First months' activities:
GHU phenomenology & $s\bar{s}$ analysis

Jesús P. Márquez Hernández

Reunion groupe 24/07/25

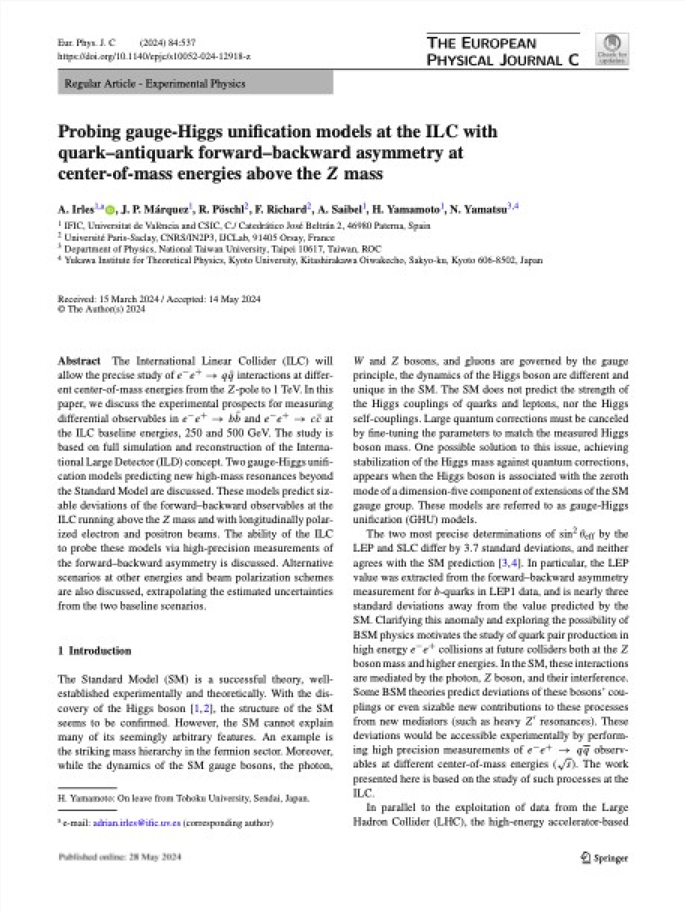
GHU Phenomenology

CALO5D

A new dimension in shower reconstruction

Long-term analysis

- Done and published (EPJ-C) with **b and c quarks**
  - Uncertainties:
    - Precision on Z-couplings
    - Statistics after the bb and cc event selection
    - Systematics calculated, but not included
  - Compared some different cases:
    - Different precision on Z-couplings (Current, Radiative returns in ILC250, Giga-Z)
    - Positron polarization (0%, 30%, 60%)
    - Different PID used in the TPC (none, dE/dx, dN/dx)



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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

A. Irles[1,a], **J. P. Márquez**[1], **R. Pöschl**[2], **F. Richard**[2], **A. Saibel**[1], **H. Yamamoto**[1], **N. Yamatsu**[3,4]
[1] IFIC, Universitat de València and CSIC, C./ Catedrático José Beltrán 2, 46980 Paterna, Spain
[2] Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
[3] Department of Physics, National Taiwan University, Taipei 10617, Taiwan, ROC
[4] Yukawa Institute for Theoretical Physics, Kyoto University, Kitashirakawa Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan

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Abstract The International Linear Collider (ILC) will allow the precise study of $e^-e^+ \rightarrow q\bar{q}$ interactions at different center-of-mass energies from the Z-pole to 1 TeV. In this paper, we discuss the experimental prospects for measuring differential observables in $e^-e^+ \rightarrow b\bar{b}$ and $e^-e^+ \rightarrow c\bar{c}$ at the ILC baseline energies, 250 and 500 GeV. The study is based on full simulation and reconstruction of the International Large Detector (ILD) concept. Two gauge-Higgs unification models predicting new high-mass resonances beyond the Standard Model are discussed. These models predict 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 $\sin^2\theta_{eff}$ 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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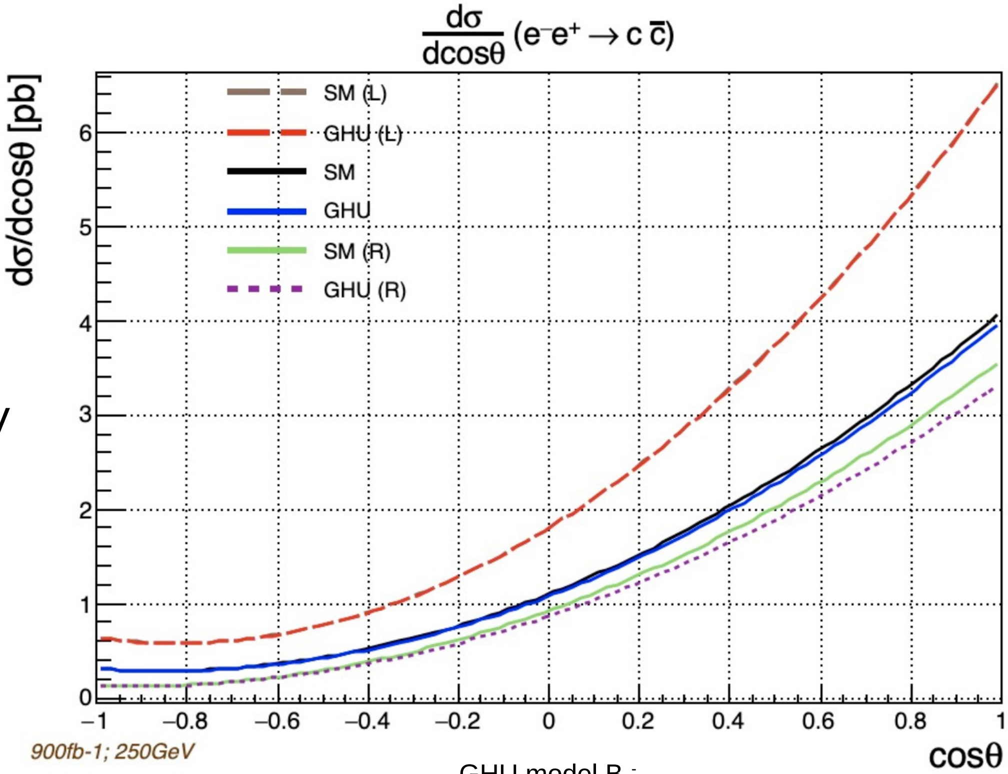
[a] e-mail: adrian.irles@ific.uv.es (corresponding author)

Springer

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



GHU model B_1^-

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

Gauge-Higgs Unification Models (GHU)

- A models: (arxiv:1705.05282)

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

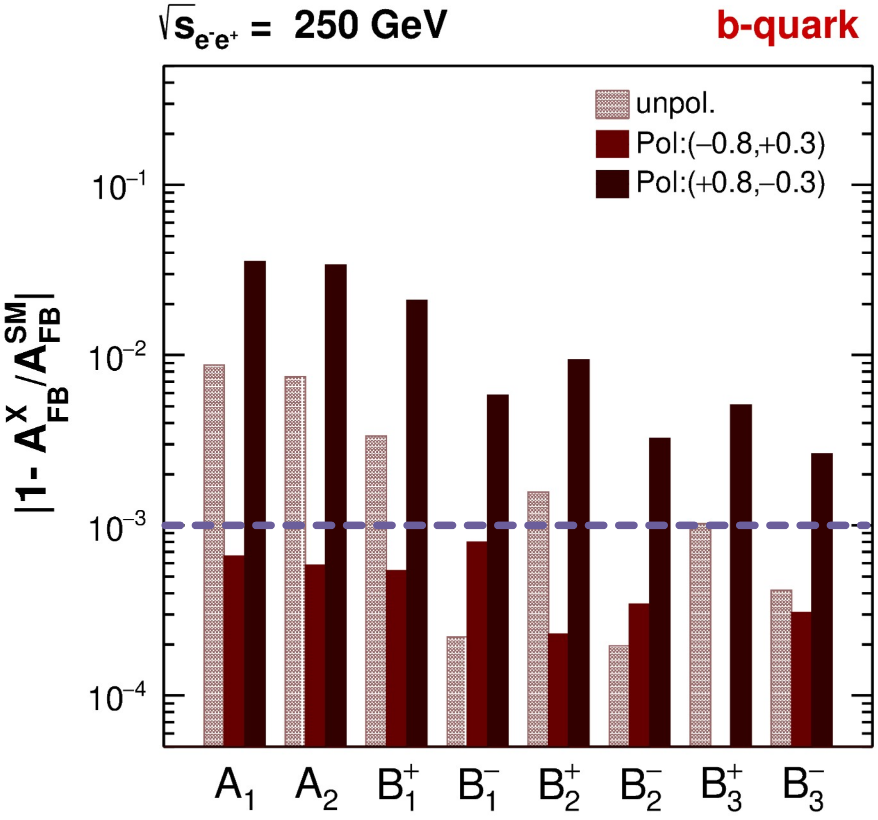
- B models: (arxiv:2309.01132) (arxiv:2301.07833)

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

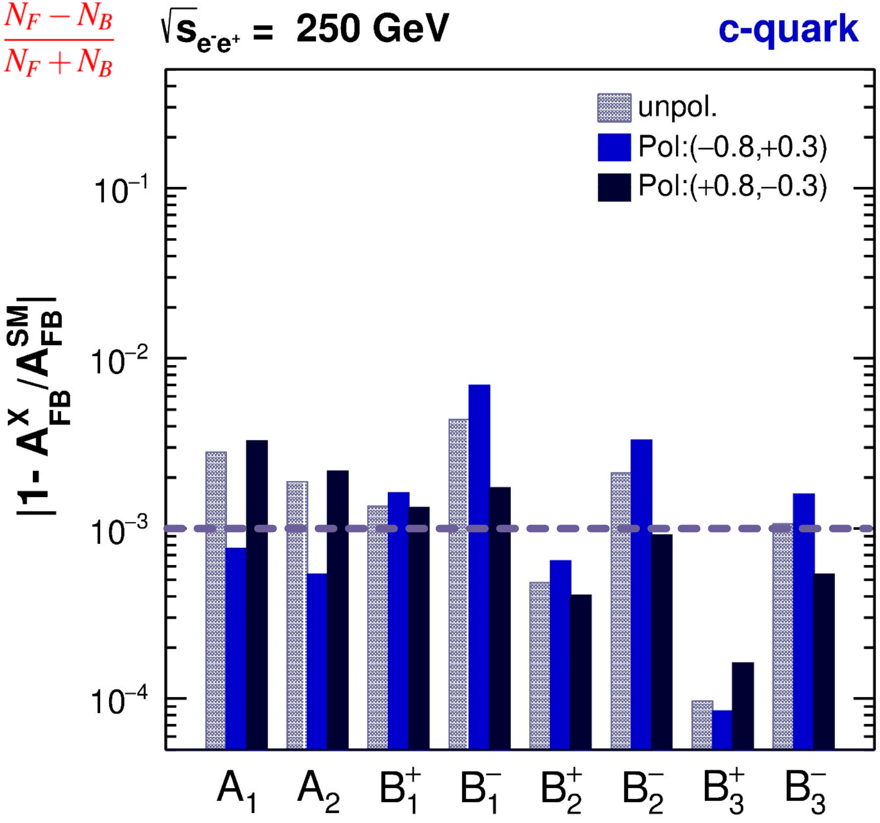
Resonances of O(10) TeV: Only indirect measurements are possible!

This work: Phenomenology at ILC H20-staged program
- **Runs at 250, 500, 1000 GeV**
- **Polarized beams (e^-, e^+) = (±0.8,±0.3)**

GHU vs SM (250 GeV)



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



Deviations at the per mil level!

Code extension for future inputs

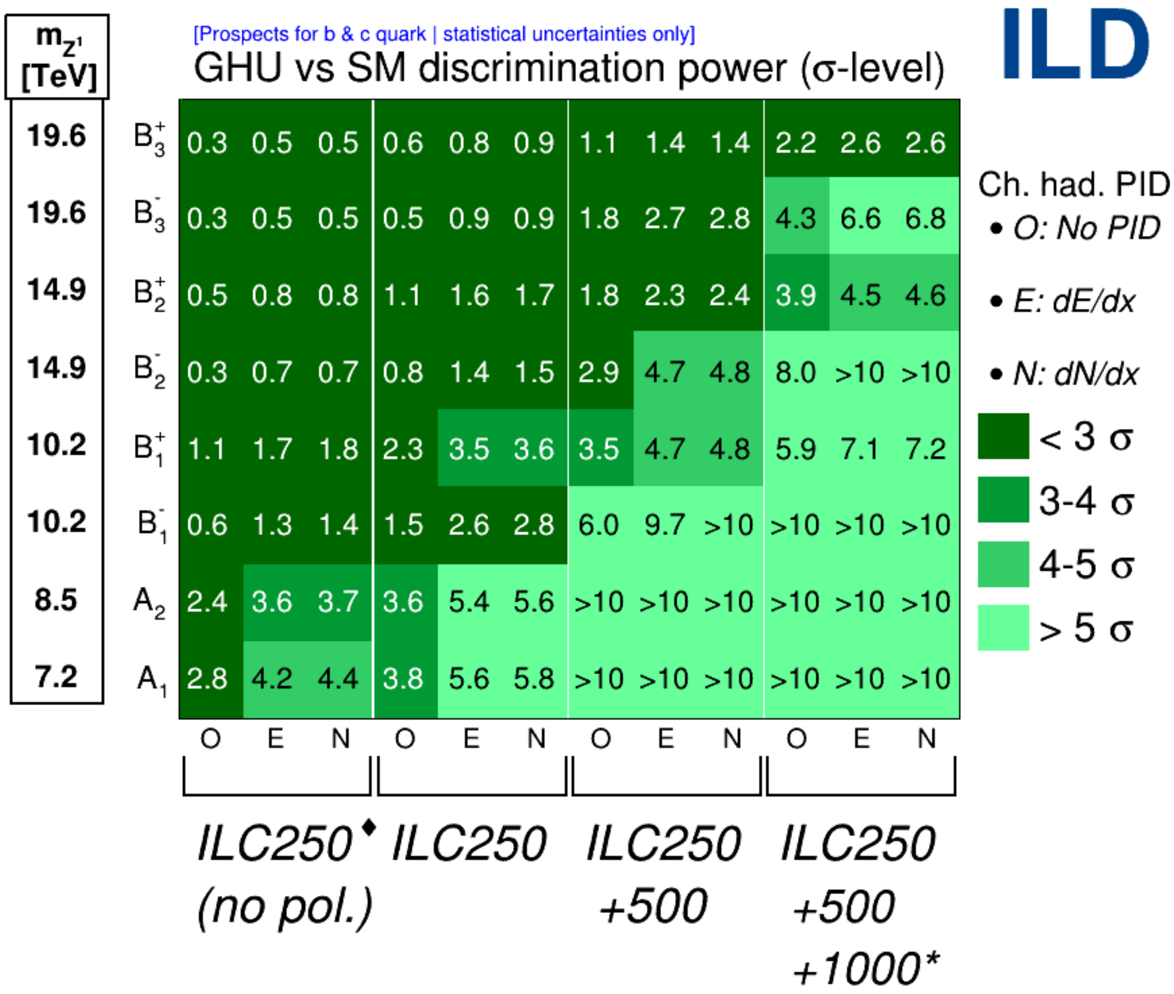
- Expanded model calculations for d, u, s, c, b, t
- Changed all the inner structure of the plotting tools:
    - Ready to add inputs from s quark
        - Once the analysis is revisited
    - Ready for any fermion pair production
- Next slides, using only *statistical uncertainties*:
    - Previous results (b & c)
    - + s quark with uncertainty of 10%, 1% or 1‰
    - + s quark with the preliminary results from Yuichi’s analysis
    - + t quark with uncertainty of 10%, 1% or 1‰

Expected statistical ΔA_{FB} (s-quark):
~0.9% for P(e-,e+) = (-0.8,+0.3)
~5.9% for P(e-,e+) = (+0.8,-0.3)
From Yuichi’s analysis

Expected ΔA_{FB} (t-quark):
~1.5% to 2%
From old ILC notes

This code could also be adapted to run with results for LCF@CERN, but the corresponding uncertainties have to be calculated first

Reference: Stat. b&c quarks combined



[Prospects for b & c quark | statistical uncertainties only]

GHU vs SM discrimination power (σ-level)

$m_{Z'}$ [TeV]		ILC250◆ (no pol.)			ILC250			ILC250 +500			ILC250 +500 +1000*		
		O	E	N	O	E	N	O	E	N	O	E	N
19.6	B_3^+	0.3	0.5	0.5	0.6	0.8	0.9	1.1	1.4	1.4	2.2	2.6	2.6
19.6	B_3^-	0.3	0.5	0.5	0.5	0.9	0.9	1.8	2.7	2.8	4.3	6.6	6.8
14.9	B_2^+	0.5	0.8	0.8	1.1	1.6	1.7	1.8	2.3	2.4	3.9	4.5	4.6
14.9	B_2^-	0.3	0.7	0.7	0.8	1.4	1.5	2.9	4.7	4.8	8.0	>10	>10
10.2	B_1^+	1.1	1.7	1.8	2.3	3.5	3.6	3.5	4.7	4.8	5.9	7.1	7.2
10.2	B_1^-	0.6	1.3	1.4	1.5	2.6	2.8	6.0	9.7	>10	>10	>10	>10
8.5	A_2	2.4	3.6	3.7	3.6	5.4	5.6	>10	>10	>10	>10	>10	>10
7.2	A_1	2.8	4.2	4.4	3.8	5.6	5.8	>10	>10	>10	>10	>10	>10

Ch. had. PID
- O: No PID
- E: dE/dx
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🟩 < 3 σ
🟩 3-4 σ
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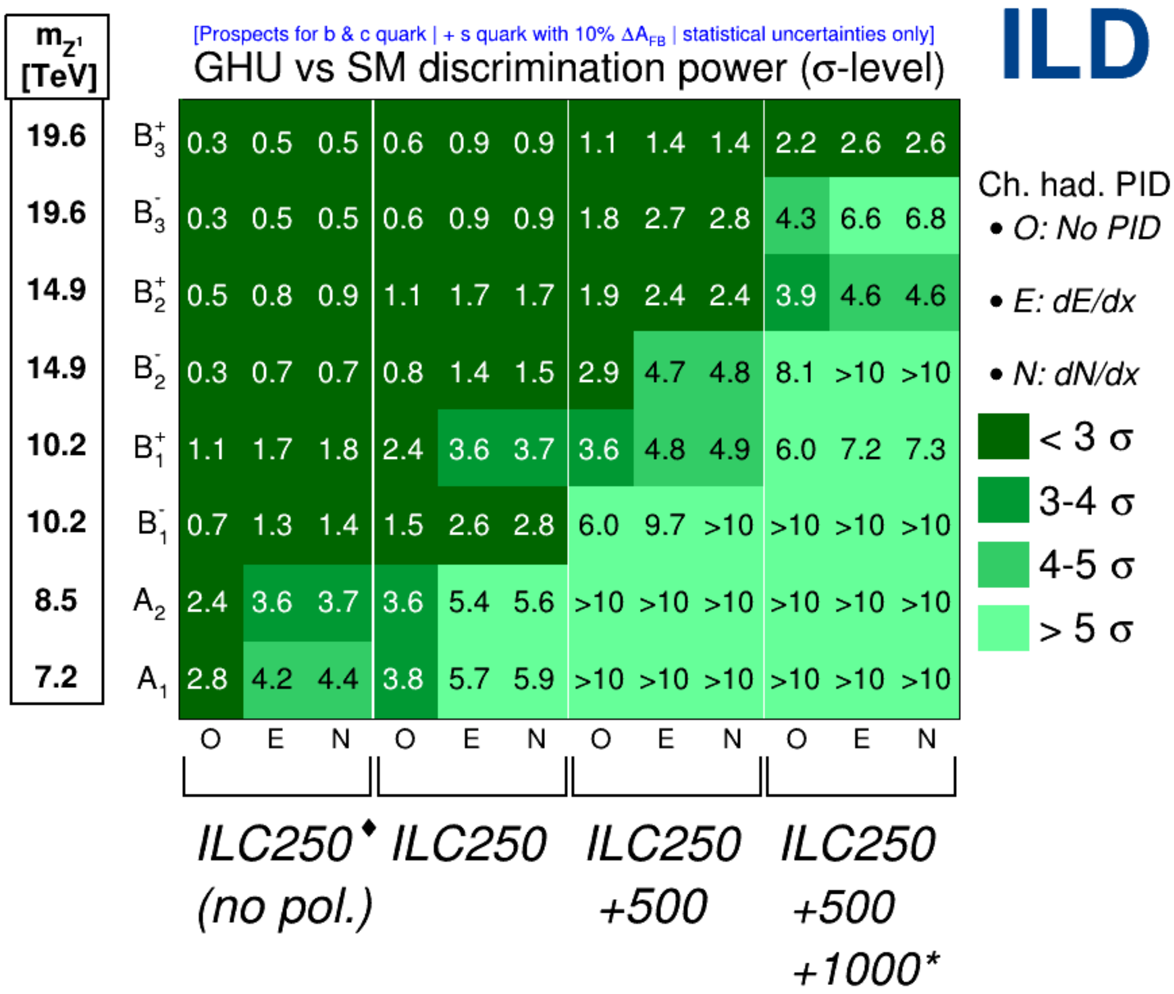
🟩 > 5 σ

+ s-quark 10% stat.



[Prospects for b & c quark | + s quark with 10% ΔA_{FB} | statistical uncertainties only]

GHU vs SM discrimination power (σ-level)

ILD

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14.9	B_2^+	0.5	0.8	0.9	1.1	1.7	1.7	1.9	2.4	2.4	3.9	4.6	4.6
14.9	B_2^-	0.3	0.7	0.7	0.8	1.4	1.5	2.9	4.7	4.8	8.1	>10	>10
10.2	B_1^+	1.1	1.7	1.8	2.4	3.6	3.7	3.6	4.8	4.9	6.0	7.2	7.3
10.2	B_1^-	0.7	1.3	1.4	1.5	2.6	2.8	6.0	9.7	>10	>10	>10	>10
8.5	A_2	2.4	3.6	3.7	3.6	5.4	5.6	>10	>10	>10	>10	>10	>10
7.2	A_1	2.8	4.2	4.4	3.8	5.7	5.9	>10	>10	>10	>10	>10	>10

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- *O: No PID*
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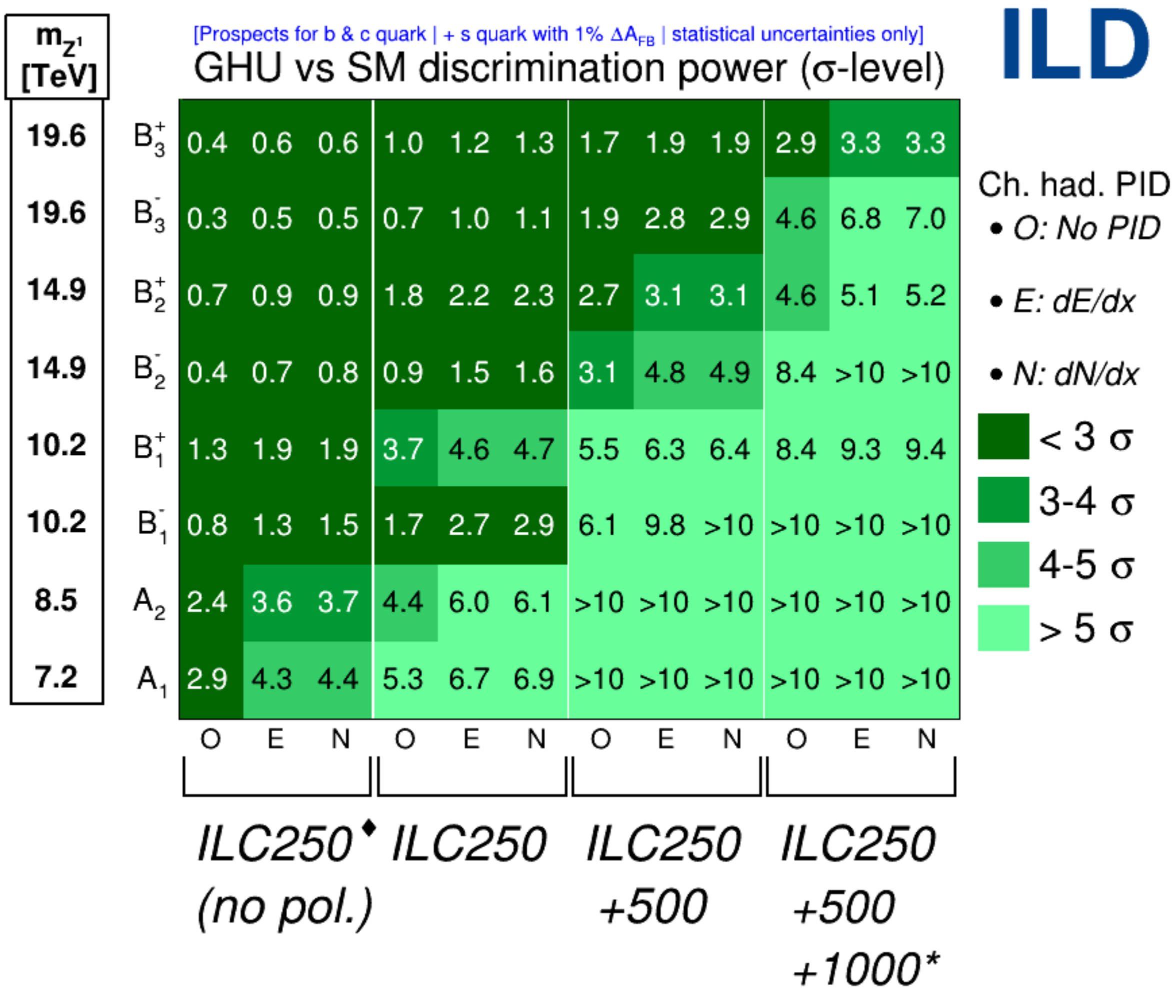
🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

+ s-quark 1% stat.



[Prospects for b & c quark | + s quark with 1% ΔA_{FB} | statistical uncertainties only]

GHU vs SM discrimination power (σ-level)

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		O	E	N	O	E	N	O	E	N	O	E	N
19.6	B_3^+	0.4	0.6	0.6	1.0	1.2	1.3	1.7	1.9	1.9	2.9	3.3	3.3
19.6	B_3^-	0.3	0.5	0.5	0.7	1.0	1.1	1.9	2.8	2.9	4.6	6.8	7.0
14.9	B_2^+	0.7	0.9	0.9	1.8	2.2	2.3	2.7	3.1	3.1	4.6	5.1	5.2
14.9	B_2^-	0.4	0.7	0.8	0.9	1.5	1.6	3.1	4.8	4.9	8.4	>10	>10
10.2	B_1^+	1.3	1.9	1.9	3.7	4.6	4.7	5.5	6.3	6.4	8.4	9.3	9.4
10.2	B_1^-	0.8	1.3	1.5	1.7	2.7	2.9	6.1	9.8	>10	>10	>10	>10
8.5	A_2	2.4	3.6	3.7	4.4	6.0	6.1	>10	>10	>10	>10	>10	>10
7.2	A_1	2.9	4.3	4.4	5.3	6.7	6.9	>10	>10	>10	>10	>10	>10

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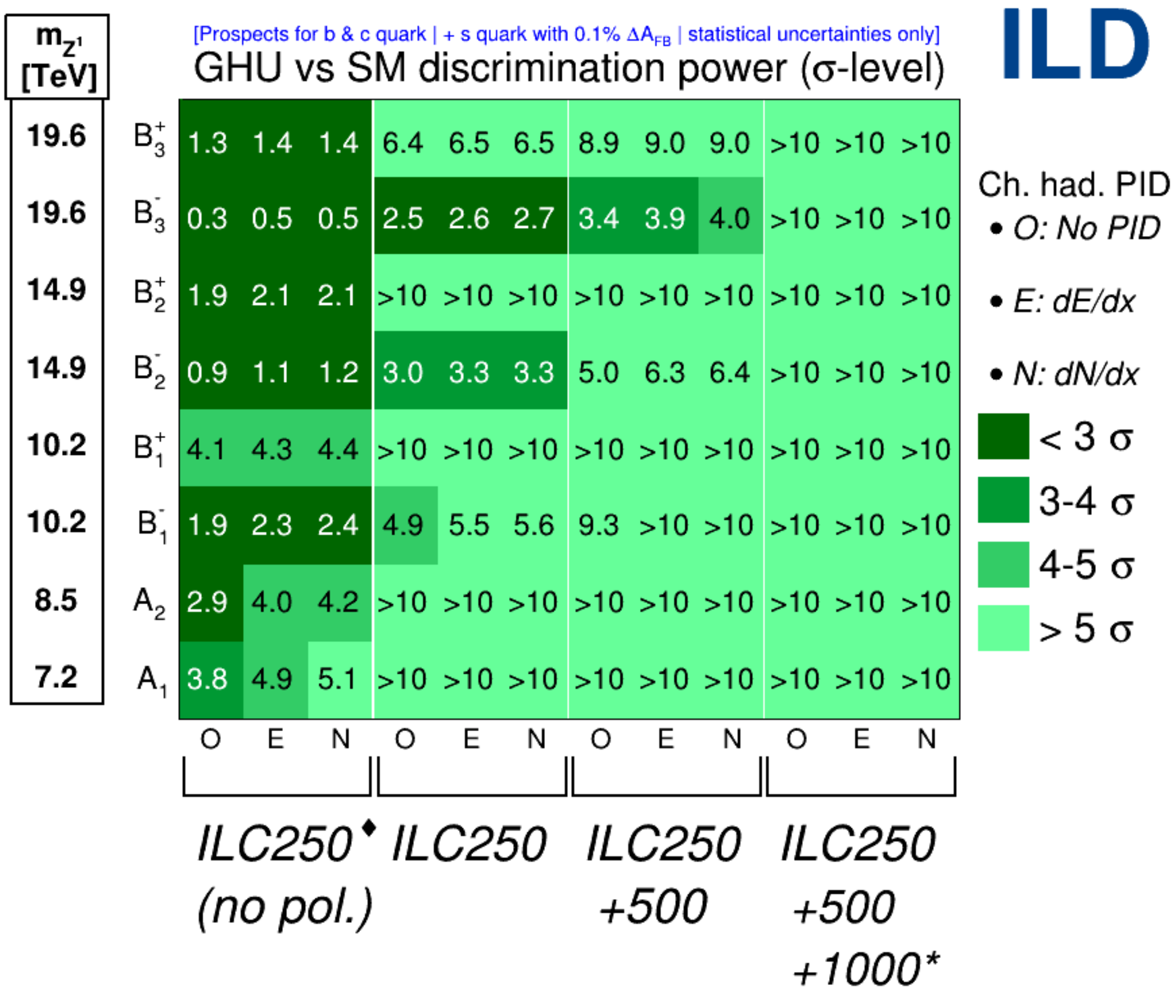
< 3 σ

3-4 σ

4-5 σ

> 5 σ

+ s-quark 1‰ stat.



[Prospects for b & c quark | + s quark with 0.1% ΔA_{FB} | statistical uncertainties only]

GHU vs SM discrimination power (σ-level)

ILD

$m_{Z'}$ [TeV]		ILC250♦ (no pol.)			ILC250			ILC250 +500			ILC250 +500 +1000*		
		O	E	N	O	E	N	O	E	N	O	E	N
19.6	B_3^+	1.3	1.4	1.4	6.4	6.5	6.5	8.9	9.0	9.0	>10	>10	>10
19.6	B_3^-	0.3	0.5	0.5	2.5	2.6	2.7	3.4	3.9	4.0	>10	>10	>10
14.9	B_2^+	1.9	2.1	2.1	>10	>10	>10	>10	>10	>10	>10	>10	>10
14.9	B_2^-	0.9	1.1	1.2	3.0	3.3	3.3	5.0	6.3	6.4	>10	>10	>10
10.2	B_1^+	4.1	4.3	4.4	>10	>10	>10	>10	>10	>10	>10	>10	>10
10.2	B_1^-	1.9	2.3	2.4	4.9	5.5	5.6	9.3	>10	>10	>10	>10	>10
8.5	A_2	2.9	4.0	4.2	>10	>10	>10	>10	>10	>10	>10	>10	>10
7.2	A_1	3.8	4.9	5.1	>10	>10	>10	>10	>10	>10	>10	>10	>10

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🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

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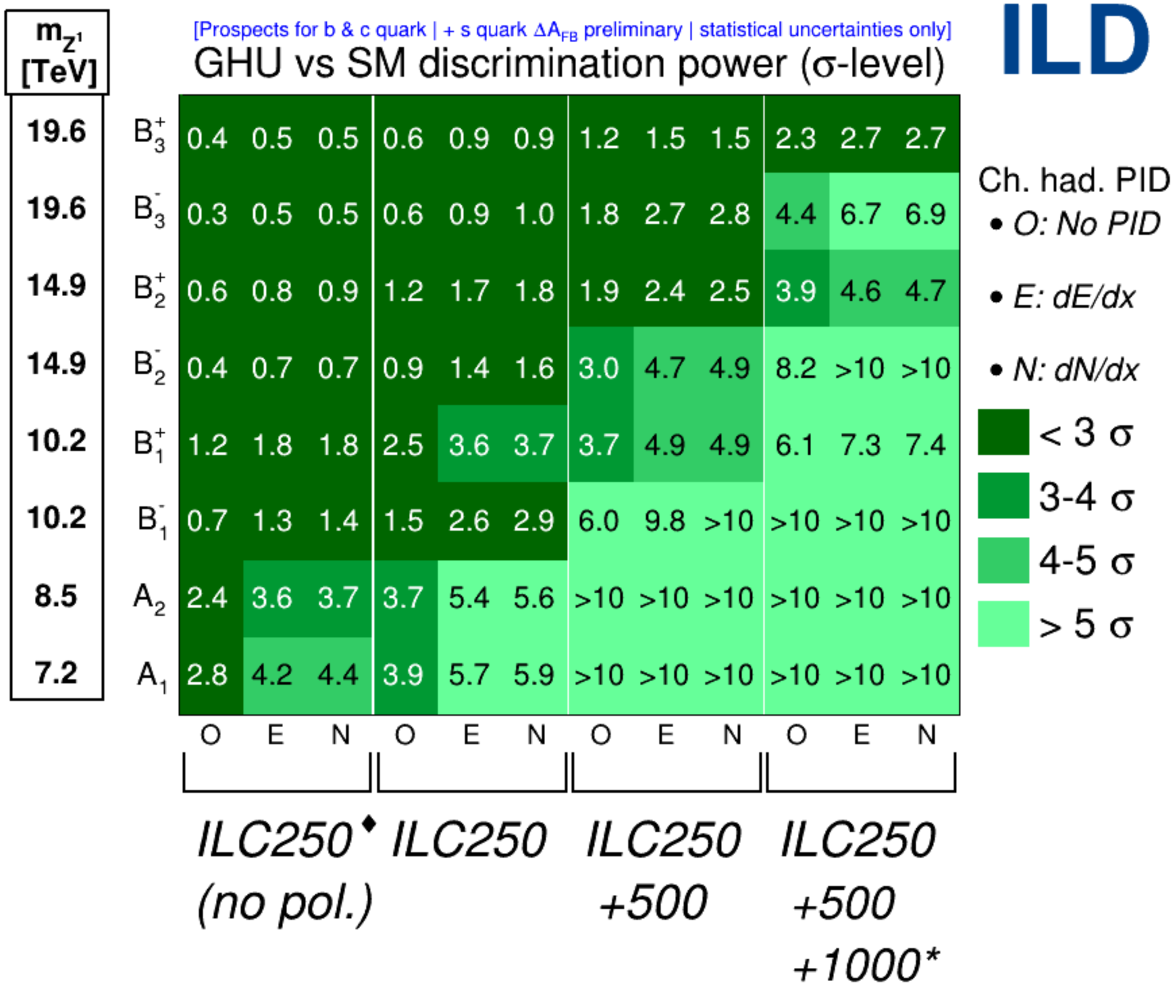
+ s-quark from preliminary studies (Yuichi's)



ILD

[Prospects for b & c quark | + s quark ΔA_{FB} preliminary | statistical uncertainties only]

GHU vs SM discrimination power (σ-level)

$m_{Z'}$ [TeV]		ILC250♦ (no pol.)			ILC250			ILC250 +500			ILC250 +500 +1000*		
		O	E	N	O	E	N	O	E	N	O	E	N
19.6	B_3^+	0.4	0.5	0.5	0.6	0.9	0.9	1.2	1.5	1.5	2.3	2.7	2.7
19.6	B_3^-	0.3	0.5	0.5	0.6	0.9	1.0	1.8	2.7	2.8	4.4	6.7	6.9
14.9	B_2^+	0.6	0.8	0.9	1.2	1.7	1.8	1.9	2.4	2.5	3.9	4.6	4.7
14.9	B_2^-	0.4	0.7	0.7	0.9	1.4	1.6	3.0	4.7	4.9	8.2	>10	>10
10.2	B_1^+	1.2	1.8	1.8	2.5	3.6	3.7	3.7	4.9	4.9	6.1	7.3	7.4
10.2	B_1^-	0.7	1.3	1.4	1.5	2.6	2.9	6.0	9.8	>10	>10	>10	>10
8.5	A_2	2.4	3.6	3.7	3.7	5.4	5.6	>10	>10	>10	>10	>10	>10
7.2	A_1	2.8	4.2	4.4	3.9	5.7	5.9	>10	>10	>10	>10	>10	>10

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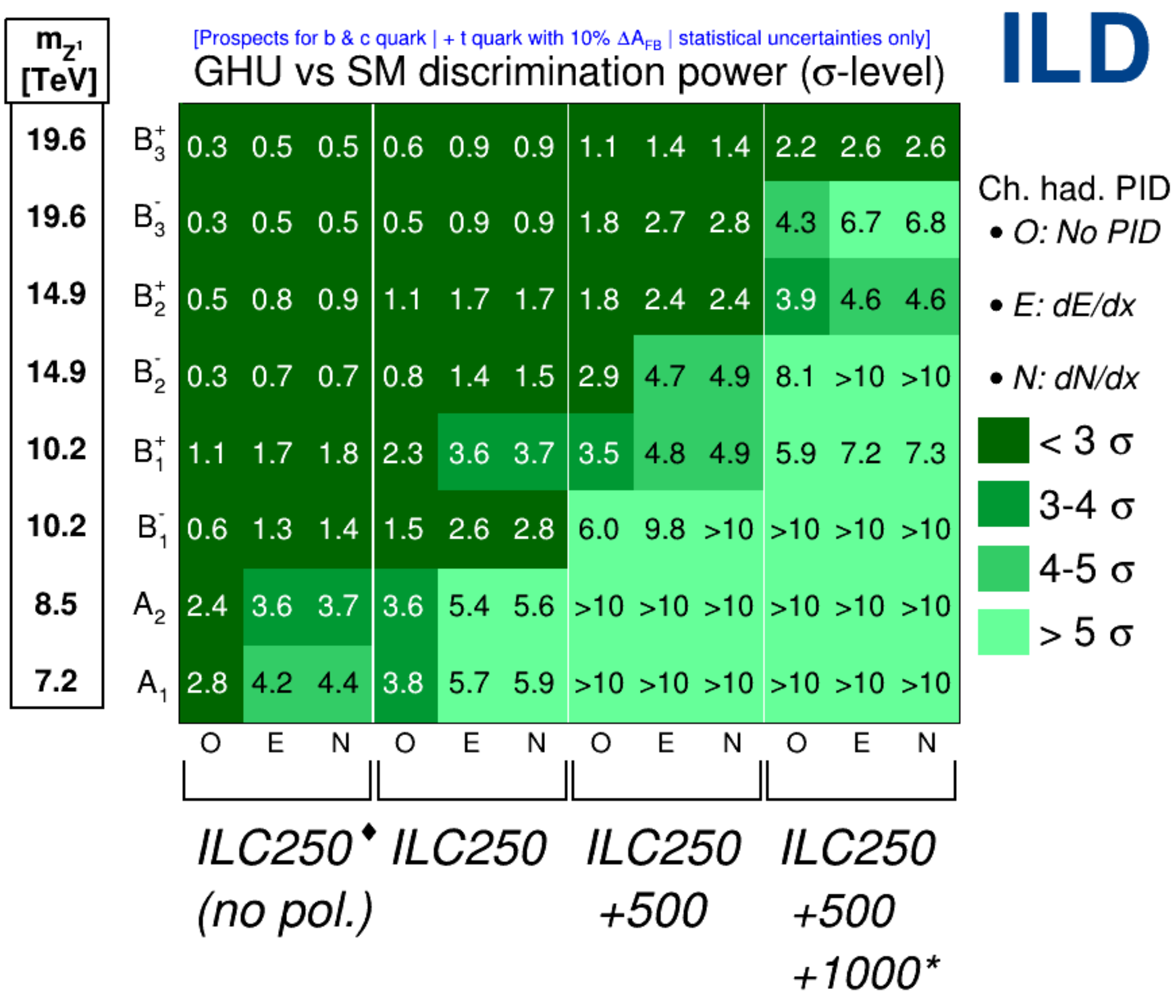
+ t-quark 10% stat.



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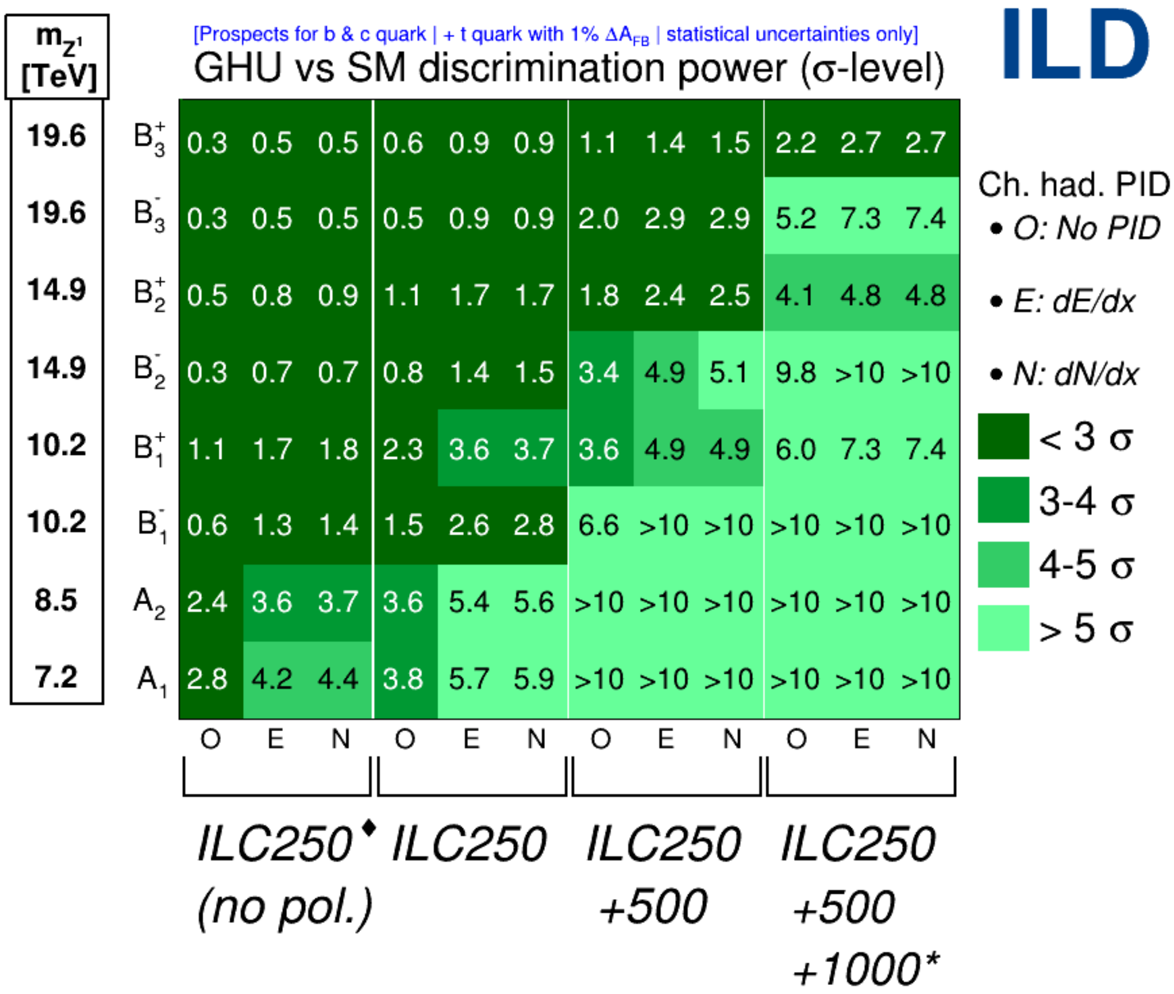

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GHU vs SM discrimination power (σ-level)

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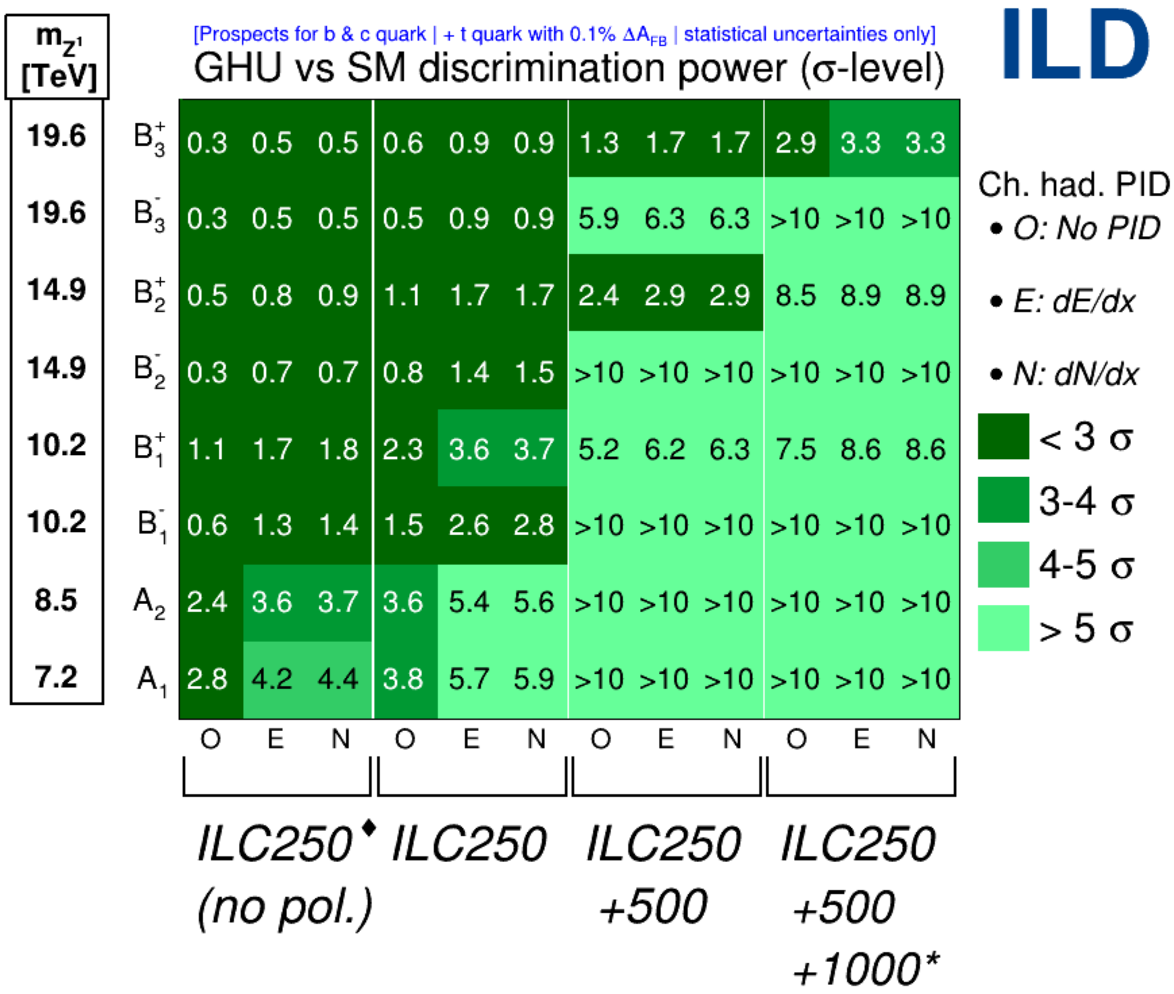

[Prospects for b & c quark | + t quark with 0.1% ΔA_{FB} | statistical uncertainties only]

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		O	E	N	O	E	N	O	E	N	O	E	N
19.6	B_3^+	0.3	0.5	0.5	0.6	0.9	0.9	1.3	1.7	1.7	2.9	3.3	3.3
19.6	B_3^-	0.3	0.5	0.5	0.5	0.9	0.9	5.9	6.3	6.3	>10	>10	>10
14.9	B_2^+	0.5	0.8	0.9	1.1	1.7	1.7	2.4	2.9	2.9	8.5	8.9	8.9
14.9	B_2^-	0.3	0.7	0.7	0.8	1.4	1.5	>10	>10	>10	>10	>10	>10
10.2	B_1^+	1.1	1.7	1.8	2.3	3.6	3.7	5.2	6.2	6.3	7.5	8.6	8.6
10.2	B_1^-	0.6	1.3	1.4	1.5	2.6	2.8	>10	>10	>10	>10	>10	>10
8.5	A_2	2.4	3.6	3.7	3.6	5.4	5.6	>10	>10	>10	>10	>10	>10
7.2	A_1	2.8	4.2	4.4	3.8	5.7	5.9	>10	>10	>10	>10	>10	>10

Ch. had. PID
- *O: No PID*
- *E: dE/dx*
- *N: dN/dx*

🟩 < 3 σ

🟩 3-4 σ

🟩 4-5 σ

🟩 > 5 σ

Future plans for GHU

- We can build new prospects covering higher mass scale and adding prospects for s-quark or even other fermion pairs
- Strategy:
  - Sit and study: New A, B- & B+ models? I need some base for discussion about it)
  - Contact Naoki Yamatsu, who produced the model parameters for previous studies
  - Produce new plots for GHU phenomenology
    - Our idea is a more holistic approach:
      - XY plots: Sigma level vs $m_{Z'}$
        - Different curves for different run plans or colliders (include the LCF@cern)
        - One plot for each type of model (A, B-, B+)

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

CALO5D

A new dimension in shower reconstruction

Jesús P. Márquez Hernández

QQbarAnalysis & SSbarAnalysis

- Code in constant evolution since ~2010
  - Last results in 2023 ($b\bar{b}$ & $c\bar{c}$)

- QQbarAnalysis produces standardized reconstructed Ntuples (tracks, vertices, PFOS, jets, jet tag, etc.) and SSbarAnalysis produces ROOT files and macros for different analyses
  - NTuples are ~13% the size of the .slcio input
  - SSbar ROOT files are ~0.5% the size of the Ntuples size

$\}$ 1TB (MC) → 600MB (analysis)

- There is disk space to redo QQbarAnalysis + SSbarAnalysis and compare different cases:
  - Possible errors in the analysis (?)
  - PID methods (dNdx for a pixel TPC)
  - Jet clustering algorithms
  - Flavor tagging (LCFI+ → Particle Transformer)

MC data available (or not…) @ DESY

- The original analysis was done with “dst” MC simulation data (eL_pR/eR_pL):
  - Signal:
    - Plenty of 2f_hadronic files
  - Backgrounds:
    - 4f_WW_hadronic: Almost no data available for eR_pL
      - Substituting it by “rec” samples (Should be fine)
    - 4f_ZZ_hadronic: Enough available
    - ZH: A bit less available, but enough.
- I’ve prepared:
  - Some small NTuples quick tests
  - Bigger samples: About 1TB of MC samples for signal and 700-800 GB for backgrounds

Summary of the first weeks

- Lots of “simple” accidents (using incorrect git branches, /cvmfs/ unmounted, naf failing, etc.)
  - Show-stopper: A *missing .root file needed as input for SsbarAnalysis*
    - I contacted Yuichi and he still had the file so I added it to the repository

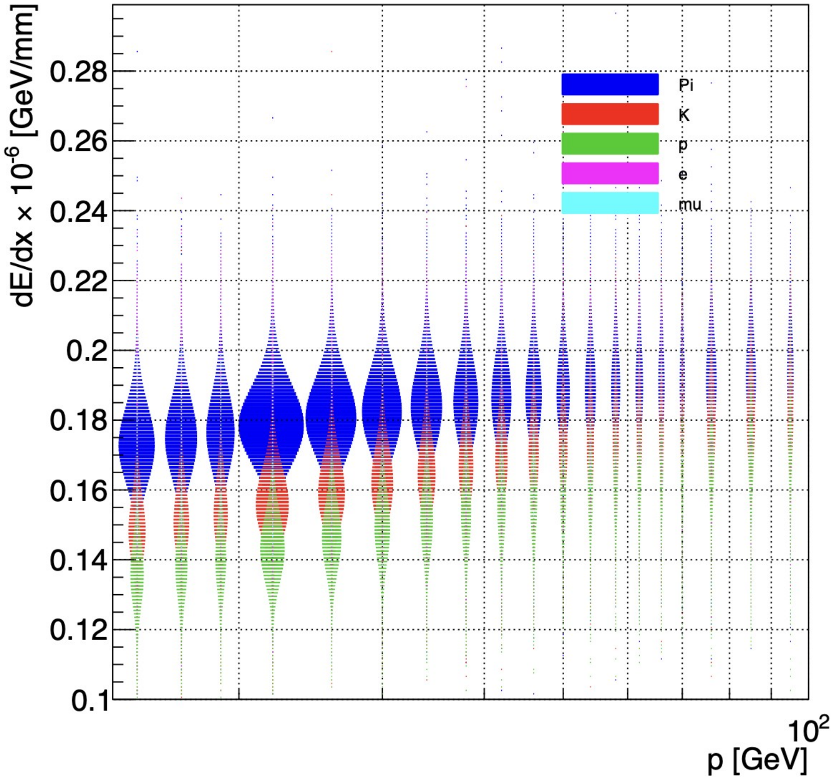
- Prepared macros to run the analysis smoothly in small batches

- Run some first test to cross-check results (next slides)

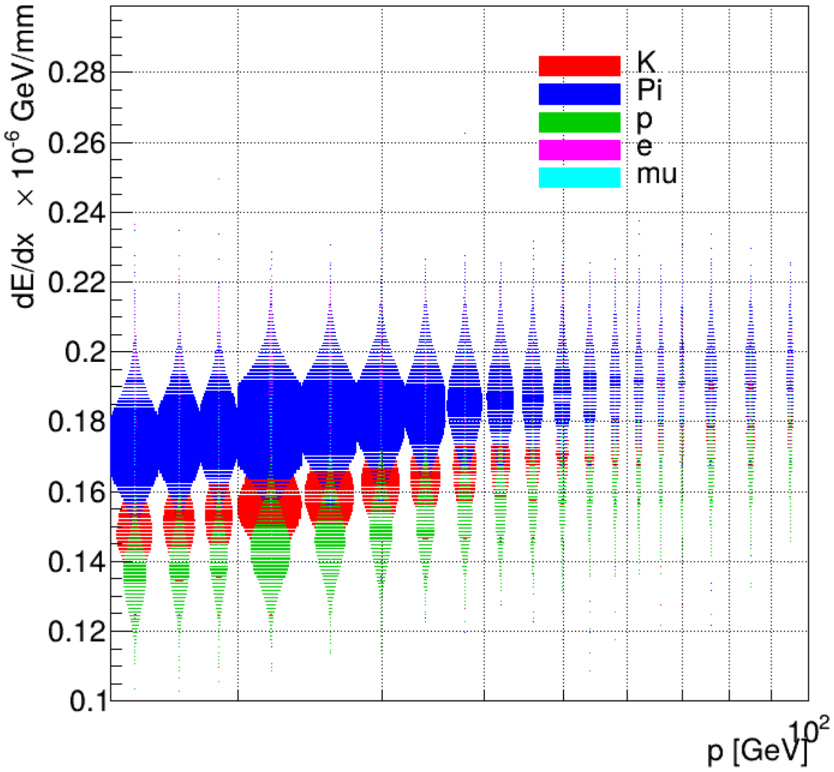
- Got some new problems in the analysis chain:
  - It seems that part of the analysis is missing
    - Checking this atm

Plots for dE/dx

- Seems to be compatible, but different statistics.



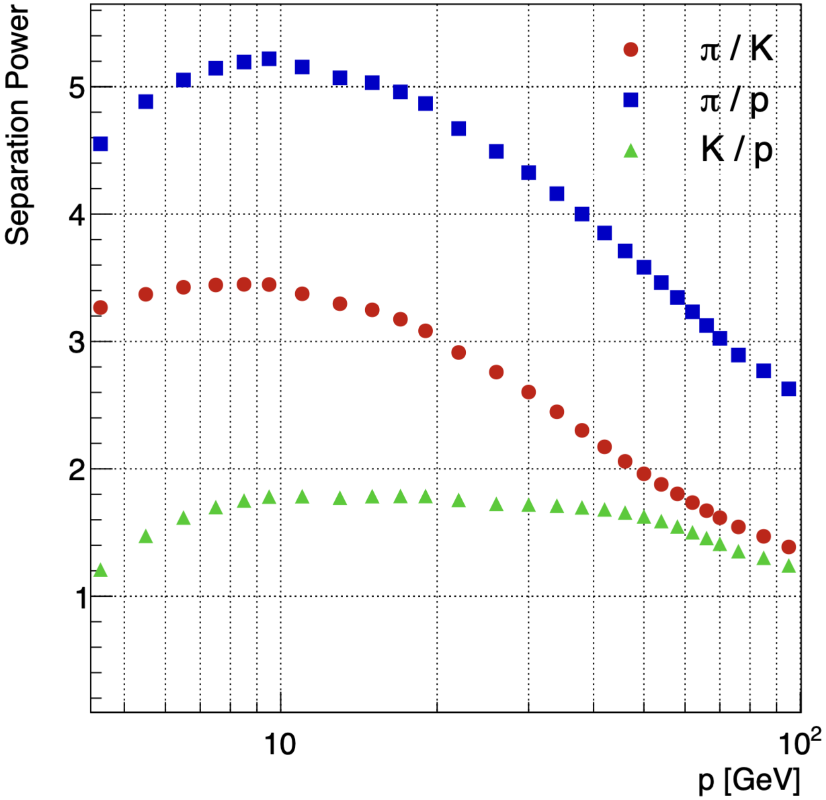
reference



new

Separation power using dE/dx

- Identical results



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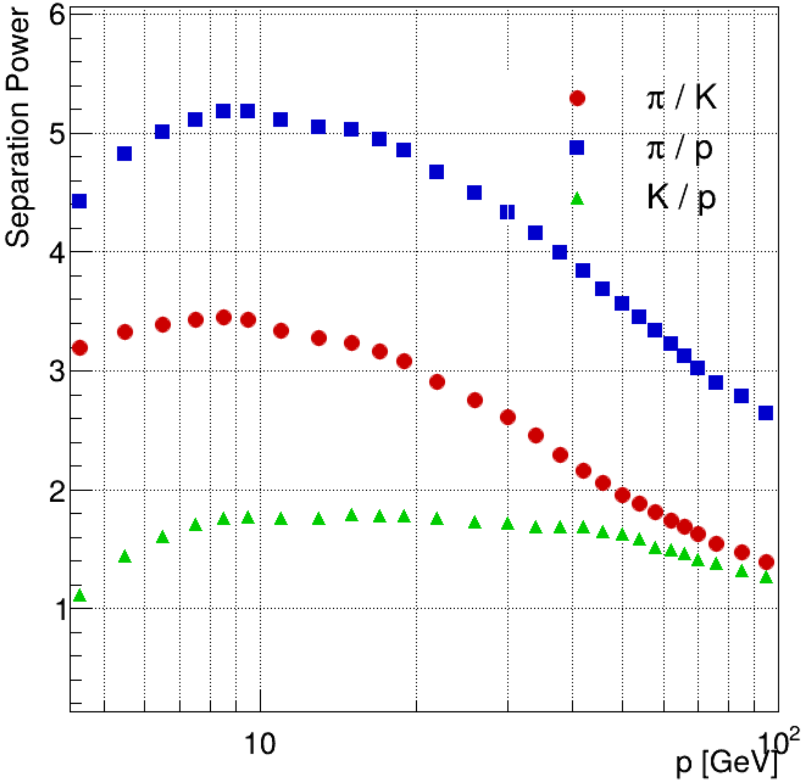
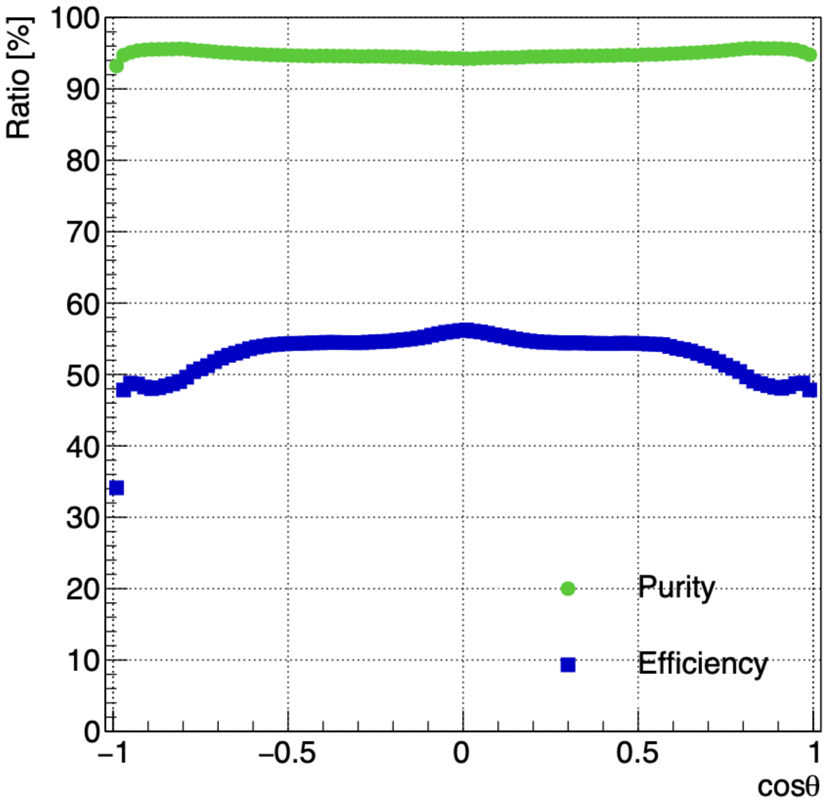


new

Pion selection efficiency (I)

- Lower efficiency?



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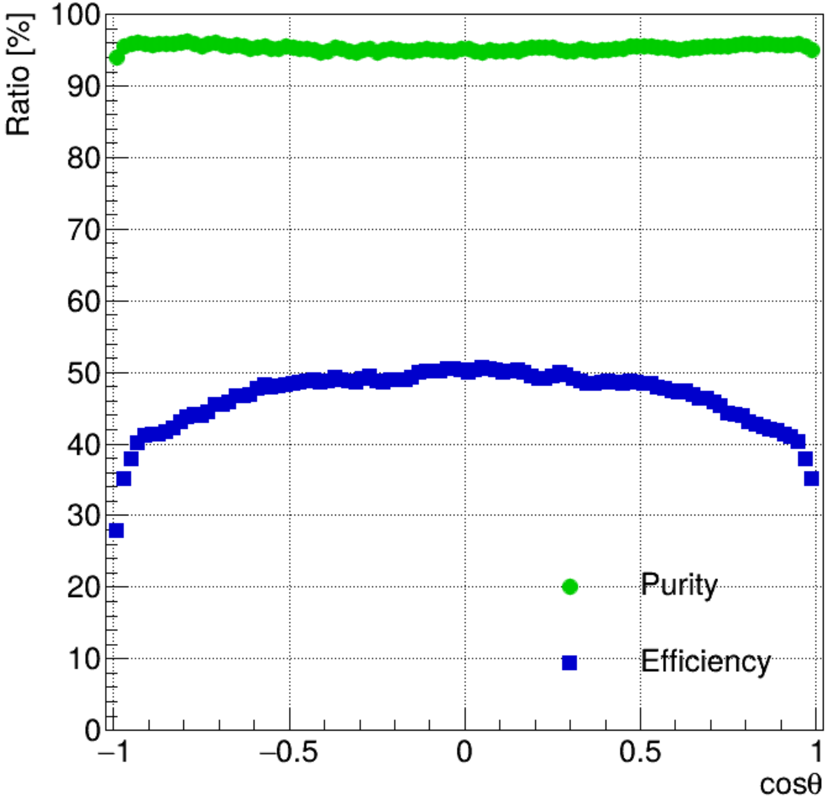
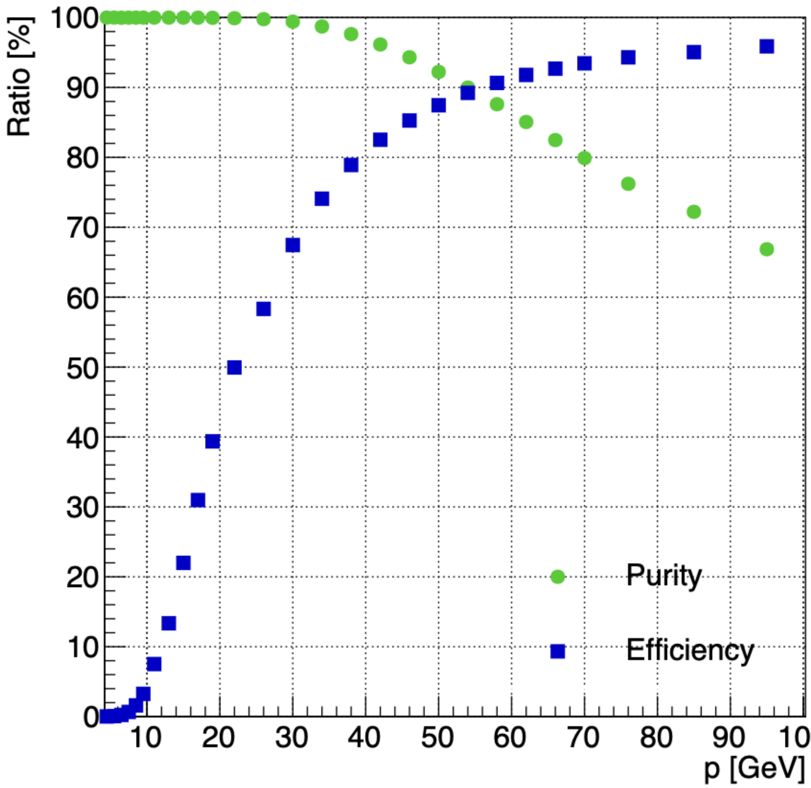


new

Pion selection efficiency (II)

- Higher purity?



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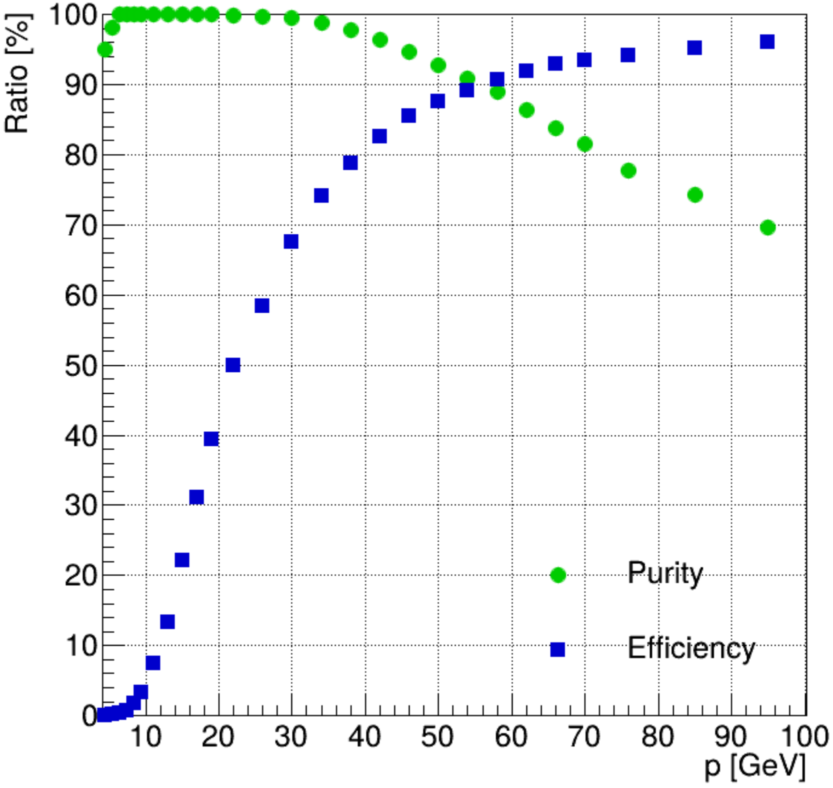


new

Future plans for SSbarAnalysis

- This first half of the analysis seems to match the previous analysis
  - Not 100% but close enough

- Right now I’m addressing an issue to reproduce the cuts to obtain the ss signal:
  - 3 out of 8 cuts are missing in the code!
    - I’ve contacted Yuichi
    - In the meantime: Do it myself in a parallel stack and check if the results match
      - Comparison cut by cut and fitted/reco A_{FB}

- Next move will be testing the same analysis chain but with an improved PID (dN/dx) and ideal PID to see how match this approach could be stretched

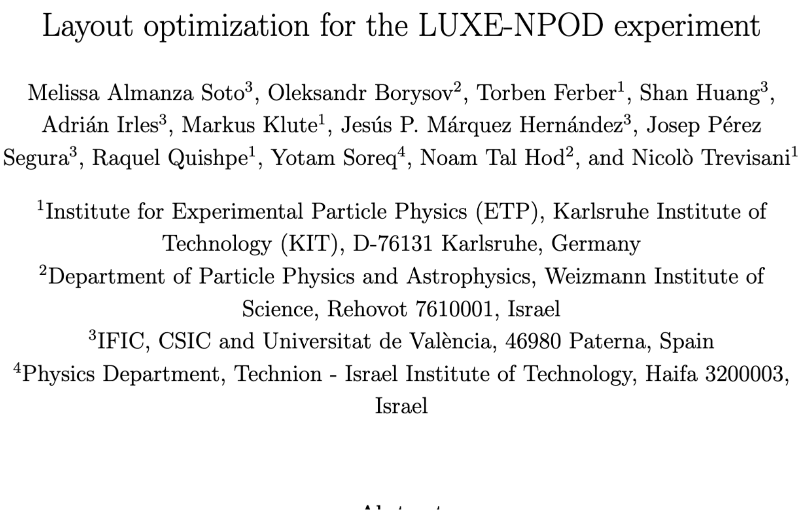
CALO5D

A new dimension in shower reconstruction

Jesús P. Márquez Hernández

Fresh new! (today morning)

- New LUXE ePRINT: A whole PID section has been done with the software I made for the last chapter of my thesis :D

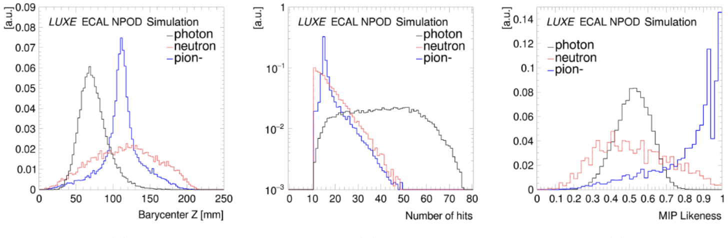


Layout optimization for the LUXE-NPOD experiment

Melissa Almanza Soto[3], Oleksandr Borysov[2], Torben Ferber[1], Shan Huang[3], Adrián Irles[3], Markus Klute[1], Jesús P. Márquez Hernández[3], Josep Pérez Segura[3], Raquel Quishpe[1], Yotam Soreq[4], Noam Tal Hod[2], and Nicolò Trevisani[1]

[1]Institute for Experimental Particle Physics (ETP), Karlsruhe Institute of Technology (KIT), D-76131 Karlsruhe, Germany
[2]Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 7610001, Israel
[3]IFIC, CSIC and Universitat de València, 46980 Paterna, Spain
[4]Physics Department, Technion - Israel Institute of Technology, Haifa 3200003, Israel

https://arxiv.org/pdf/2507.17716



(a) (b) (c)

Figure 9: The distributions of three PID variables for the hits on the detector caused by incoming photon, neutron, and pion: the z coordinate of the barycenter (a), the number (b), and the MIP likeness [defined in Eq. (3)] (c) of the hits. Only the events where the particle deposits more than 10 hits in the detector are shown in the plots.

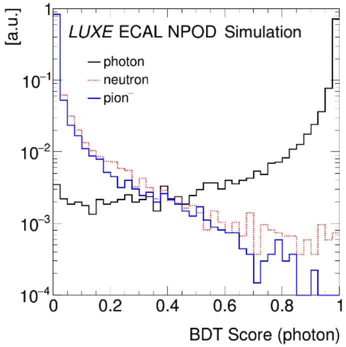


Figure 10: BDT score distributions for photon, neutron, and pion samples.

CALO5D

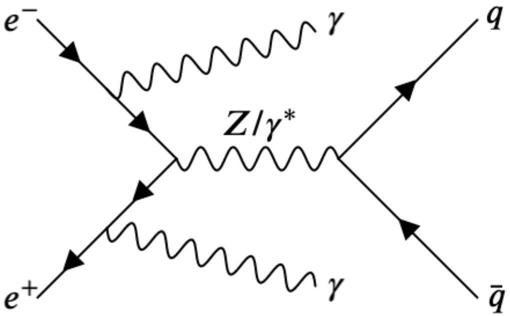
A new dimension in shower reconstruction

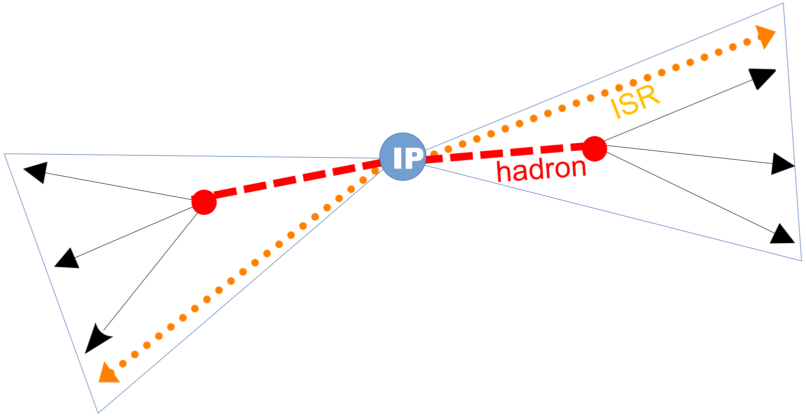
Jesús P. Márquez Hernández

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 (plots in back-up):
  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.

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





High-purity & independent samples for each quark flavour.

J. P. Márquez

Results for ILC250 & ILC500

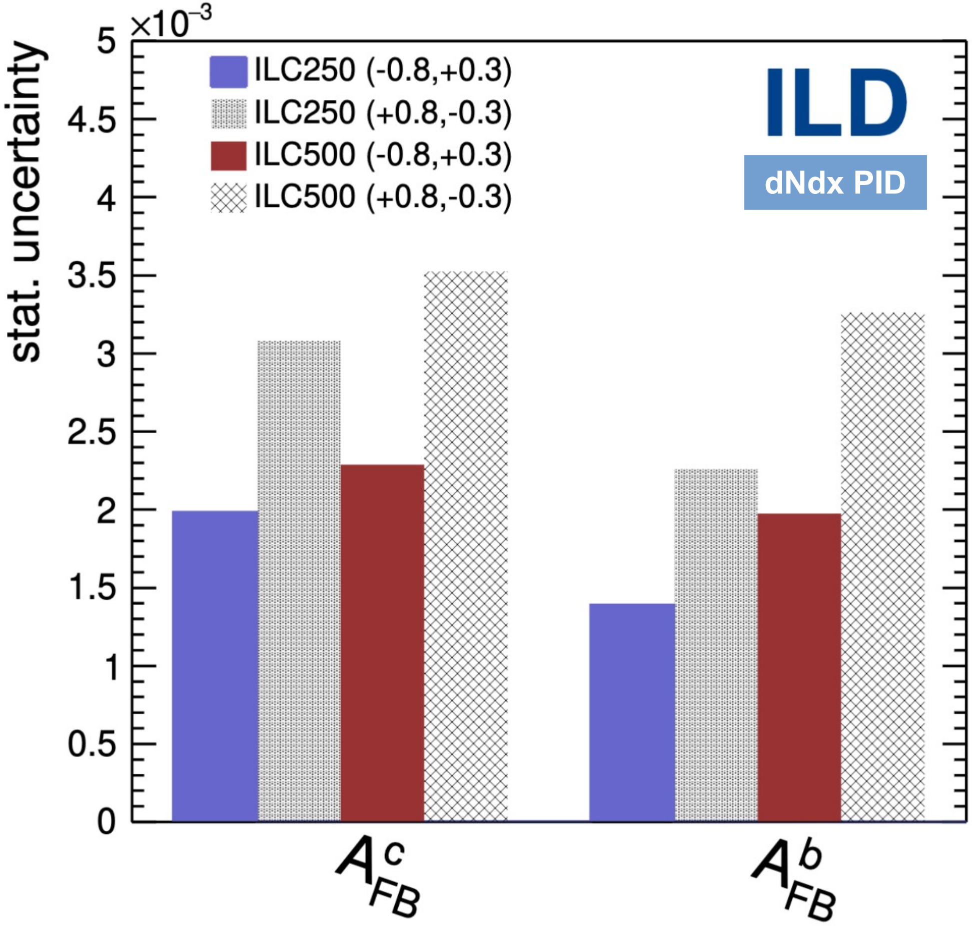
- **A_{FB} definition:**

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

- **or 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.



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: Beam scenarios

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

Full ILD simulation assuming no beam pol.

H20-staged program

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

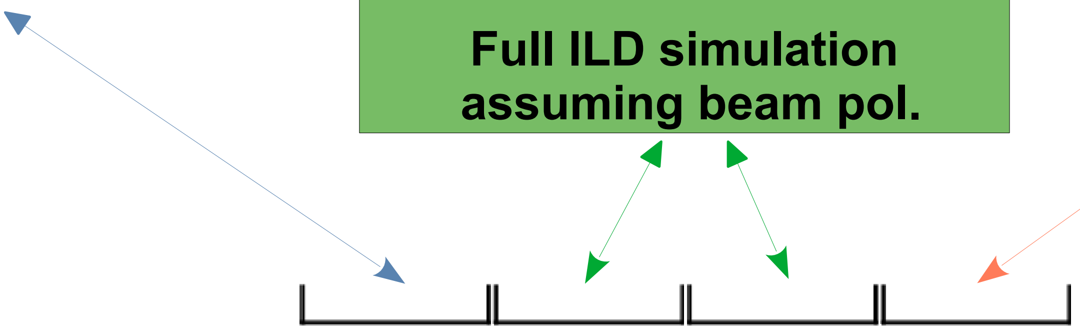
ILC500
(Pe-=0.8, Pe+=0.3)
$\int L = 4000\ \mathrm{fb}^{-1}$

Full ILD simulation assuming beam pol.

H20 staged program

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

Not full simulation studies but extrapolations from ILC500



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

ILC250

ILC250 +500

*ILC250 +500 +1000**