLIC, FCC+Muon collider, etc.
    - Future colliders + Detector R&D: CLIC+AWAKE, ILC+ILD+DRD6 (my case!), etc.
- **R&D**
  - A dense work field itself that permeates all HEP.
  - Many of the technologies developed can be readapted for other experiments.
  - Examples of synergies: CLIC → HL-LHC, ILC/CLIC → EIC, ILC → XFEL → (LUXE)
- **Particle flow**
  - Single particle ID in the detector, being explore in CMS nowadays.
  - Plays a central role in *most* future colliders.

Particle flow

- Development of new Particle Flow Algorithms (PFA).
- Determination of single particles.
- Jet energy measurements improvement.
    - Accounting for each particle contribution.
- Powerful PID tools.
    - MANY applications

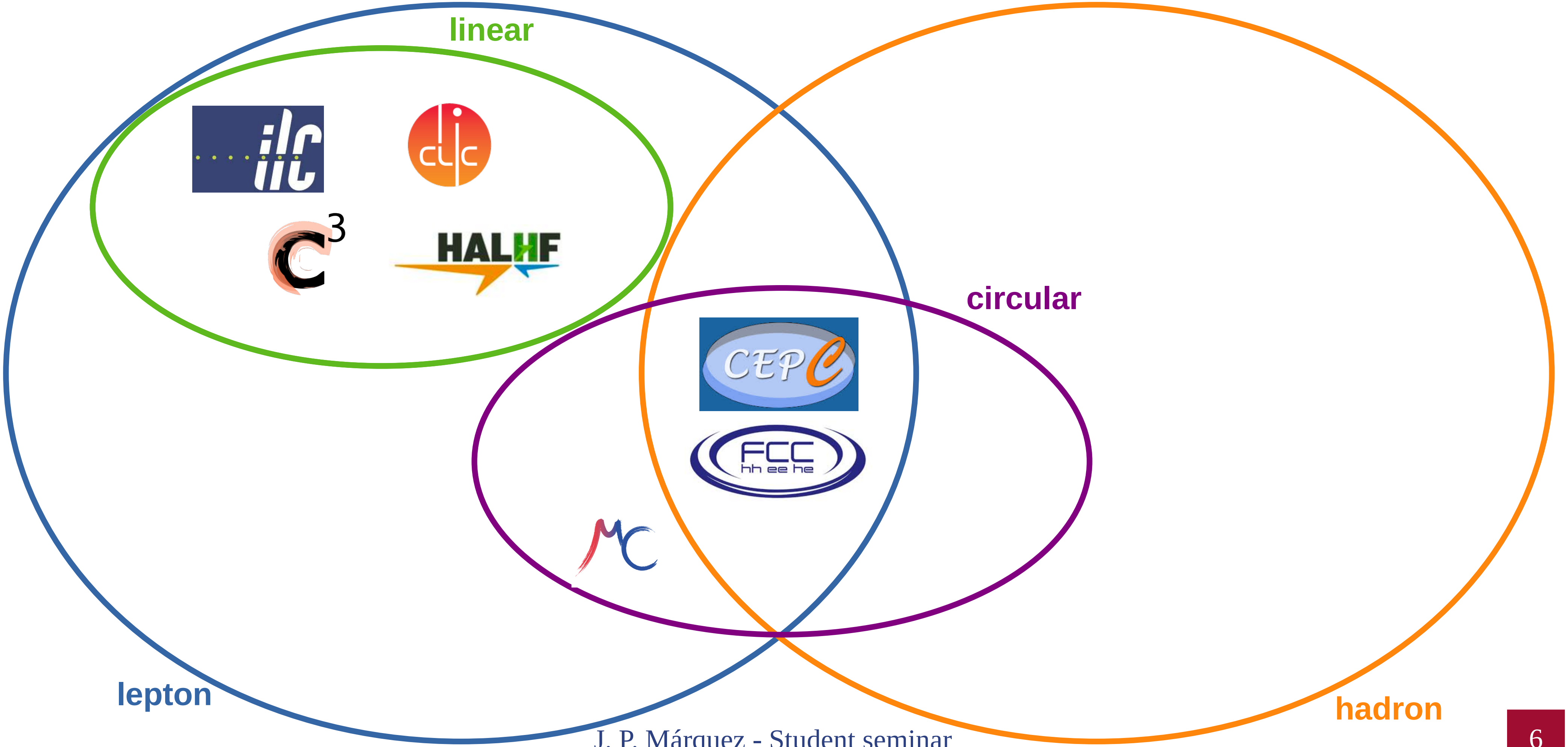




$E_{JET} = E_{ECAL} + E_{HCAL}$ $E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

The Higgs factories’ landscape

Higgs factories / high energy future colliders



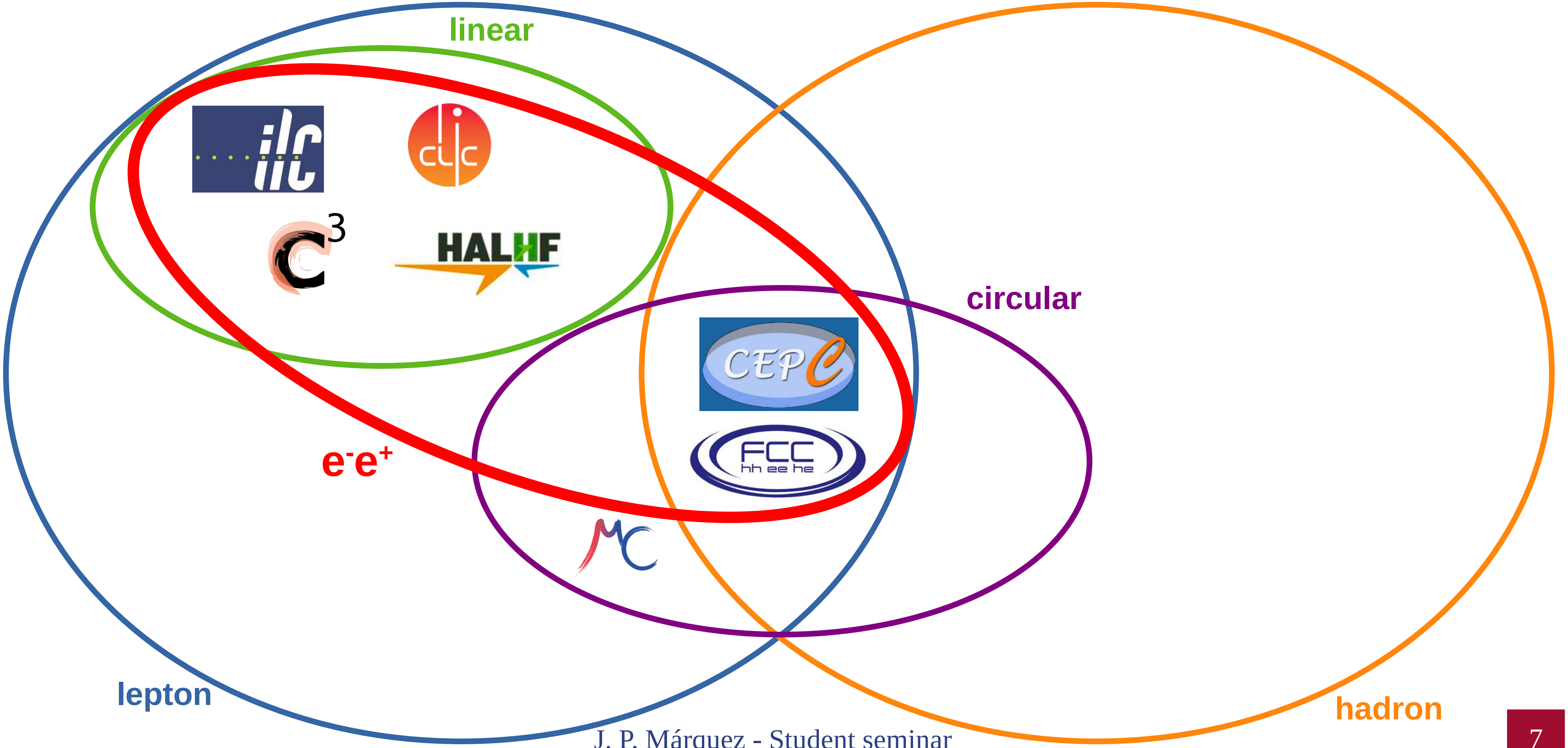
linear

circular

lepton

hadron

Higgs factories / high energy future colliders



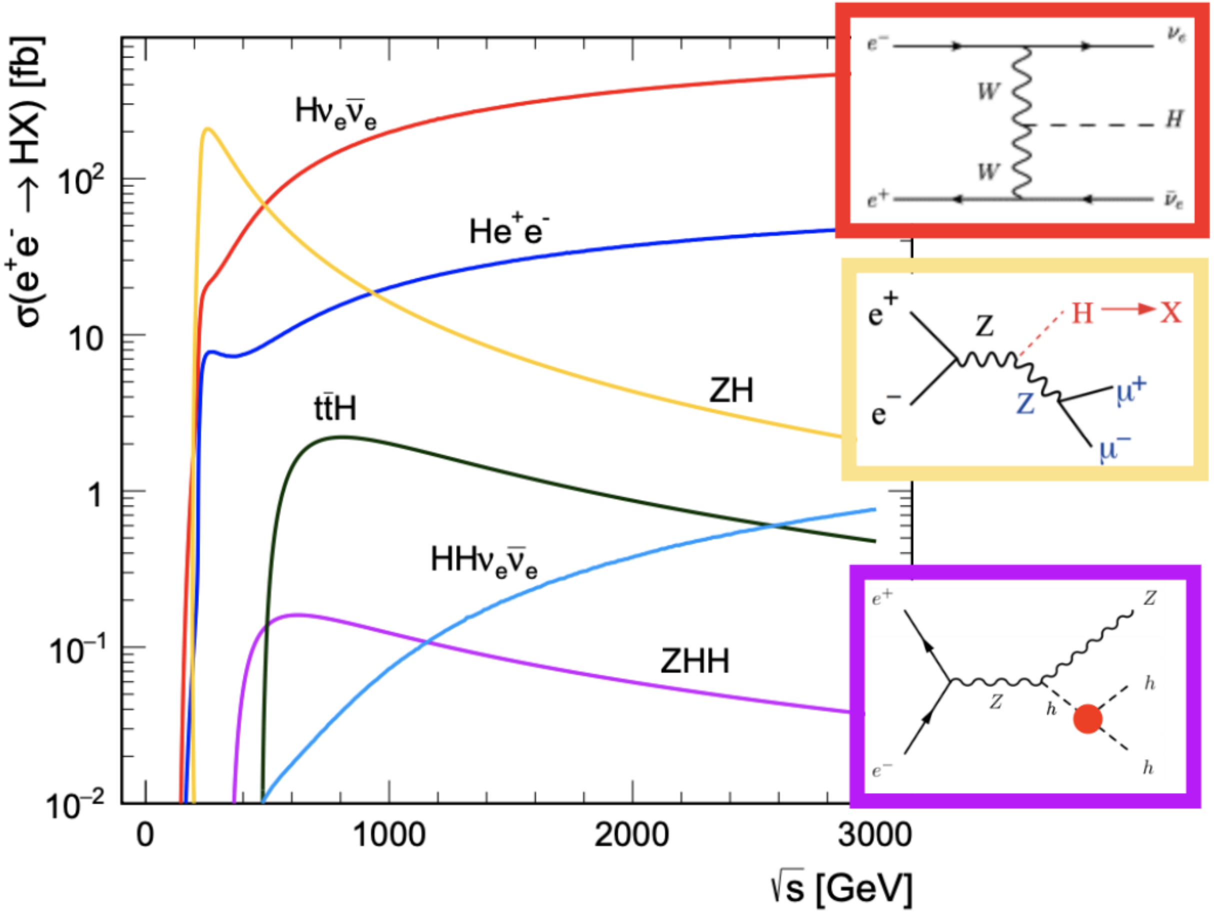
The Higgs factories

- Physics goals: Higgs production (HZ, $t\bar{t}$H, ZHH, Hνν), EW (W^-W^+, Z), top ($t\bar{t}$).
  - Additional: Dedicated Z-pole runs. High energy reach (extra power for BSM)
- Options:
  - Leptons vs hadrons: Cleaner environment for leptons (no PDFs, no QCD ISR, etc.).
    - Pile-up for hadrons can get very bad.
    - Lepton colliders could use particle flow in a optimal way.
  - Linear vs circular: Synchrotron radiation sets the limit.
    - Higher luminosities in circular colliders.
- Factors that impact the $$$ and feasibility of the projects:
  - Accelerator and detector technologies.
  - Power consumption and environmental impact.
  - Civil engineering: Tunneling is VERY expensive!

Synchroton radiation:

$$E_{rad} \propto \frac{E^4}{m^4 r}, \text{ per turn,}$$

The Higgs thresholds



At 240-250 GeV:

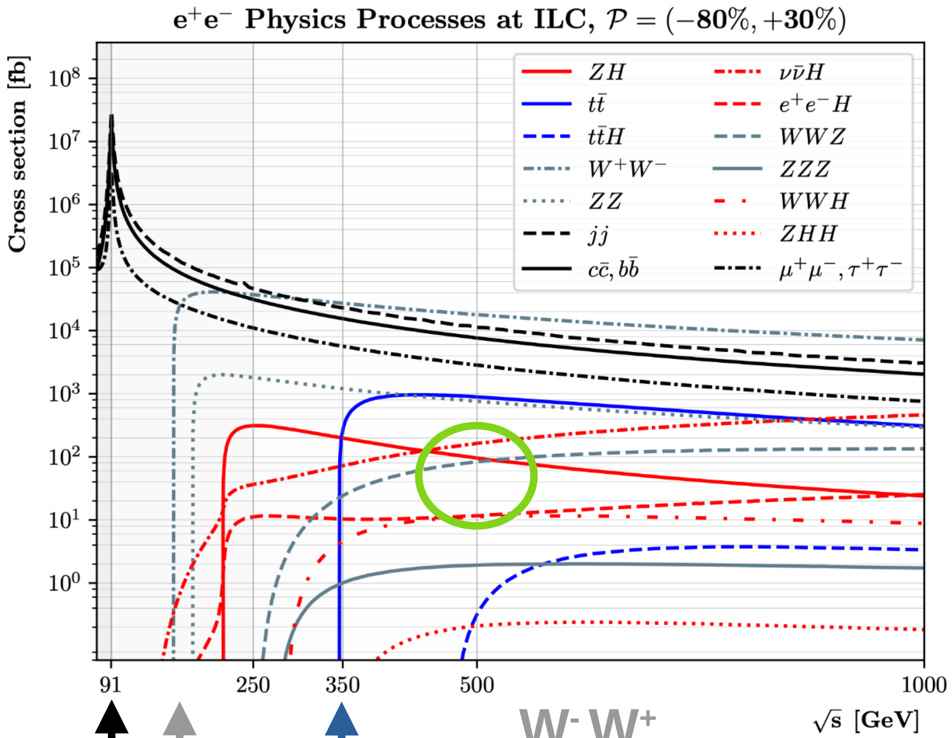
- ZH dominates.

Above 500 GeV:

- Hνν dominates.
- $t\bar{t}H$ opens up.
- ZHH opens up.

This is for unpolarized e^-e^+

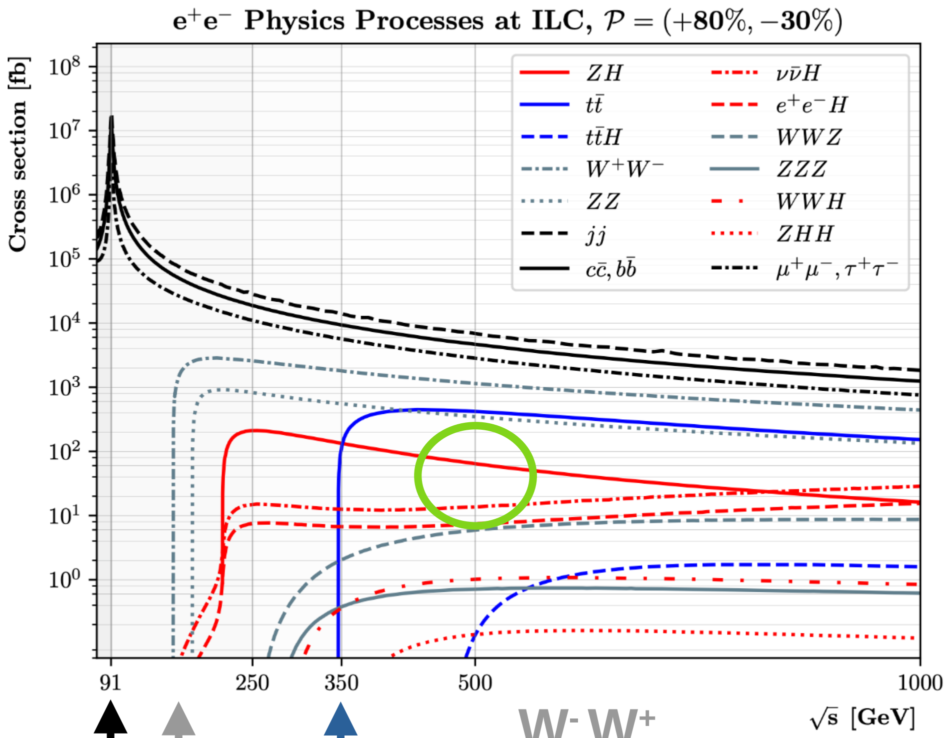
No-Higgs energy thresholds (ILC reference)



W^-W^+
(160 GeV)

Z-pole
(91.2 GeV)

$t\bar{t}$
(350 GeV)



W^-W^+
(160 GeV)

Z-pole
(91.2 GeV)

$t\bar{t}$
(350 GeV)

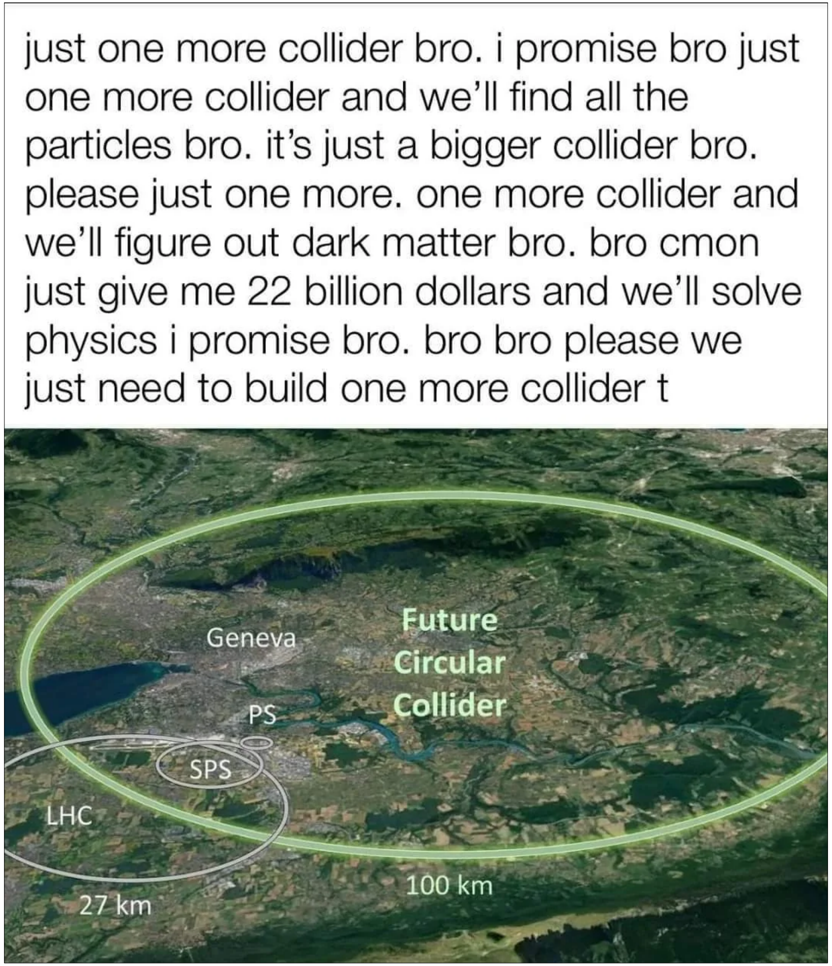
This is polarized!

Circular colliders


FCC
hh ee he
CEPC
Corporate needs you to find the differences between this picture and this picture.
They're the same picture.

FCC & CEPC

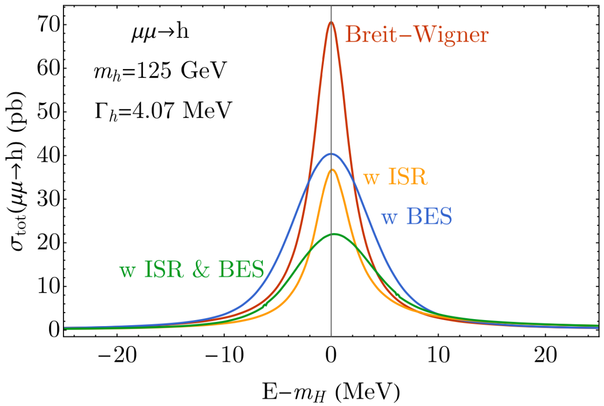
- **Both are 100km in circumference MASSIVE.**
- **Energy points:**
  - $e^- e^+$ runs:
    - Both: 91.2, 160, 240, and 365 GeV.
  - p p runs:
    - 75 TeV (CEPC) and 100 TeV (Both).
  - p e^- runs: runs:
    - Only FCC: up to 3.5 TeV.
- **Some differences:**
  - China (CEPC) vs Europe (FCC).
  - 2030 (CEPC) vs 2040 (FCC).
  - FCC can integrate the LHC.
- **Thing to consider:**
  - VERY expensive (construction and operation).

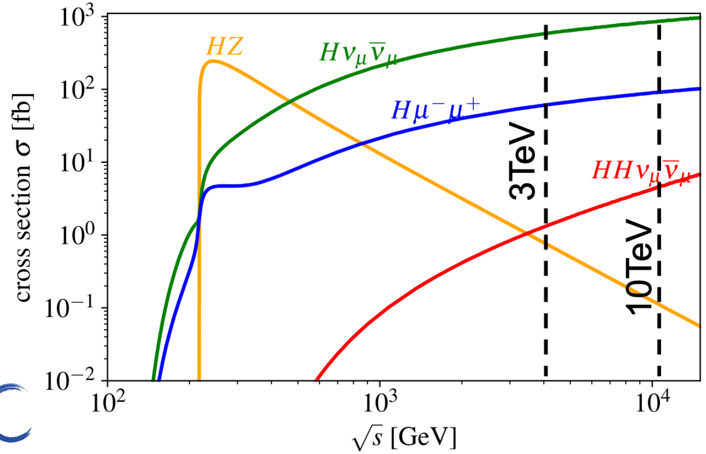


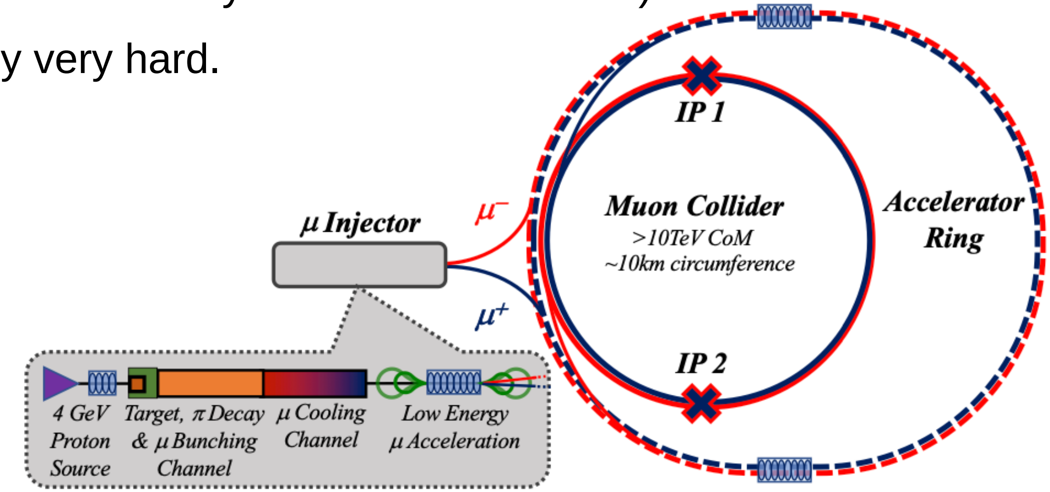
just one more collider bro. i promise bro just one more collider and we'll find all the particles bro. it's just a bigger collider bro. please just one more. one more collider and we'll figure out dark matter bro. bro cmon just give me 22 billion dollars and we'll solve physics i promise bro. bro bro please we just need to build one more collider t

Muon collider

- **Energy points:**
  - (H-pole), 3, (6), and 10 TeV.
- **Things to consider:**
  - Clean Initial State (lepton collider).
  - Great Yukawa coupling (measuring a Higgs-pole is possible?).
  - CERN project.
  - Incredibly high neutrino flux (uncontrolled radioactivity far from the collider?).
  - Stabilizing muons to this level seems very very hard.



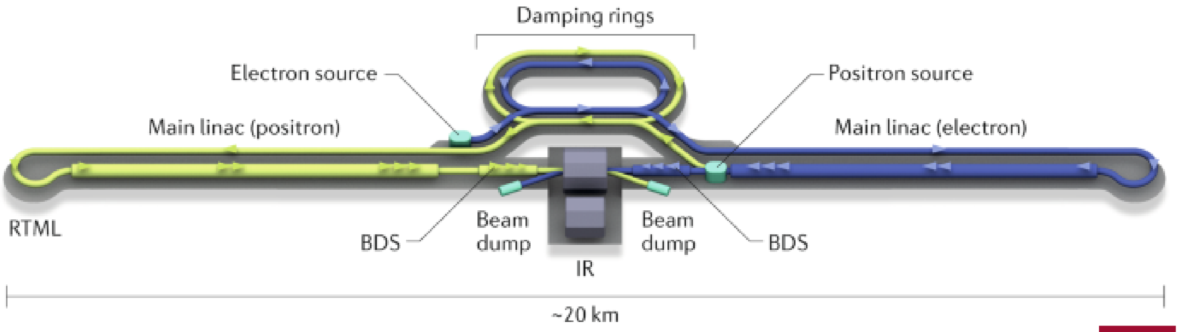




Linear colliders

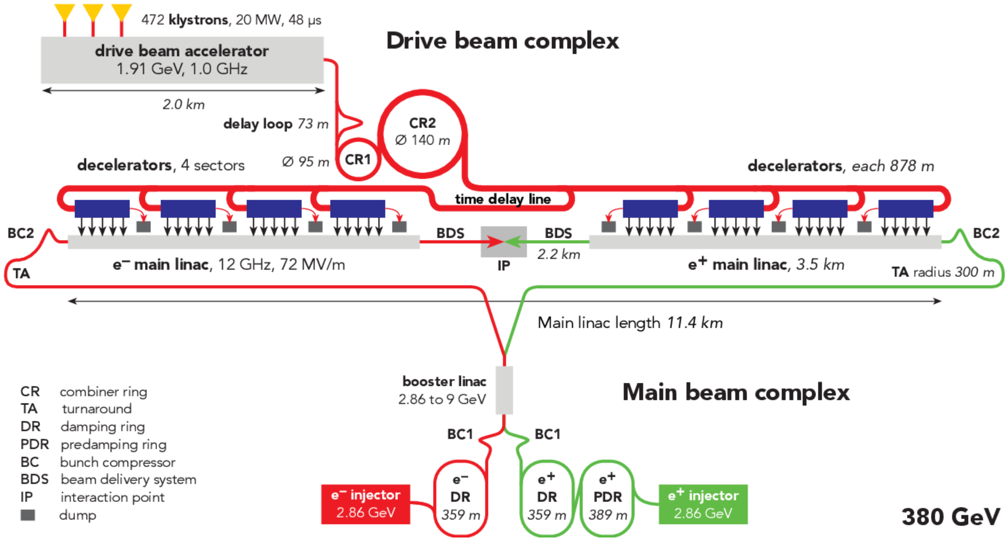
International Linear Collider (ILC)

- **Energy points:**
  - $e^- e^+$: (Z-pole), 250, 350, 500, and (1000) GeV.
- **Things to consider:**
  - Polarization (±80% e^-, ±30% e^+), could be extended up to 60% for e^+.
  - Reachable technology (RF cavities)… But kinda big (>20km).
  - Long project: A lot of software development, R&D, and feasibility studies available!
    - Established as *the baseline Higgs factory*.
  - Japan (+ Europe + EEUU + …) But global politics are difficult.
  - Power pulsing / Low consumption.



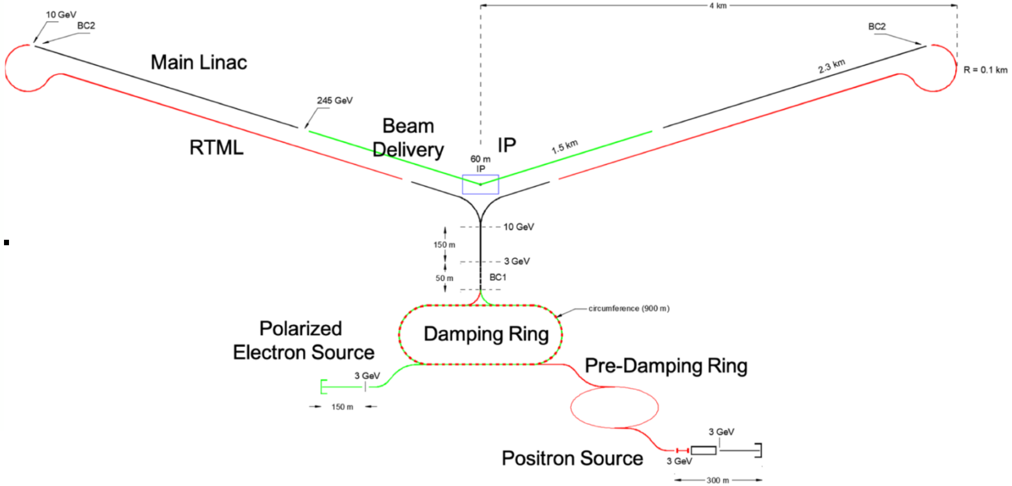
Compact LInear Collider (CLIC)

- **Energy points:**
  - $e^- e^+$: 380, 1500, and 3000 GeV.
- **Things to consider:**
  - Polarization (±80% e^-).
  - High energy reach (great for BSM).
  - Not so good for Higgs study and EW.
  - Drive beam acceleration… Not yet ready.
  - Compact (~ILC/2).
  - CERN project.



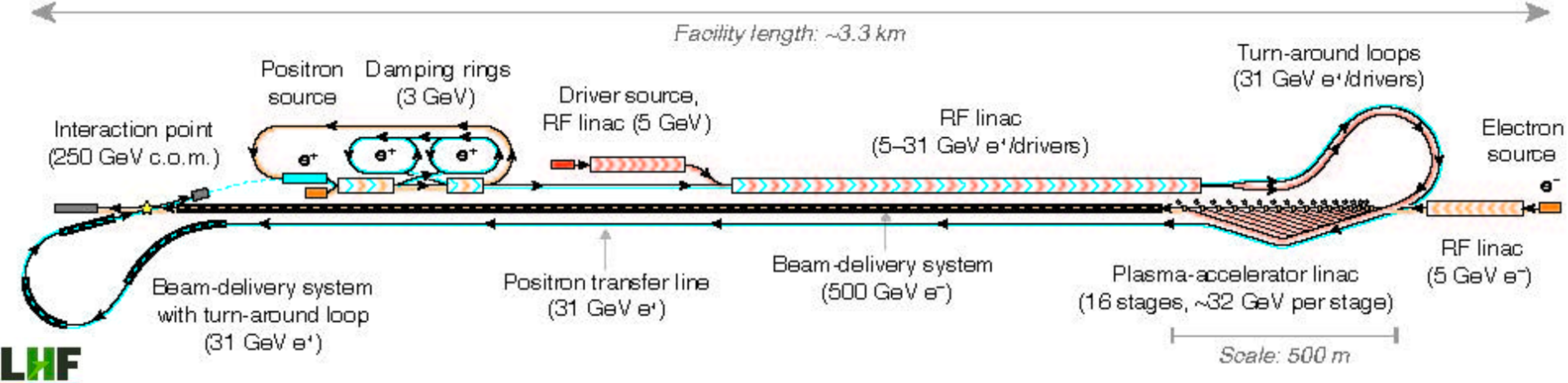
Cool Copper Collider (C^3)

- **Energy points:**
  - $e^- e^+$: 250, (380), 500-550, (1000) GeV.
- **New evolution of the ILC/CLIC concepts.**
- **Things to consider:**
  - Polarization like ILC or CLIC.
  - High-performance cryogenic RF cavities
    - WIP.
  - Very compact (~ILC/3).
  - Aims to be more economic than ILC/CLIC.
  - Mostly an EEUU project.



Hybrid Asymmetric Linear Half Factory (HALHF)

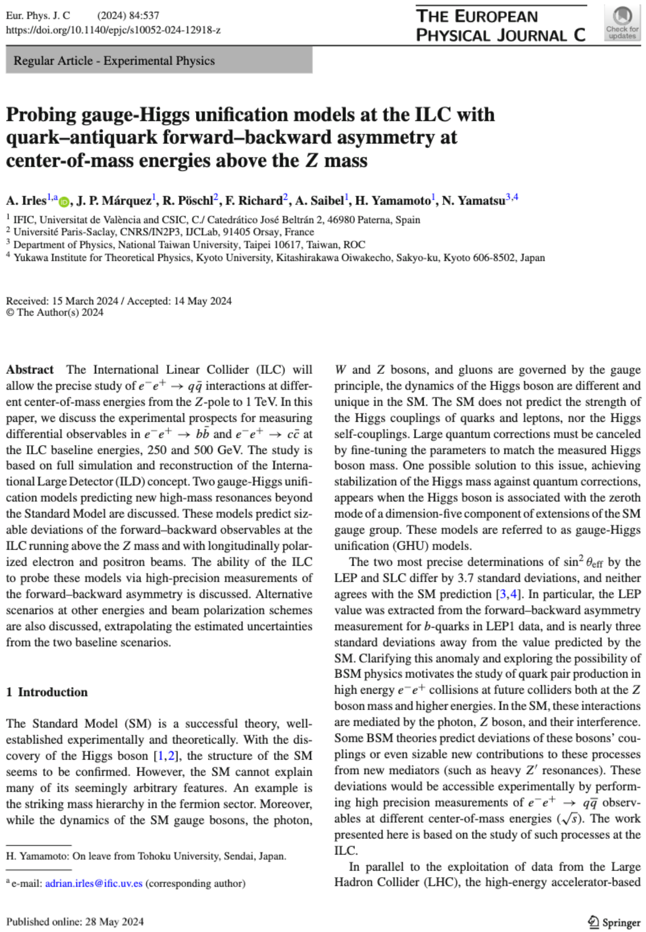
- **Energy points:**
  - $e^- e^+$: 250, 350-380, 500 GeV. (maybe more)
- **New evolution of the ILC/CLIC concepts.**
- **Things to consider:**
  - Polarization like ILC or CLIC**.**
  - Mixed accelerator technologies: RF for e^+. Plasma wakefield for e^- (WIP).
  - Very compact (ILC/6).



Studying gauge-Higgs Unification with heavy quark production at ILC

Published in EPJ-C

- Paper recently published in EPJ-C!
  - DOI: 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)



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

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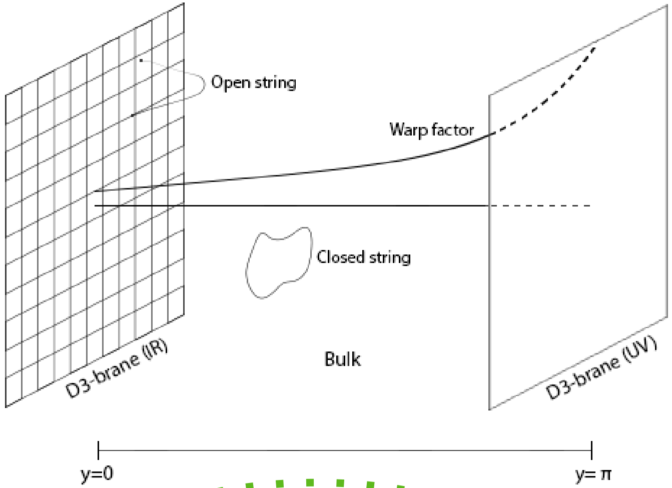
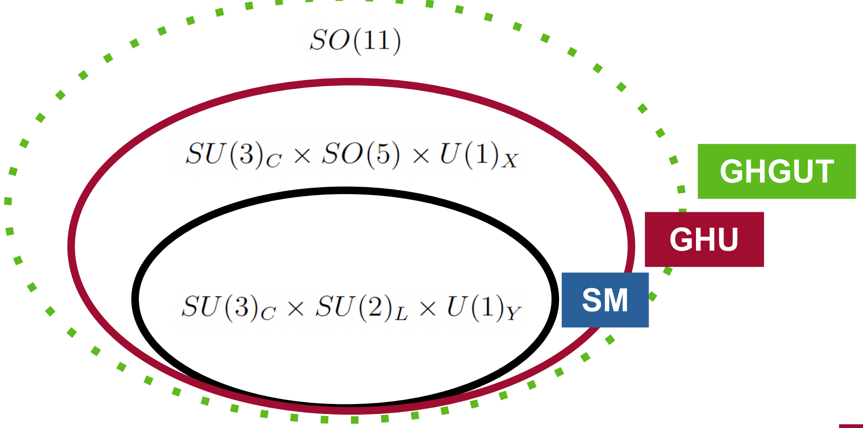
Springer

Gauge-Higgs Unification models

- 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.
  - Higgs boson appears like any other gauge boson.
- 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 $m_{kk} \sim$ 10-25 TeV.
  - Modifications and new ***EW couplings**/helicity amplitudes.*

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





Gauge-Higgs Unification Models (GHU)

- A models: (arxiv:1705.05282)

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

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

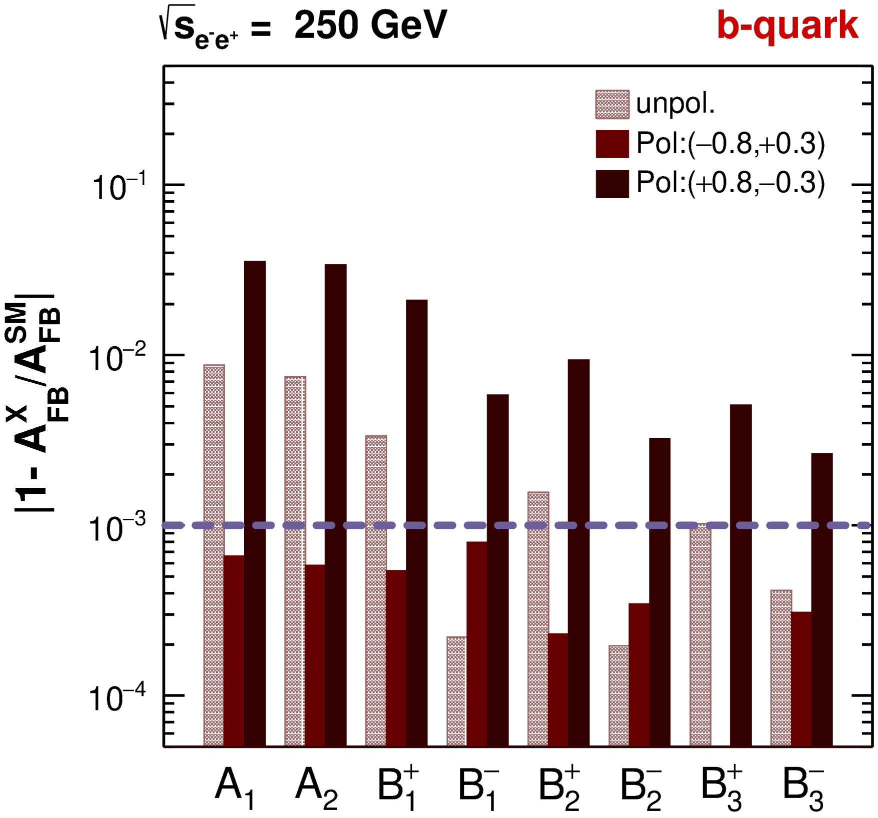
$$B_1^{\pm}: \theta_H = 0.10, m_{KK} = 13 \text{ TeV} \to m_{Z^1} = 10.2 \text{ TeV};$$
$$B_2^{\pm}: \theta_H = 0.07, m_{KK} = 19 \text{ TeV} \to m_{Z^1} = 14.9 \text{ TeV};$$
$$B_3^{\pm}: \theta_H = 0.05, m_{KK} = 25 \text{ TeV} \to m_{Z^1} = 19.6 \text{ TeV};$$

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

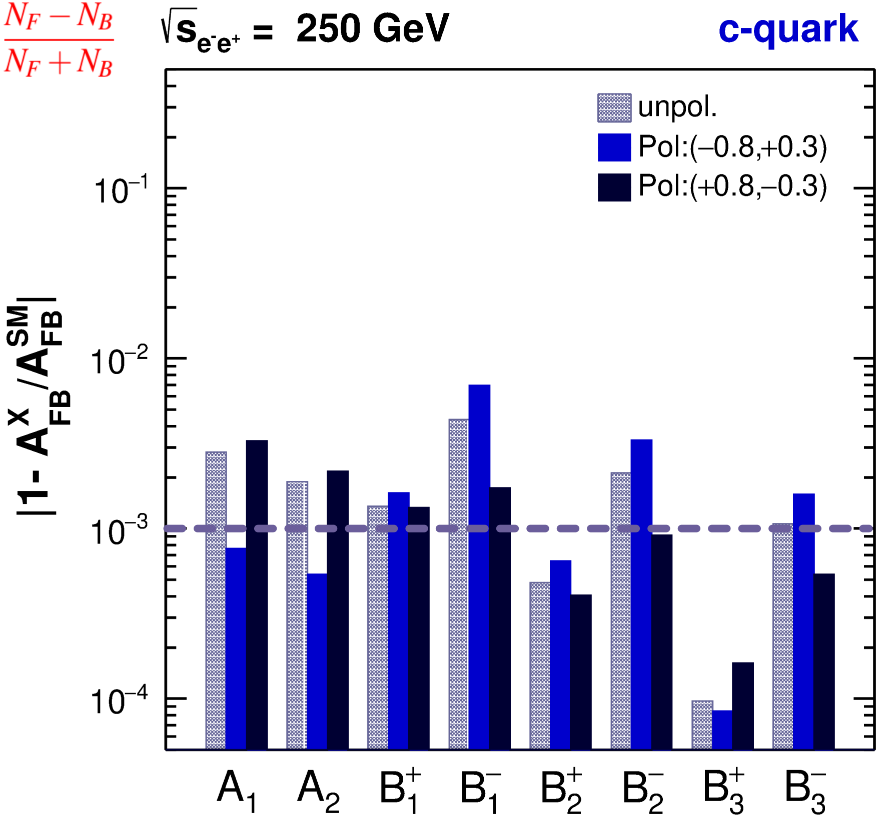
This talk: Phenomenology at ILC H20-staged program.

- **Runs at 91.2, 250, 500, 1000 GeV.**
- **Polarized e$^-$ and e$^+$ beams.**

GHU vs SM (250 GeV)



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



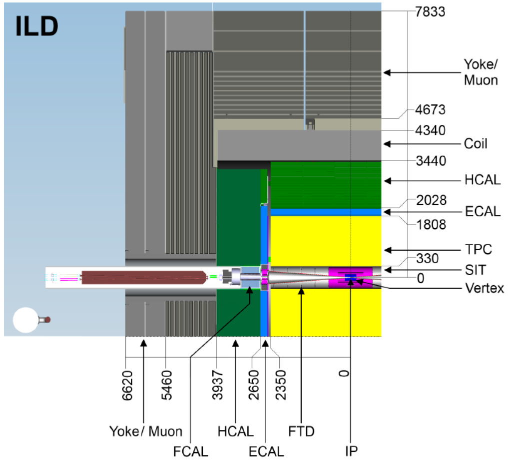
Deviations at the per mil level!

Experimental study with full simulation

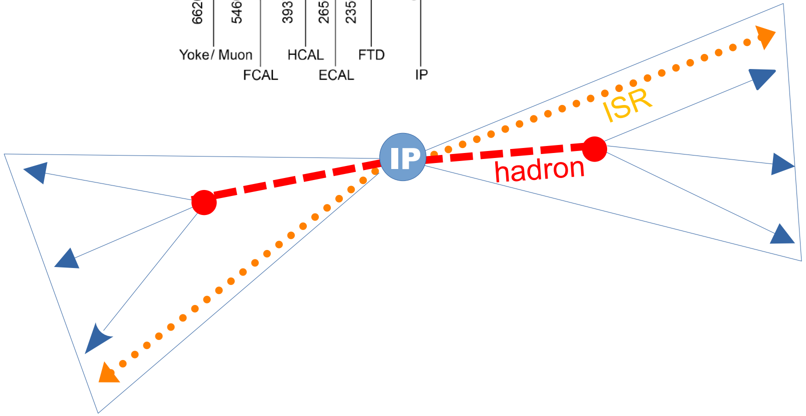
Heavy flavor production in $e^- e^+$ collisions

- 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.



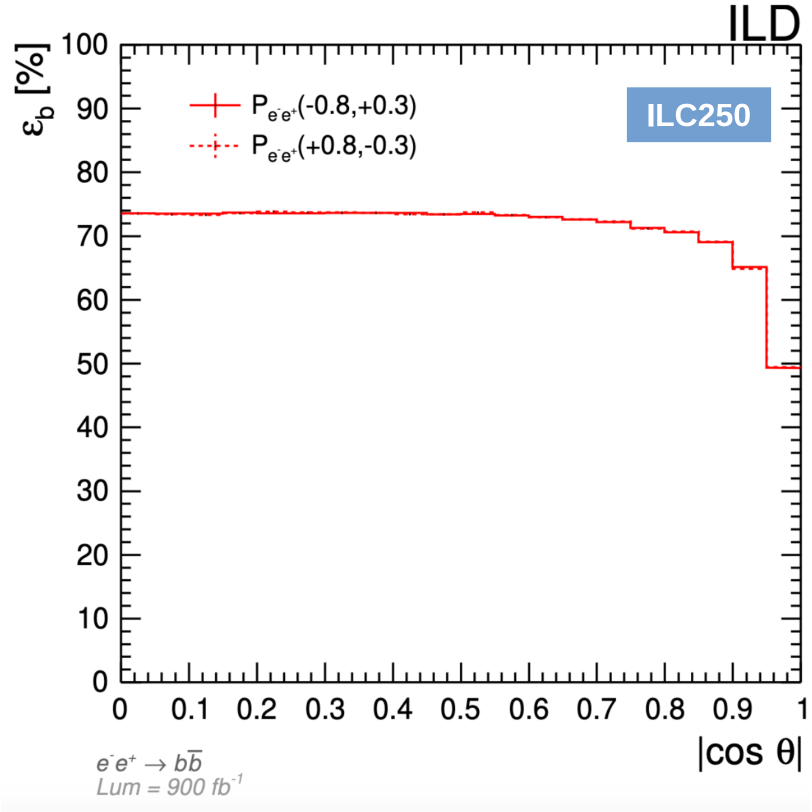
Particle flow detector

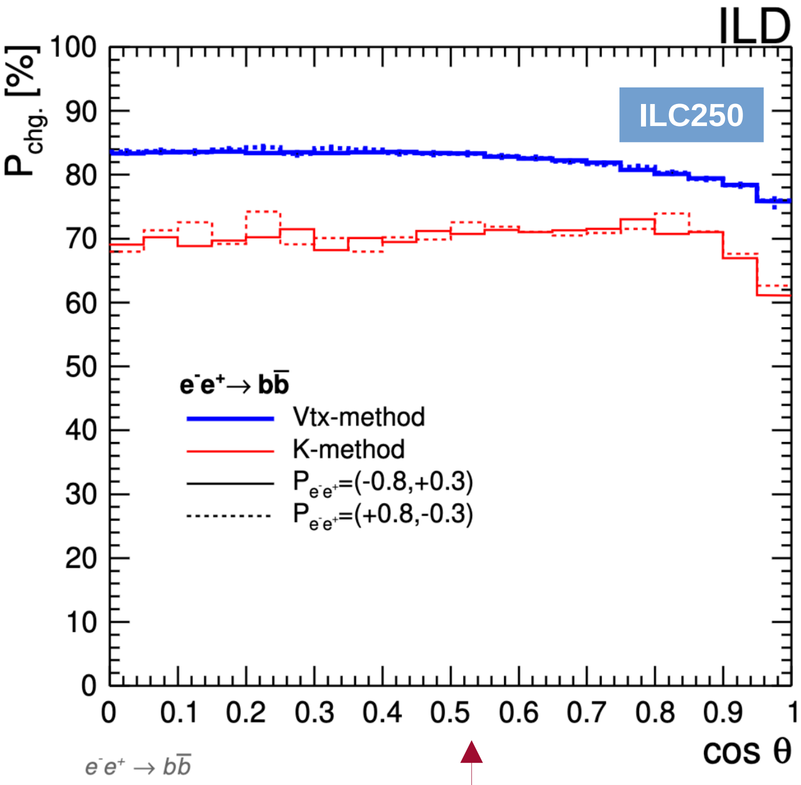


High-purity & independent samples for each quark flavour.

Jet flavor tagging & charge measurement

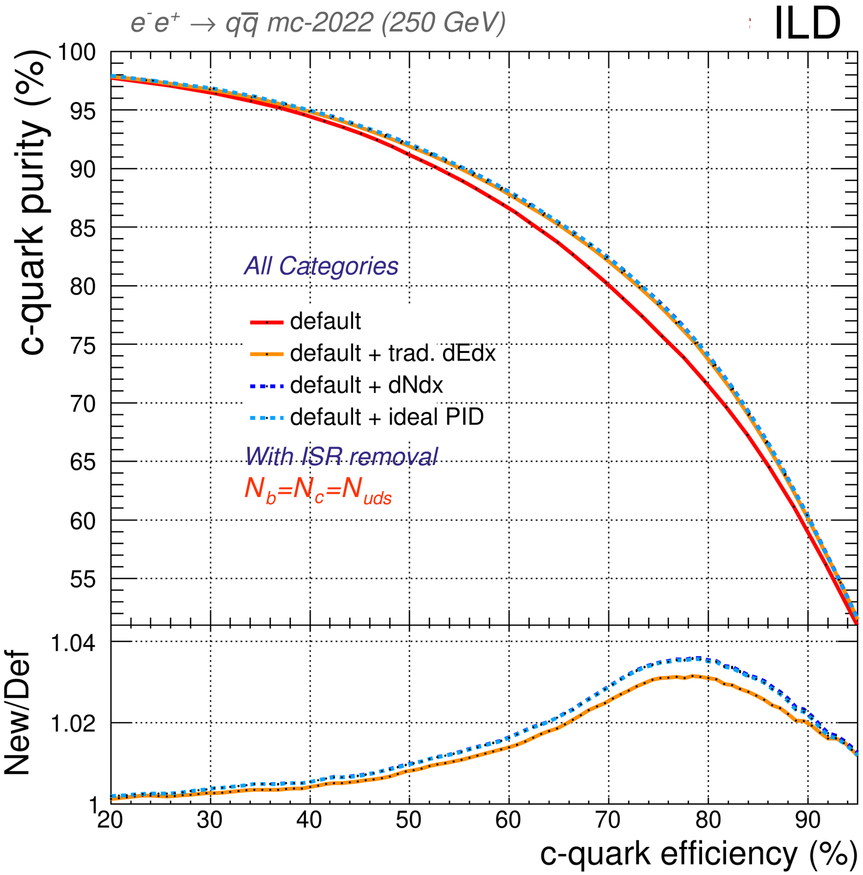
- Double tagging & double charge measurement methods. (described in previous ILD Note 2306.11413 (2022))
  - To maximally reduce the usage of MC tools (control of fragmentation, QCD correlations… uncertainties)

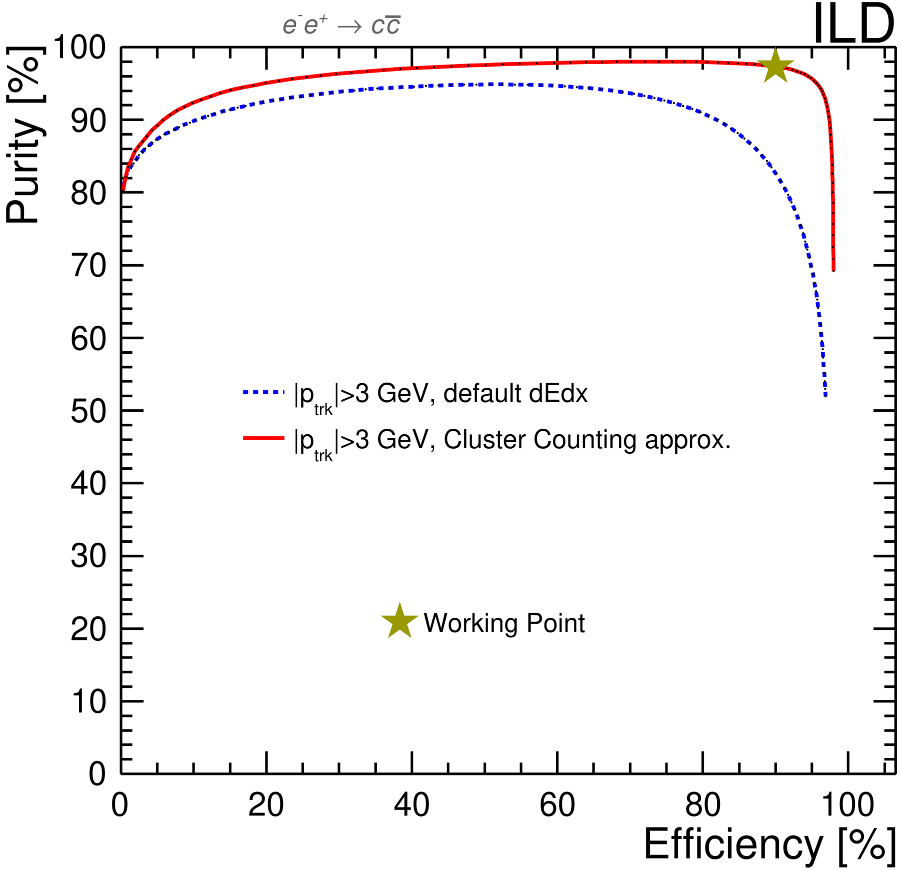




PID is very important for this measurement!

Effects of improving the use of PID



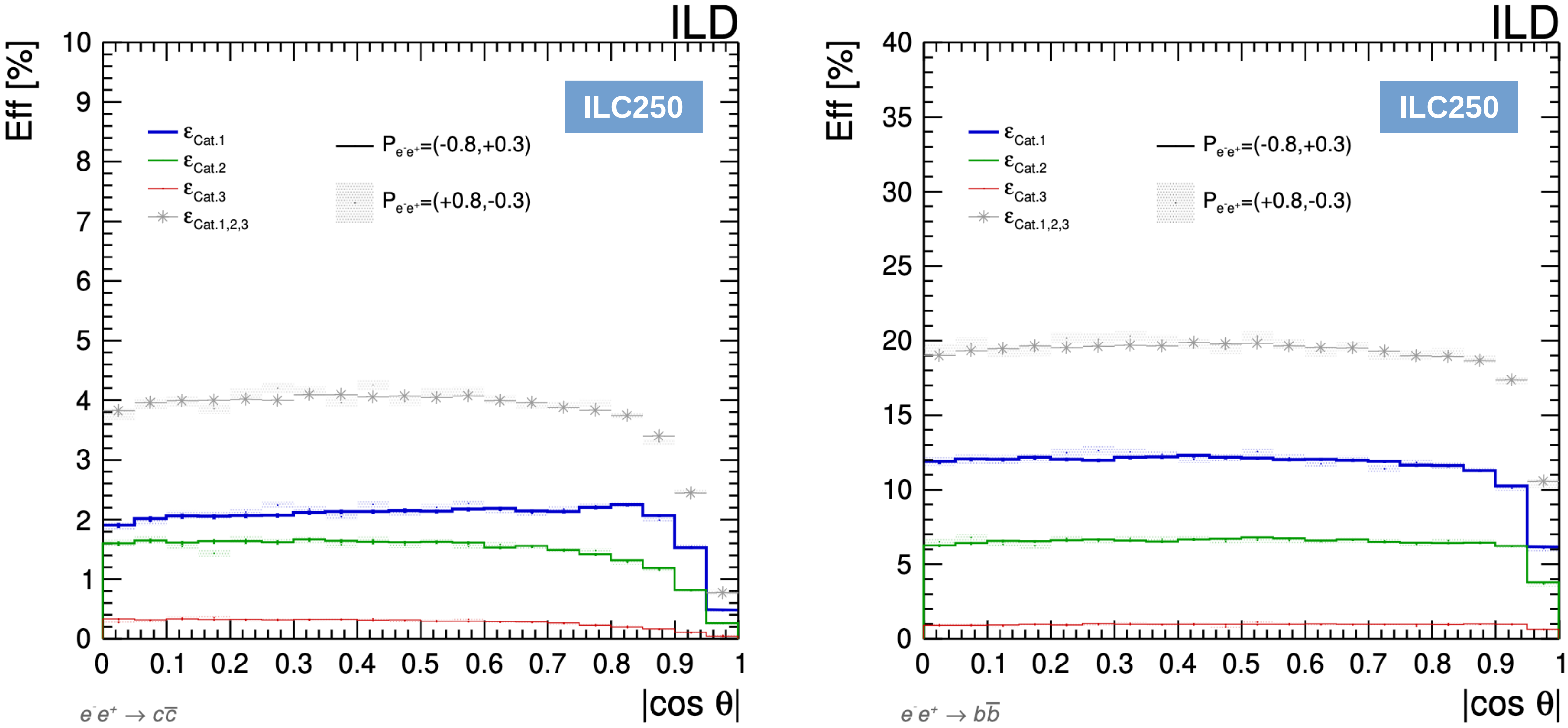


Effects in **Flavour Tagging**

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

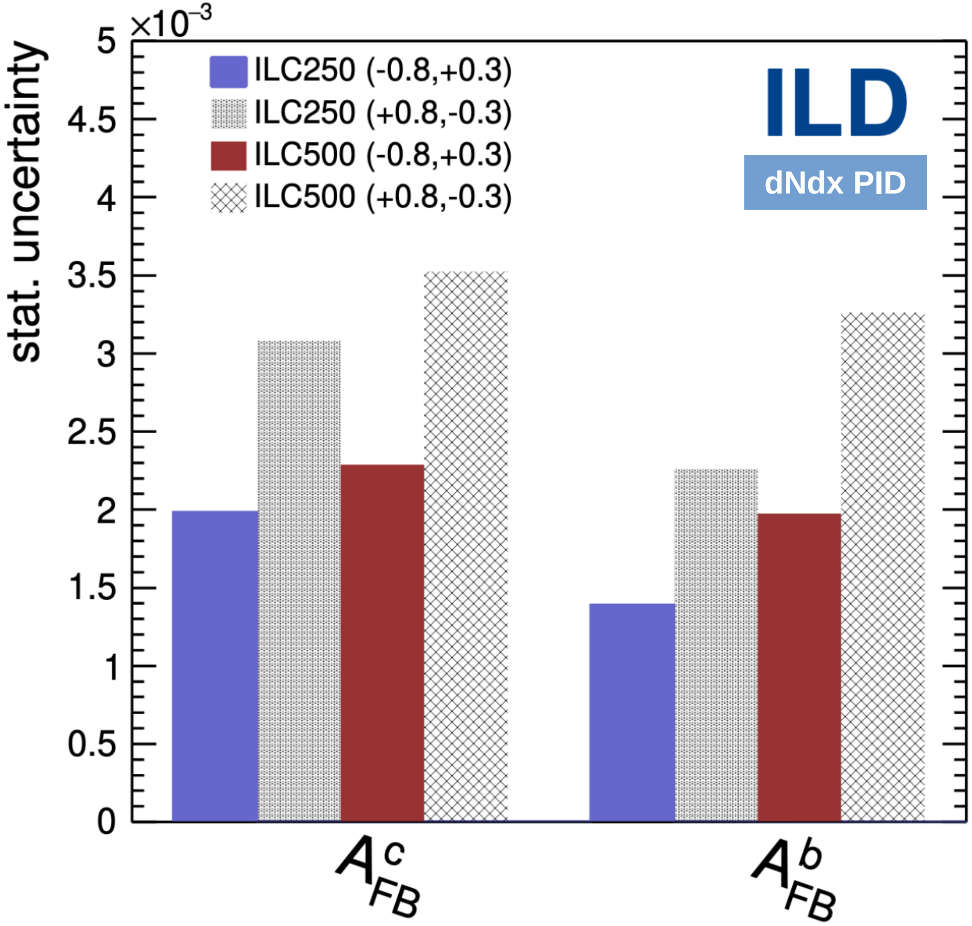
Results for ILC250 & ILC500

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

- **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 $\mathrm{AFB}_{\mathrm{test}}$ vs a reference model $\mathrm{AFB}_{\mathrm{ref}}$ assuming that one of then is measured.

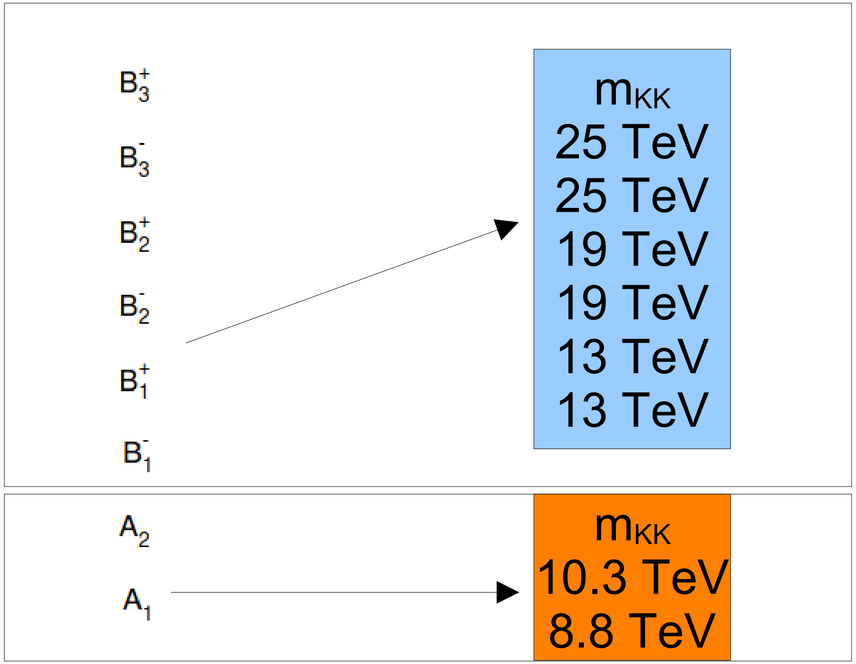
- The uncertainties are considered normally distributed:
  - Significance in σ.
  - P-value: Gaussian at d_σ.

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

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

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)
$\int L = 2000\ fb^{-1}$

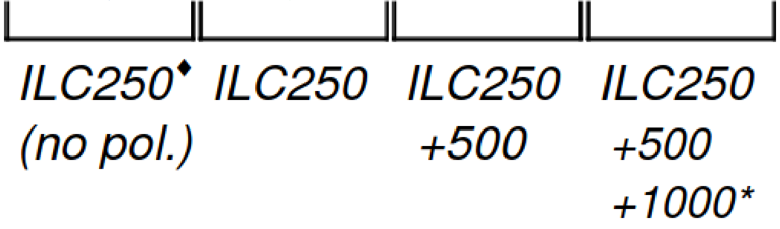
ILC500
(Pe-=0.8, Pe+=0.3)
$\int L = 4000\ fb^{-1}$

Full ILD simulation assuming beam pol.

H20 staged program

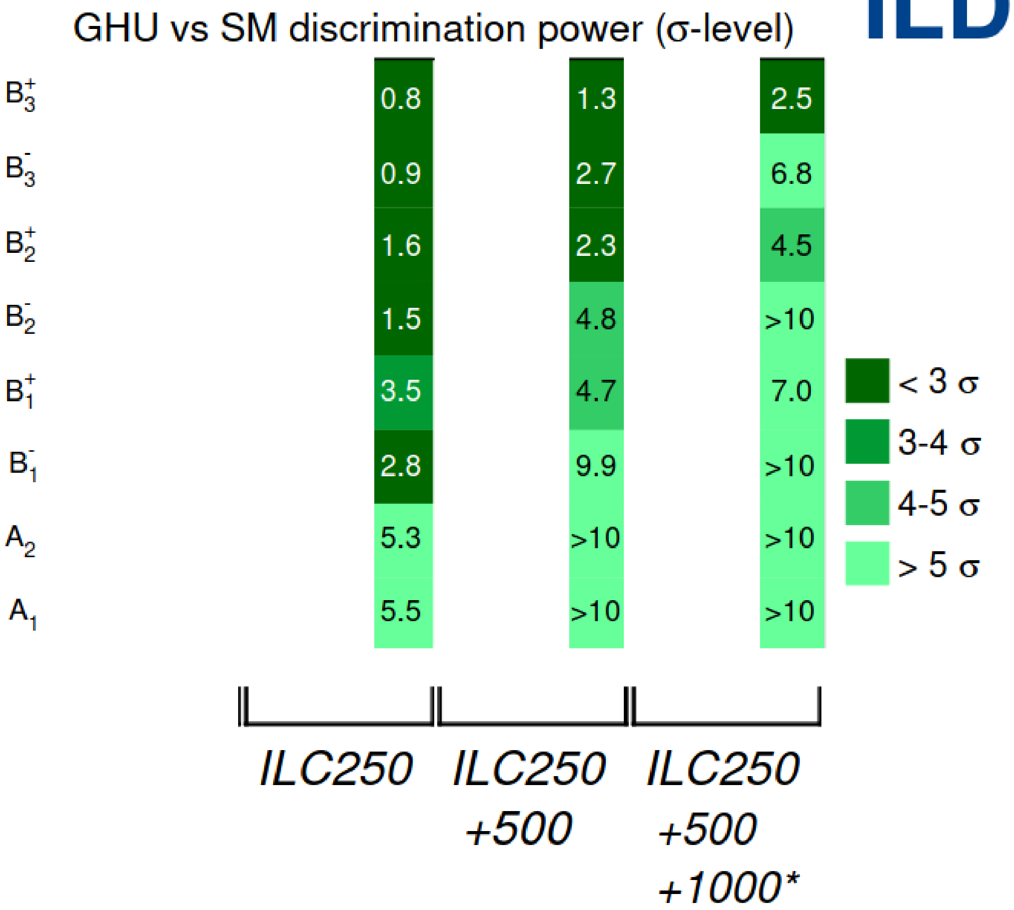
ILC1000
(Pe-=0.8, Pe+=0.2)
$\int L = 8000\ fb^{-1}$

Not full simulation studies but extrapolations from ILC500



GHU vs SM: center of mass energy

ILD



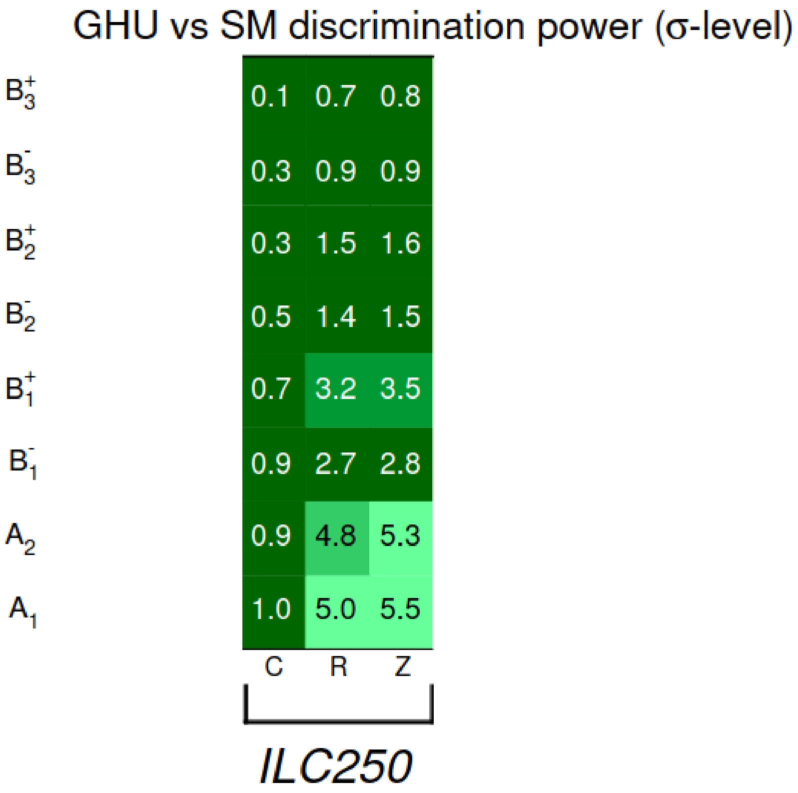
GHU vs SM discrimination power (σ-level)

	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

ILD



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

Z-fermion couplings

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

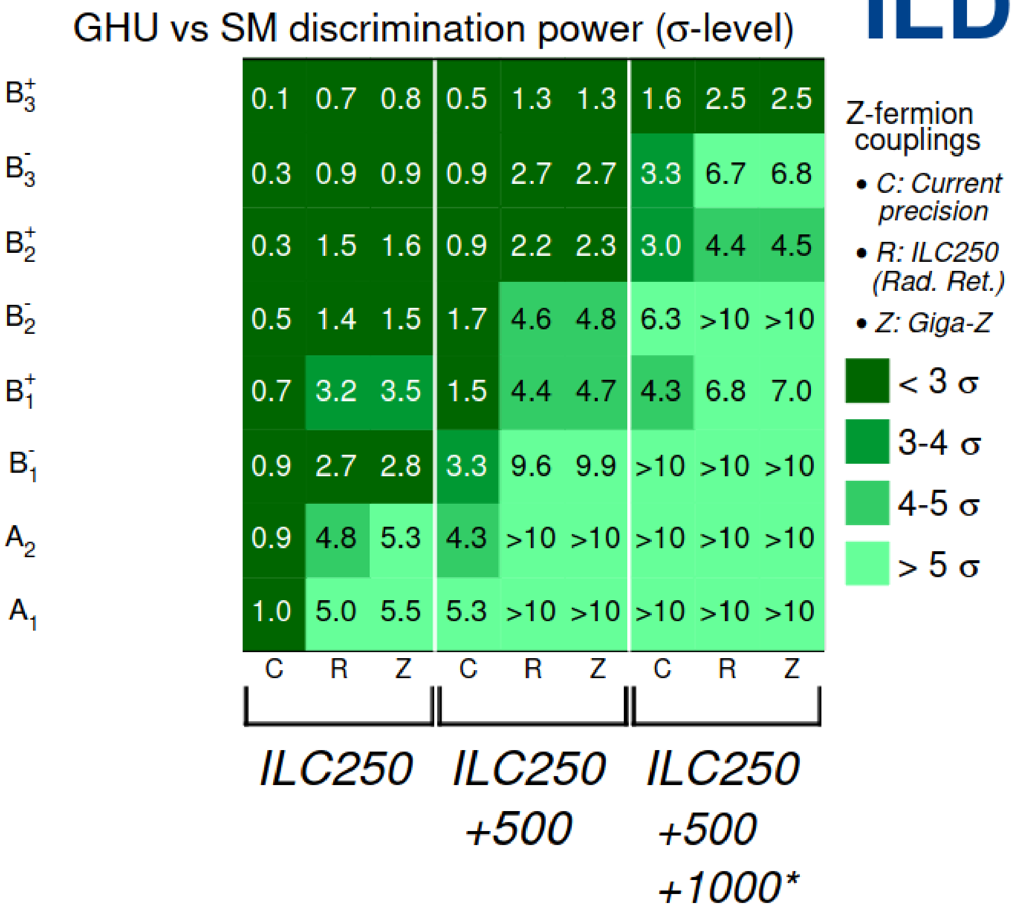
🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

GHU vs SM: Precision on Z-couplings



GHU vs SM discrimination power (σ-level)

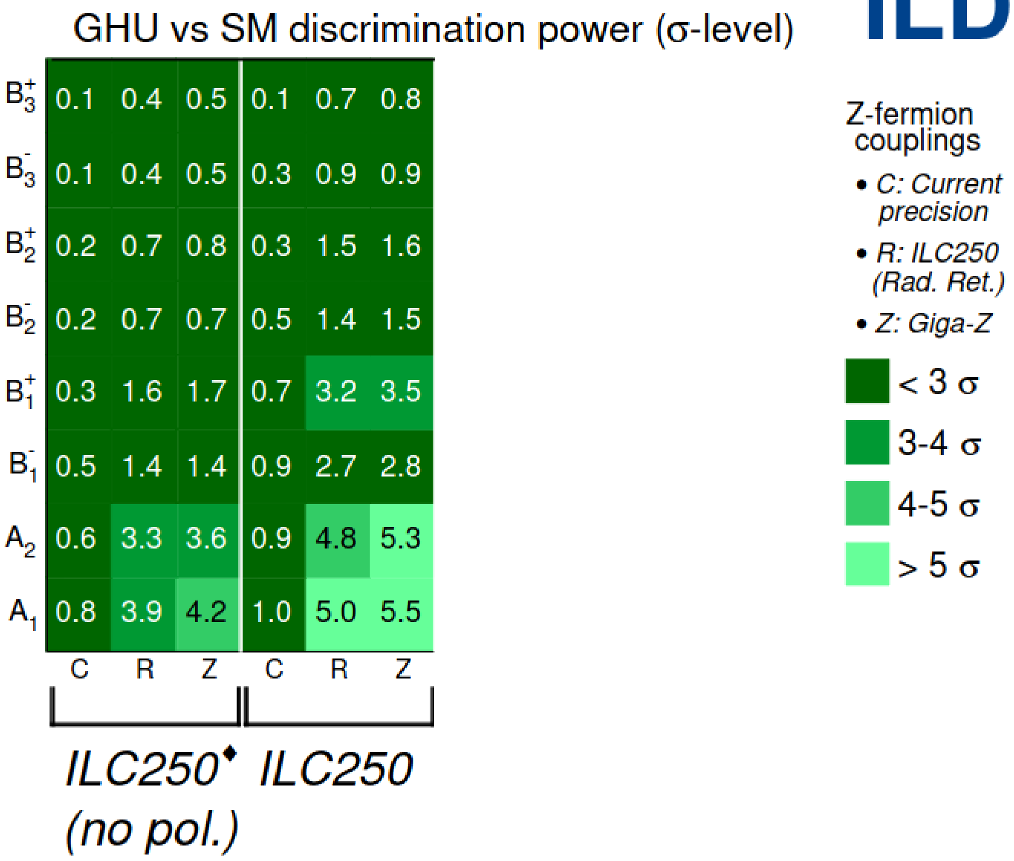
	ILC250			ILC250 +500			ILC250 +500 +1000*		
	C	R	Z	C	R	Z	C	R	Z
B_3^+	0.1	0.7	0.8	0.5	1.3	1.3	1.6	2.5	2.5
B_3^-	0.3	0.9	0.9	0.9	2.7	2.7	3.3	6.7	6.8
B_2^+	0.3	1.5	1.6	0.9	2.2	2.3	3.0	4.4	4.5
B_2^-	0.5	1.4	1.5	1.7	4.6	4.8	6.3	>10	>10
B_1^+	0.7	3.2	3.5	1.5	4.4	4.7	4.3	6.8	7.0
B_1^-	0.9	2.7	2.8	3.3	9.6	9.9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



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*

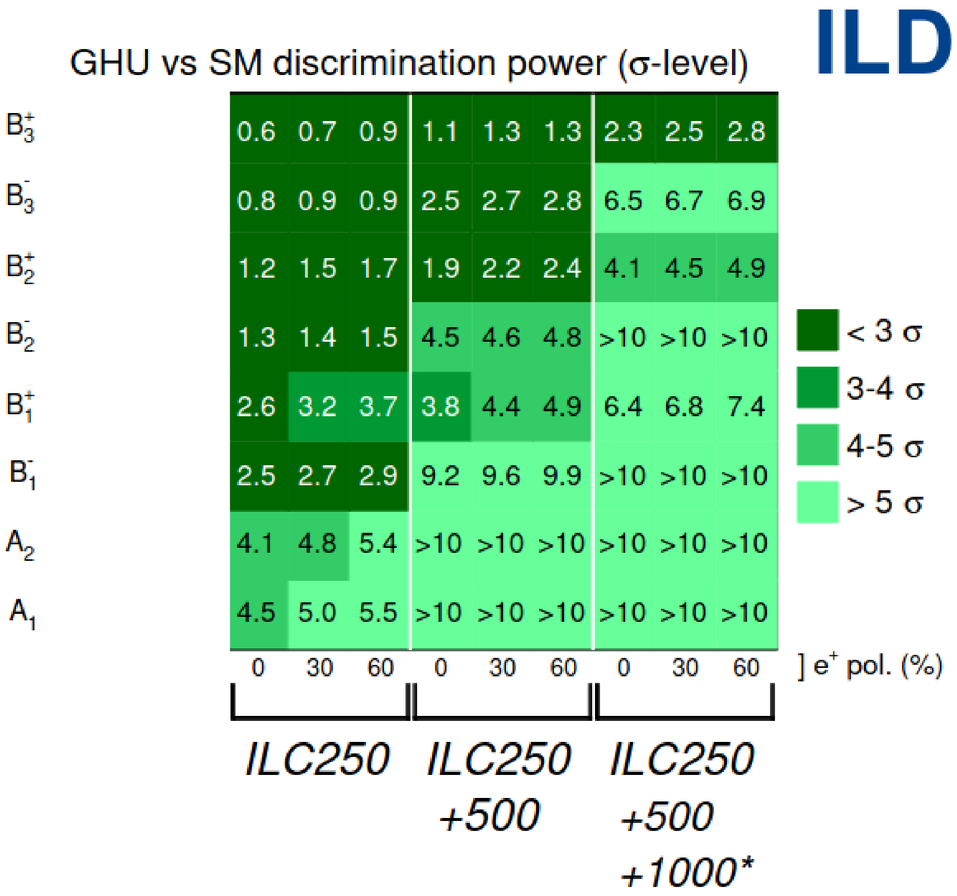
🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

GHU vs SM: Positron beam polarization

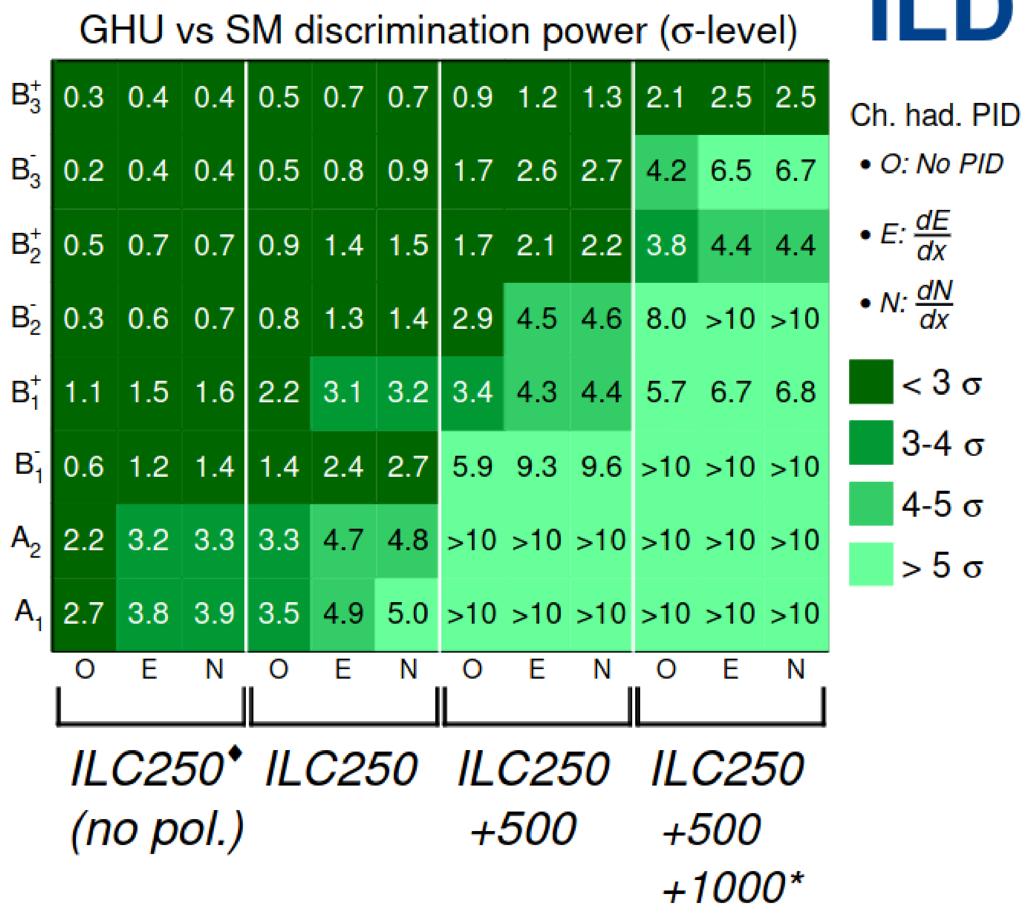


GHU vs SM discrimination power (σ-level)

	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

e- polarization at 80% in all of these scenarios

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:* $\frac{dN}{dx}$

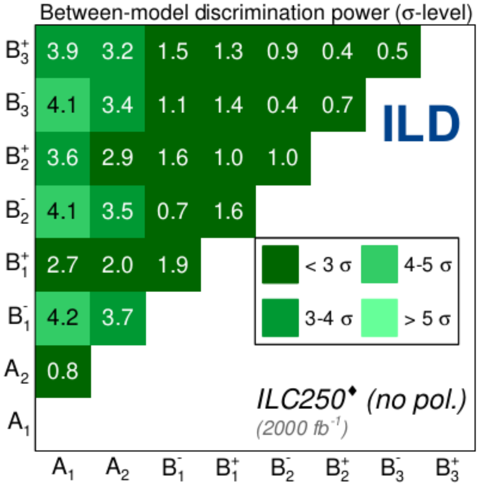
🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

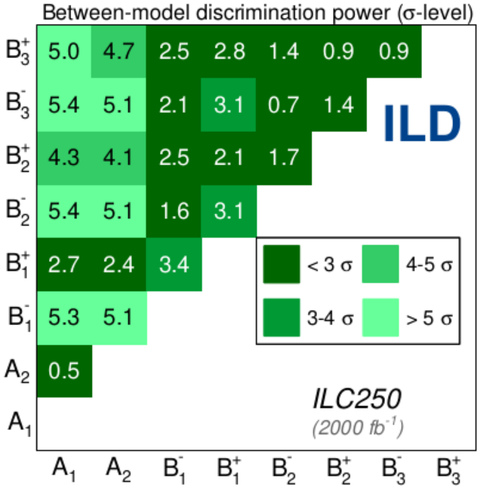
GHU between model discrimination



Between-model discrimination power (σ-level)

	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								

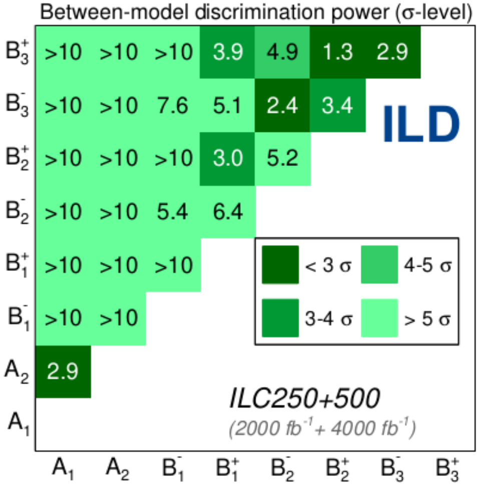
ILC250♦ (no pol.)
($2000\ fb^{-1}$)



Between-model discrimination power (σ-level)

	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								

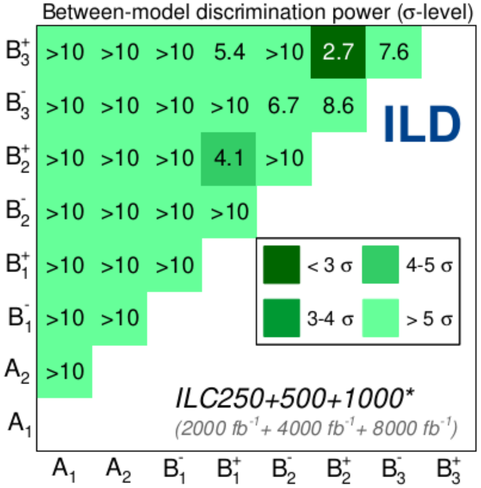
ILC250
($2000\ fb^{-1}$)



Between-model discrimination power (σ-level)

	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								

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



Between-model discrimination power (σ-level)

	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								

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

Conclusion/ summary

Conclusions and summary (GHU)

- 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!**

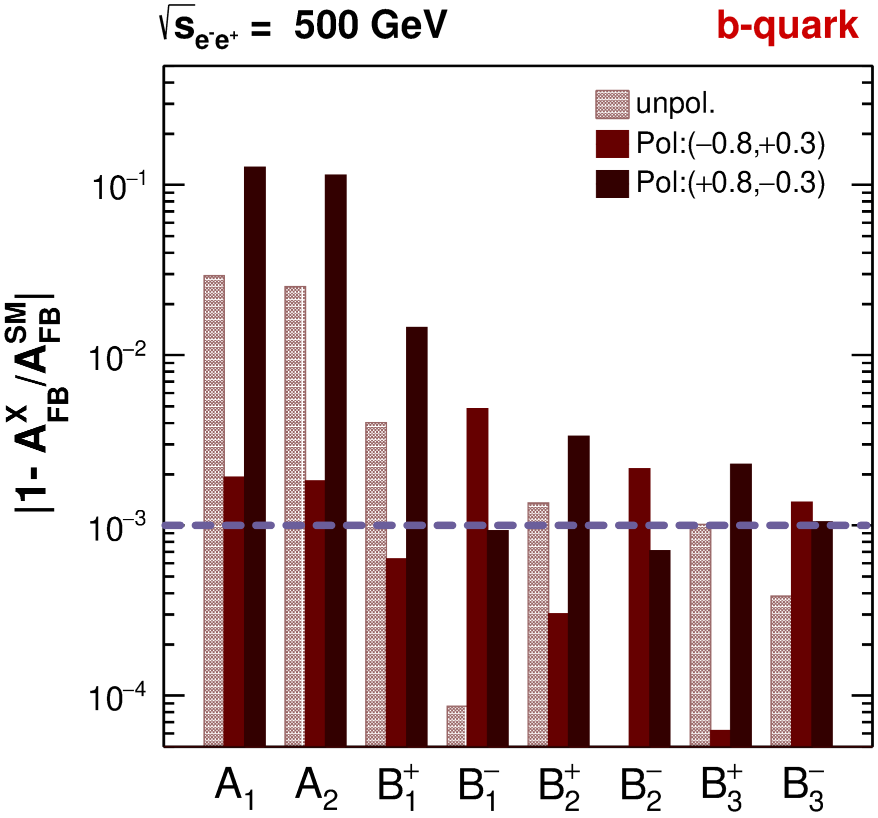
END
OF THE
PRESENTATION

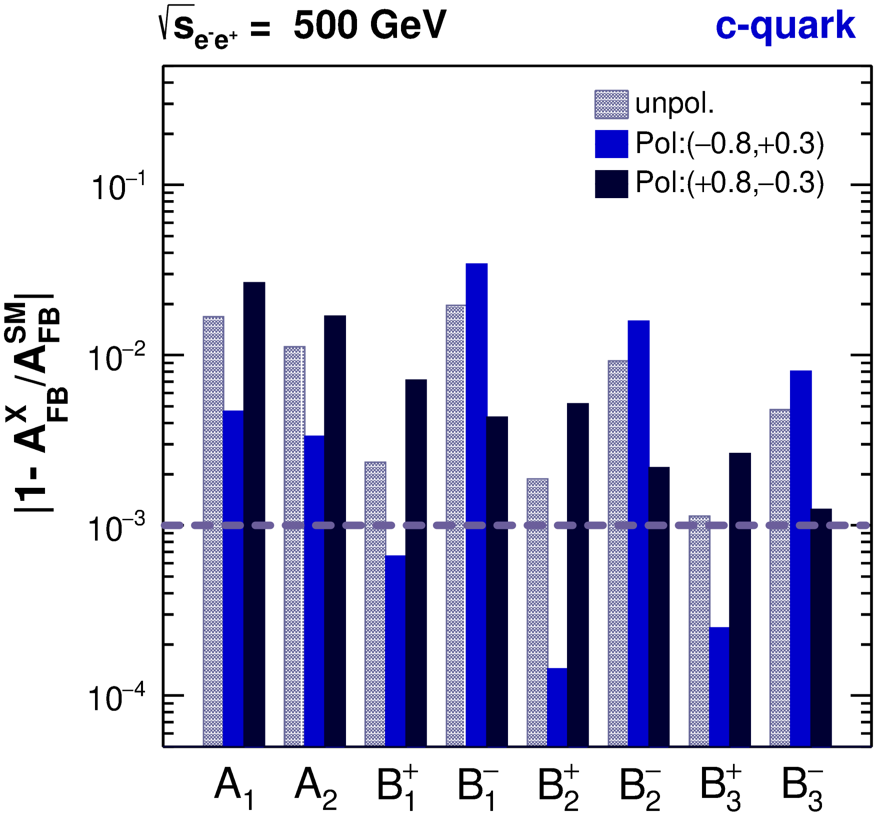
THANKS FOR YOUR ATTENTION,

Jesús P. Márquez Hernández

back-up

GHU vs SM (500 GeV)

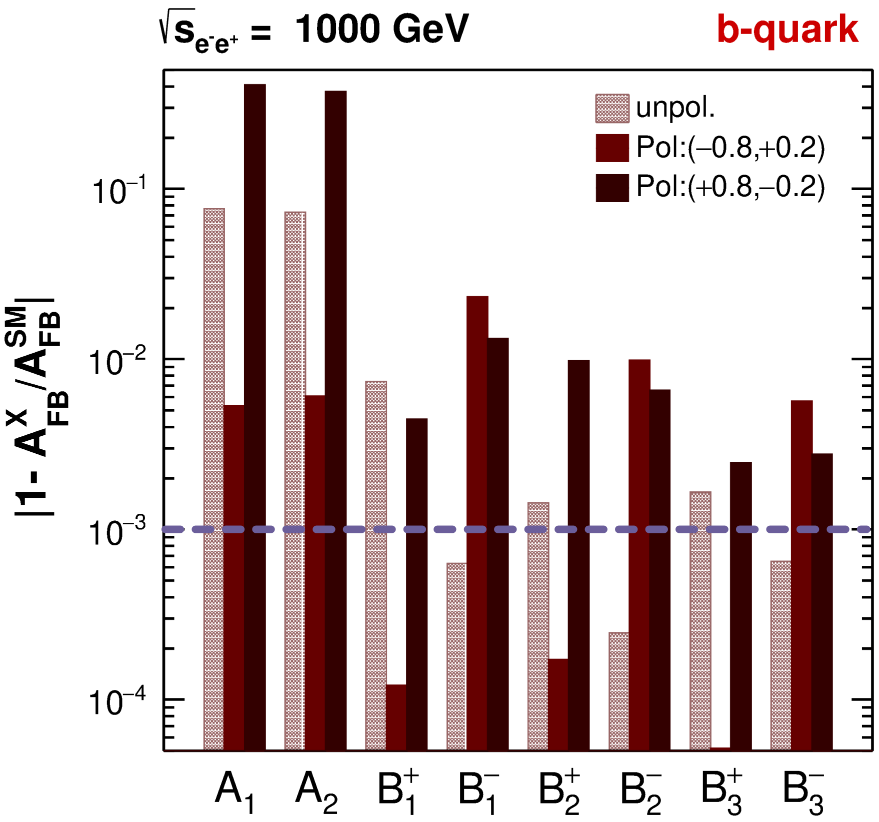


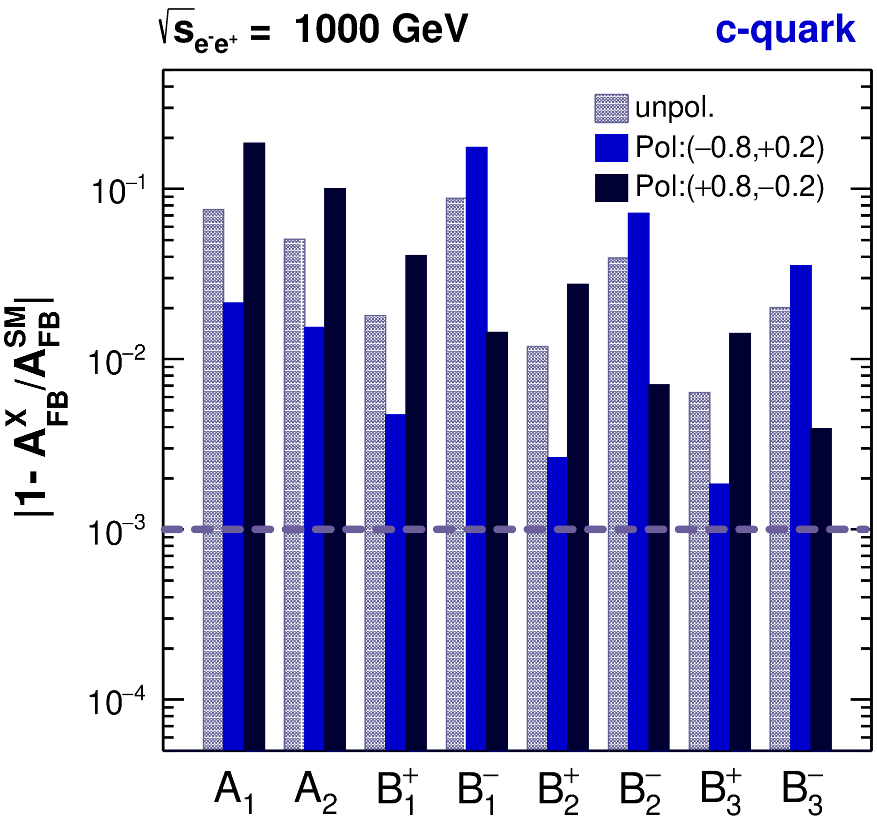


Deviations at the per mil level

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

GHU vs SM (1 TeV)



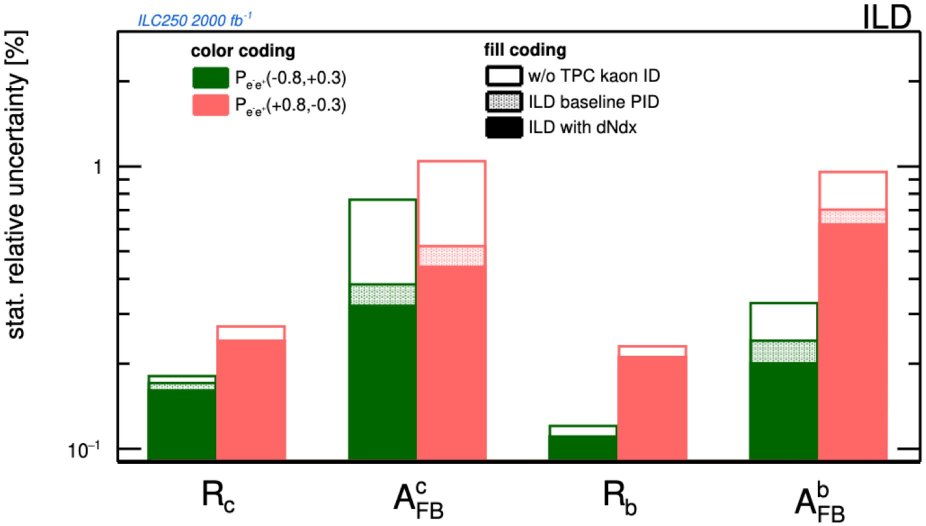


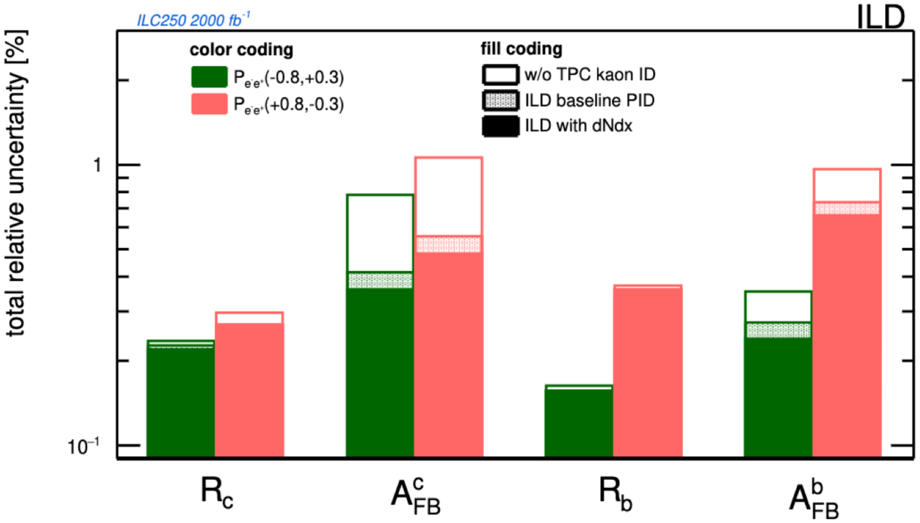
Deviations at the per mil level

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

Uncertainties ILC250

- Presented in LCWS (2023) 2307.14888

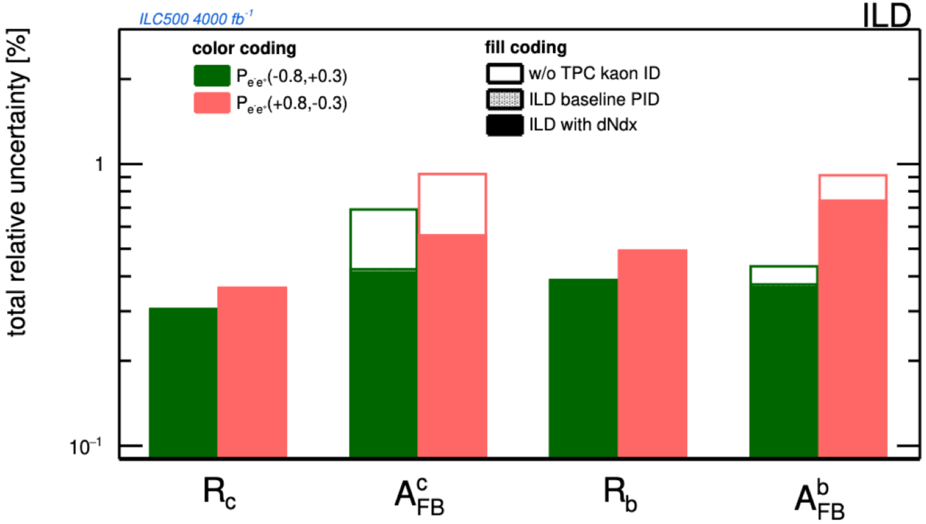


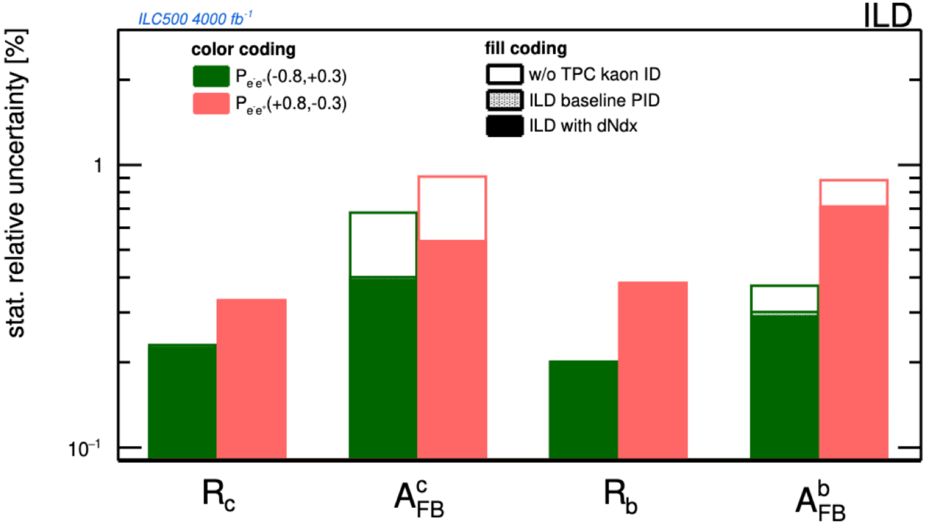


Statistical uncertainties dominate over systematic uncertainties

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.

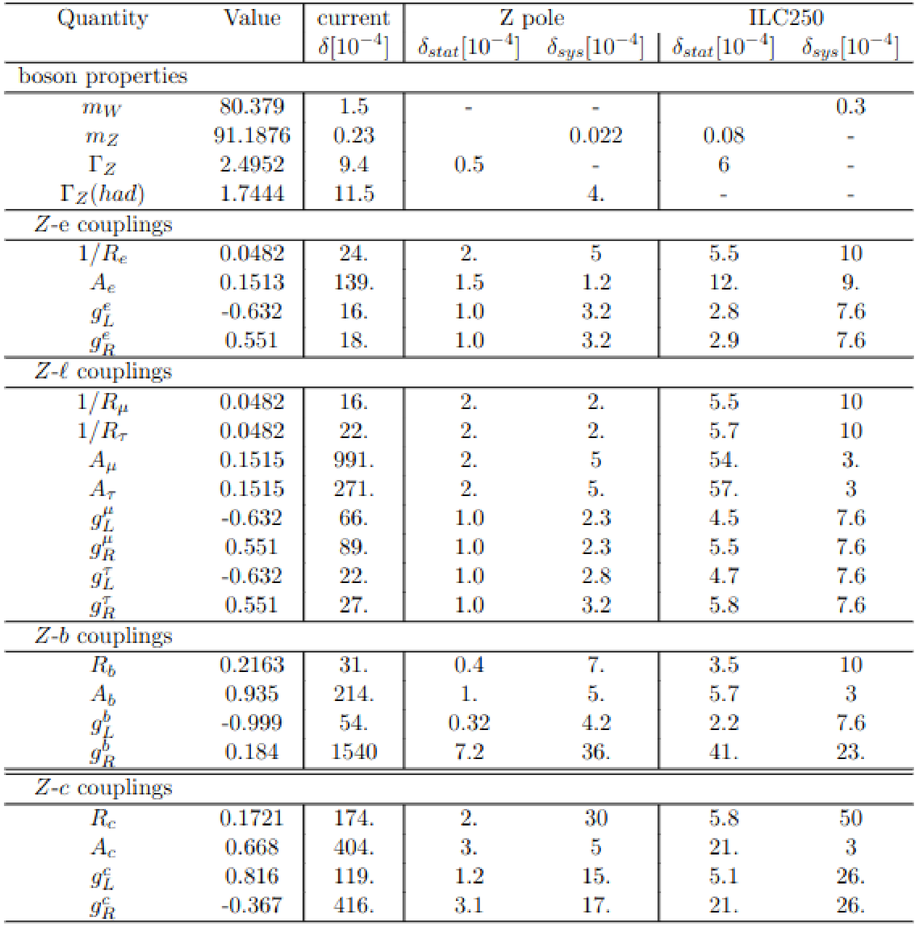




Statistical uncertainties dominate over systematic uncertainties

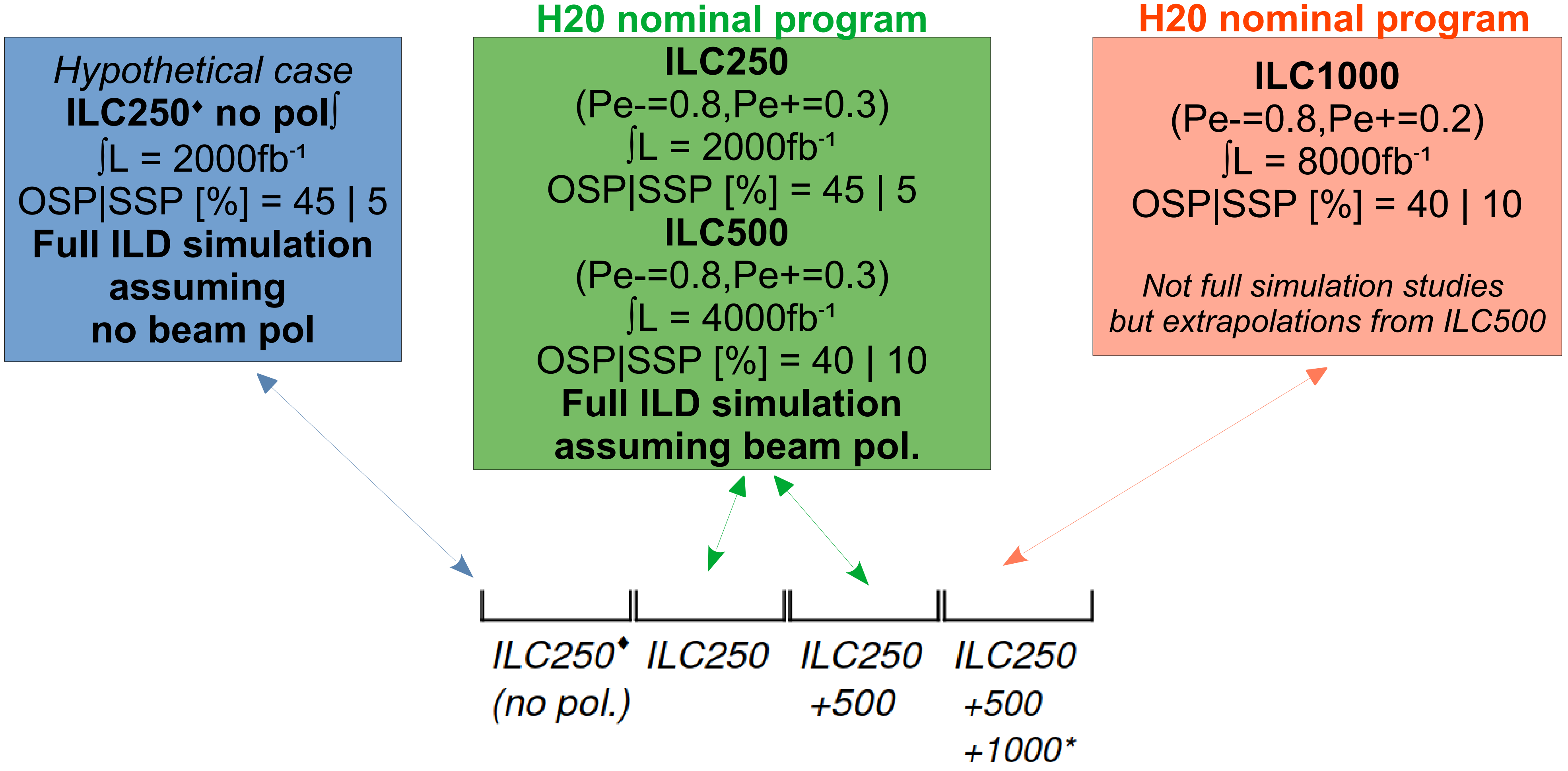
Z-couplings

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



Quantity	Value	current	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.

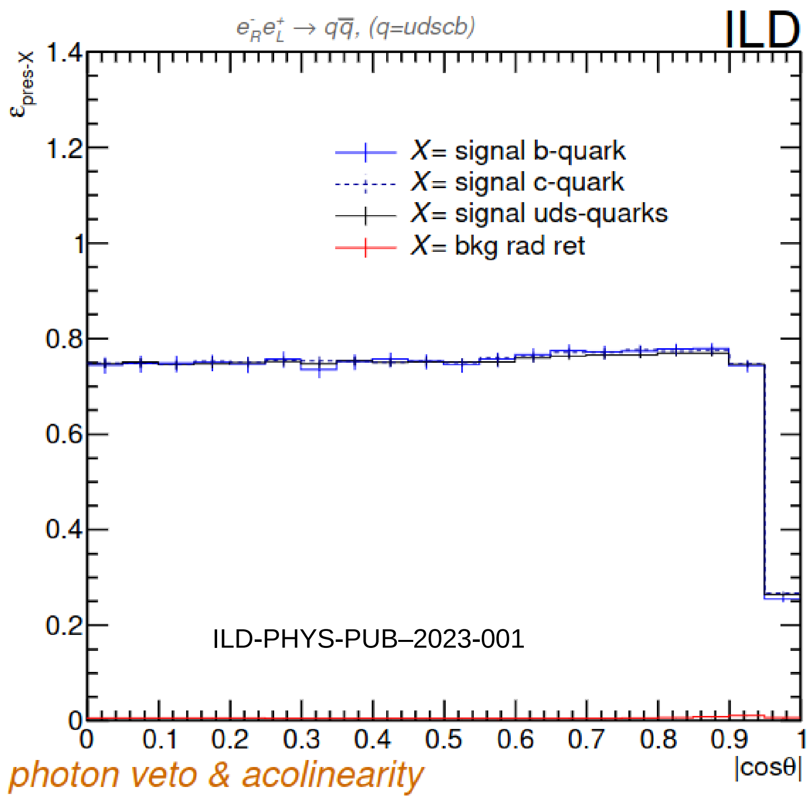
H20 nominal program

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

Not full simulation studies but extrapolations from ILC500

Preselection

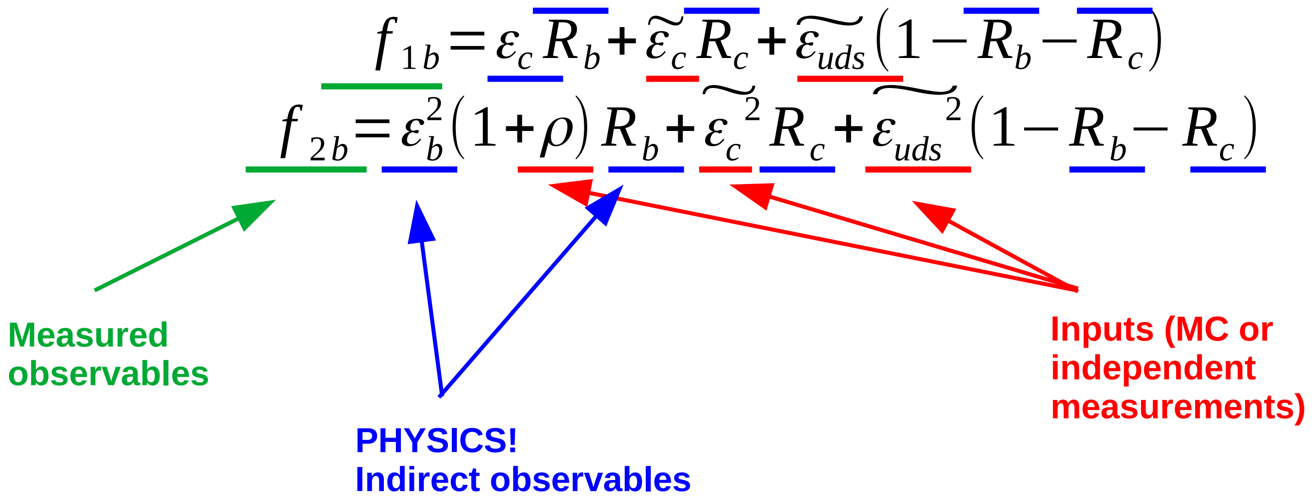
- **Topology: 2 back-to-back jets (pencil-like topology)**
- **Preselection aiming for high background rejection and high efficiency.**
- Main bkg ee→ Zγ(radiative return through ISR)
  - ~x10 larger than signal
  - **~90% of such ISR photons are lost in the beam pipe** → events filtered by energy &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



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

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

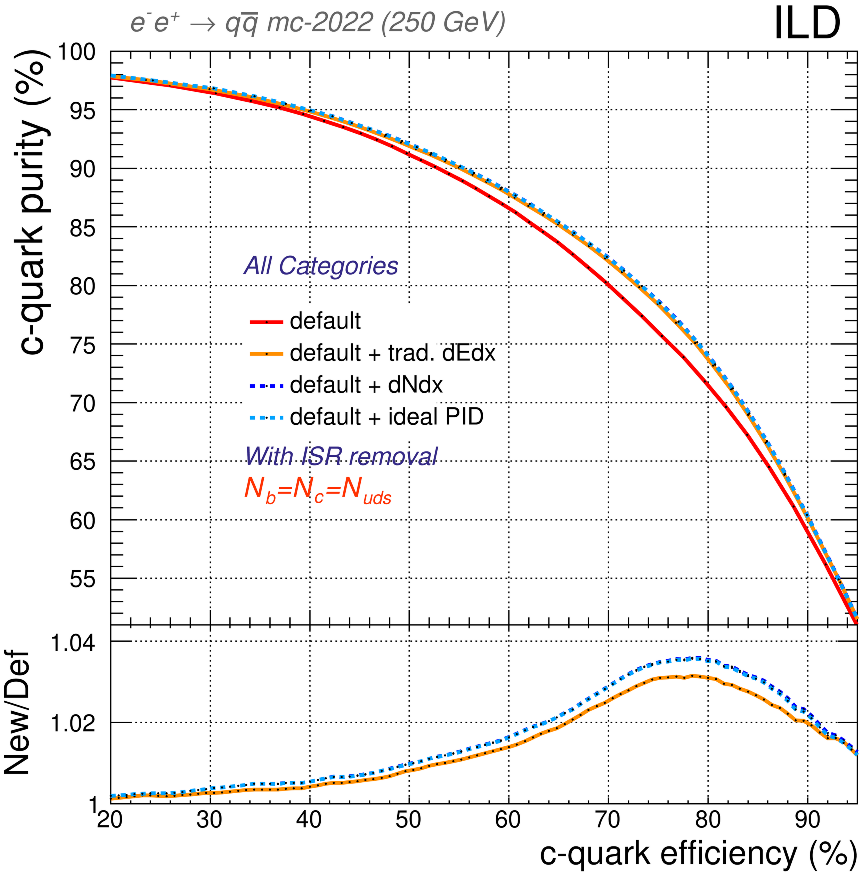
Measured
observables

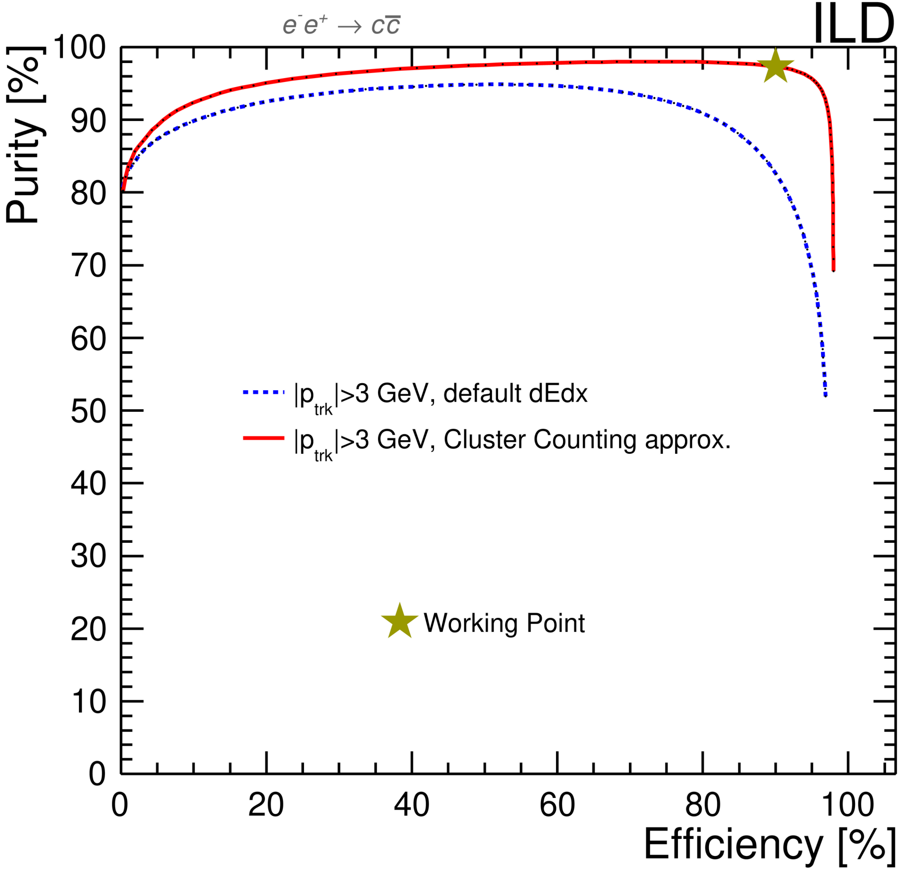
PHYSICS!
Indirect observables

Inputs (MC or
independent
measurements)

Similar set of equations
for the c-quark
solved simultaneously

PID: From dEdx to dNdx





Effects in **Flavour Tagging**

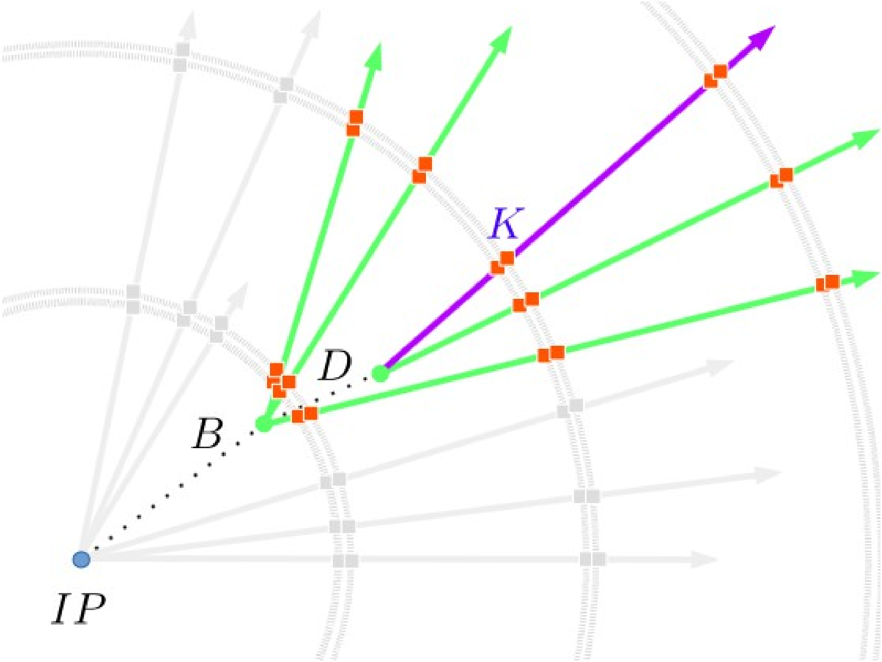
Effects in **Kaon ID** for charge reco.

Jet charge

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

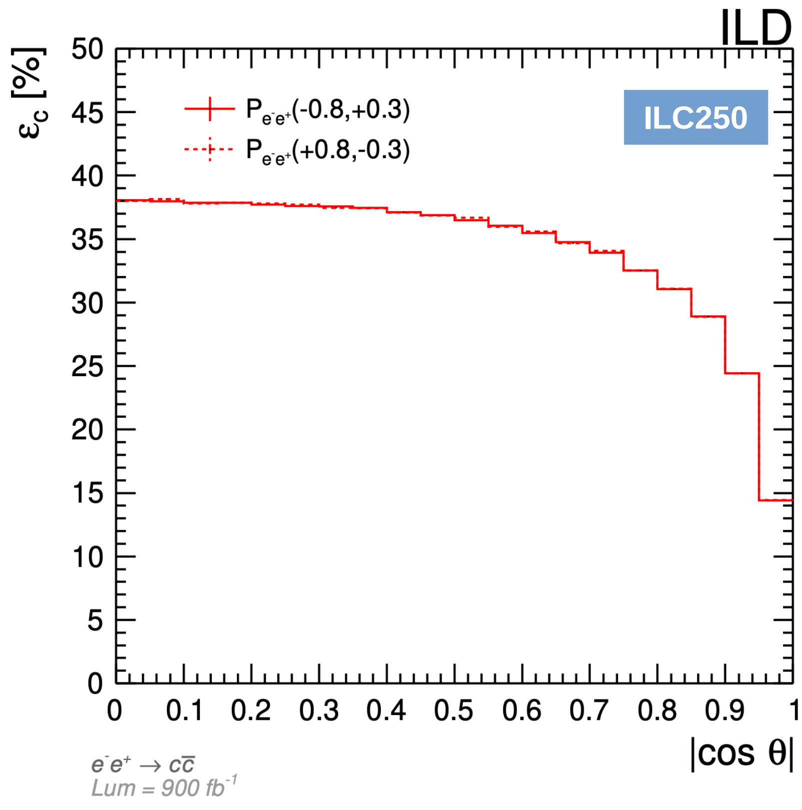
- ▶ We are required to **measure the jet charge**
  - Using K-ID and/or full Vtx charge measurement
  - K-ID is better suited for the C-quark (Vtx is better suited for b-quark)

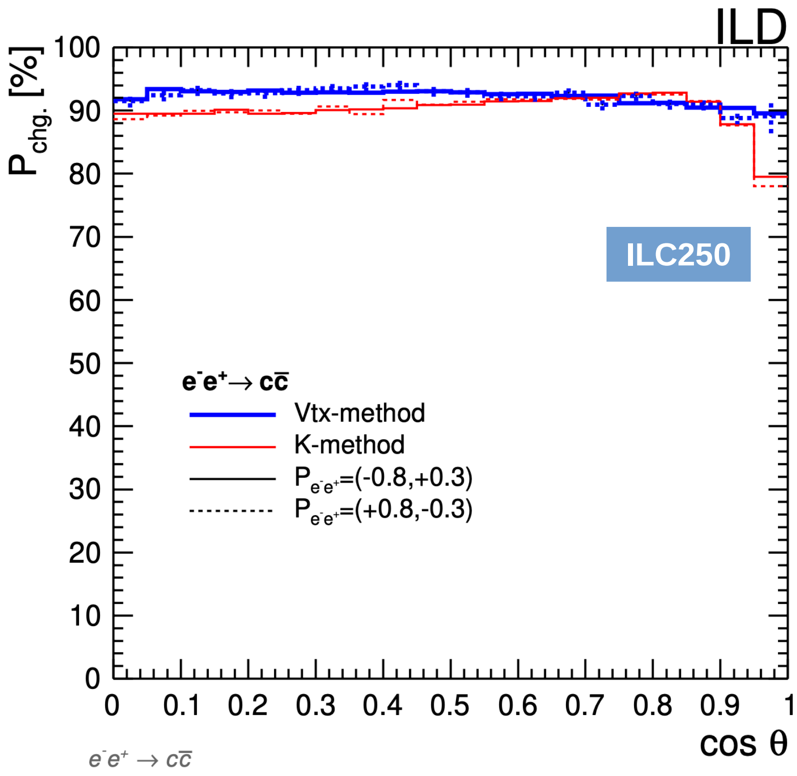
- ▶ We use the **double charge** measurements
  - To control / reduce the systematic uncertainties



Jet flavour tagging & charge measurement

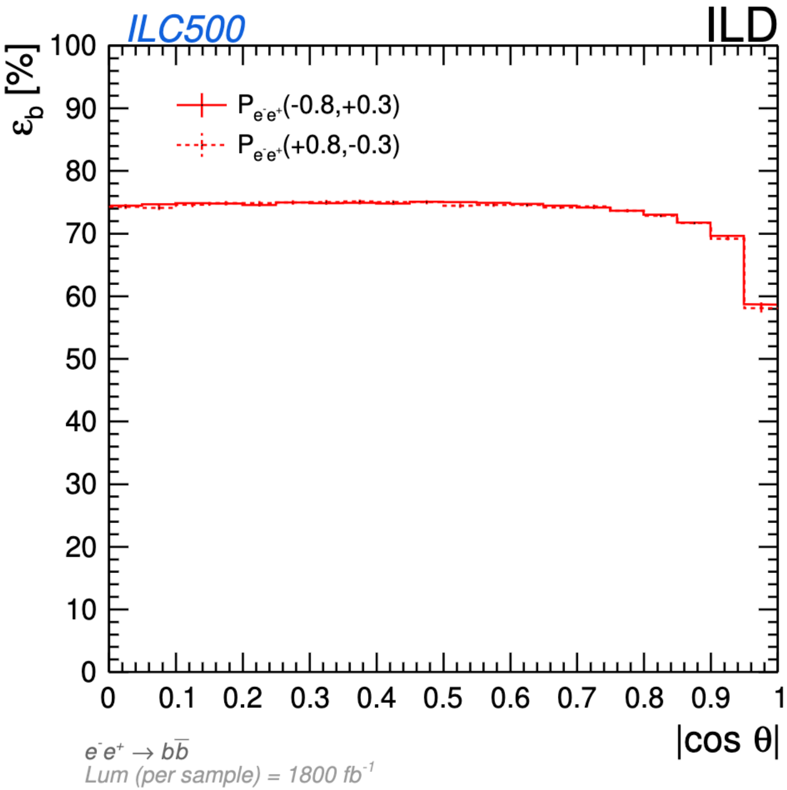
- Double tagging & double charge measurement methods. (described in previous ILD Note 2306.11413 (2022))
  - To maximally reduce the usage of MC tools (control of fragmentation, QCD correlations… uncertainties)

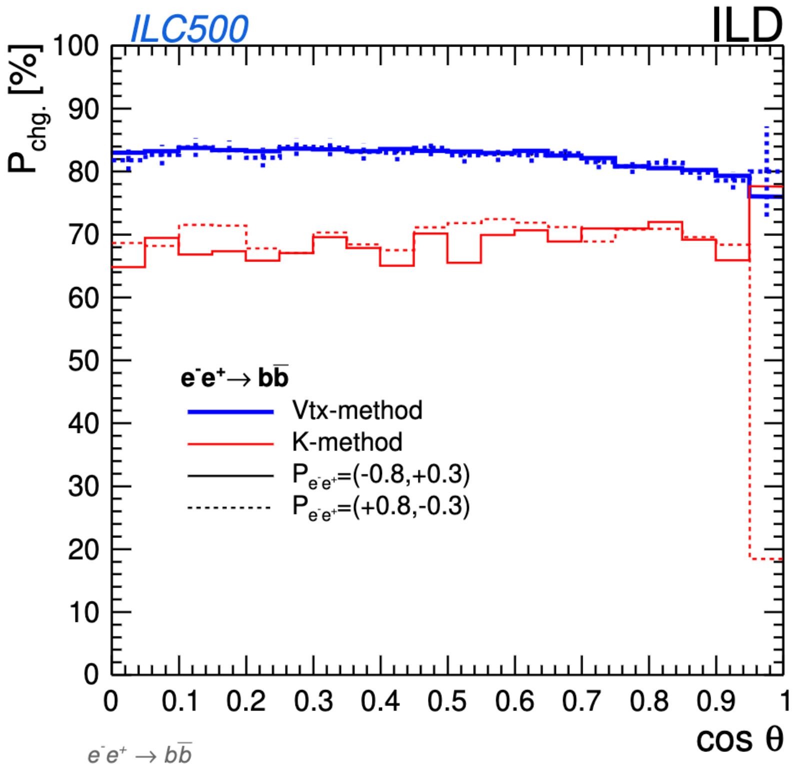




Jet flavour tagging & charge measurement

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





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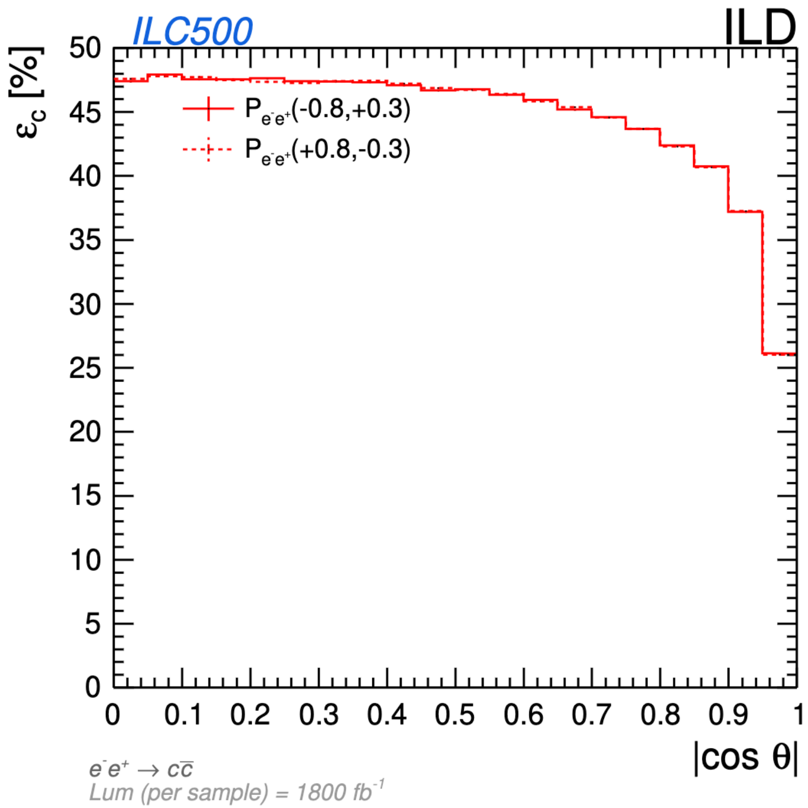

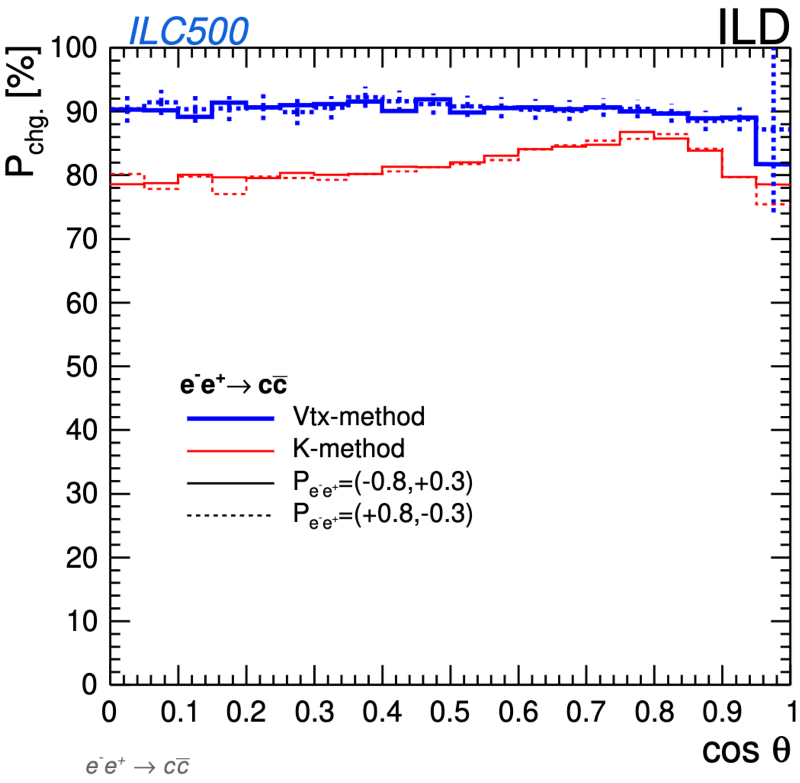

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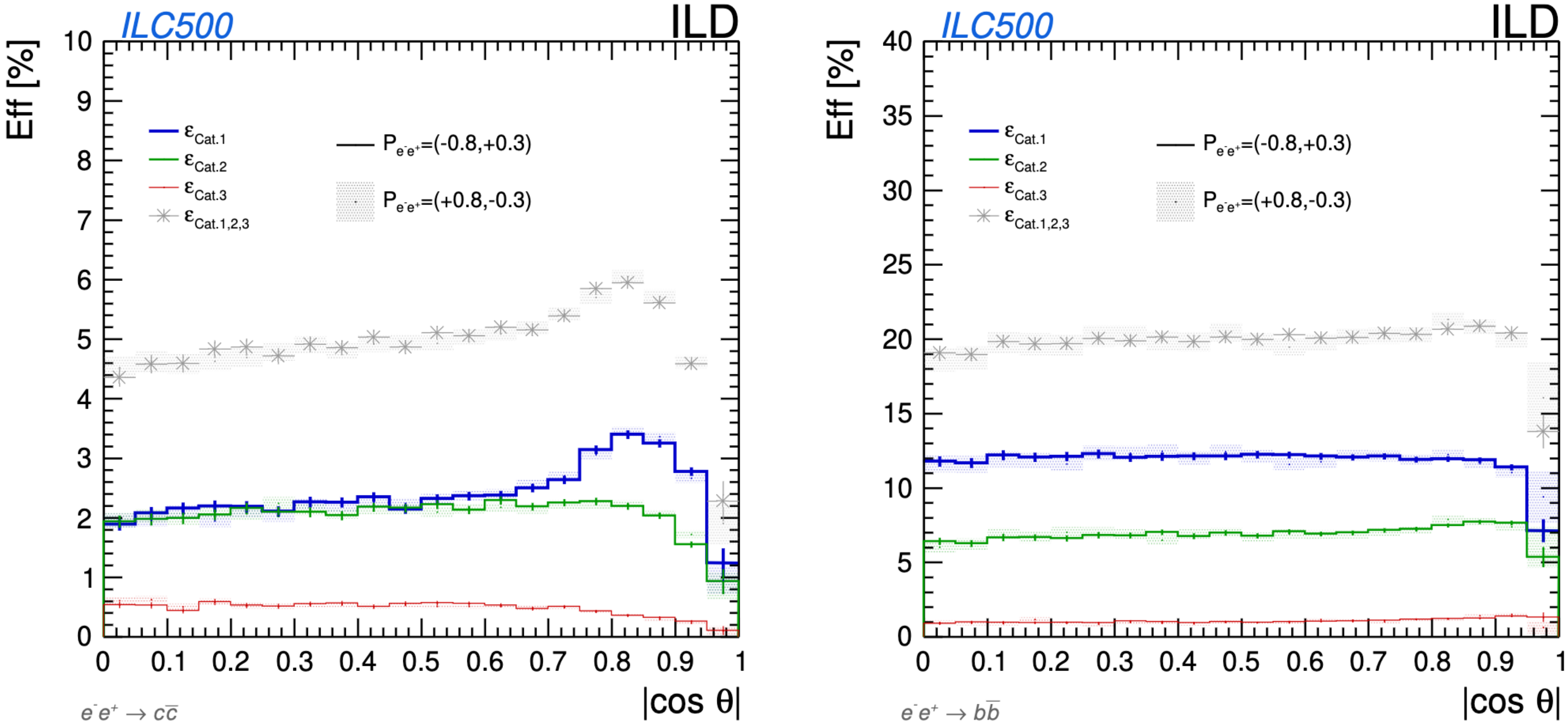

Selection for the A_{FB} measurement at 500 GeV

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

- **Per mil level statistical uncertainties** reachable for the nominal **ILC program**

- **Smaller exp syst. Uncertainties.**
  - Fragmentation, angular correlations, preselection efficiency, mistag, etc.