BSM physics at ILC250/500 with ILD

From b & c quark production using TPC PID

LCWS2023
INTERNATIONAL WORKSHOP ON LINEAR COLLIDERS

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ILD Concept Group: [†]AITANA Group (IFIC), [◊]IJCLab Orsay

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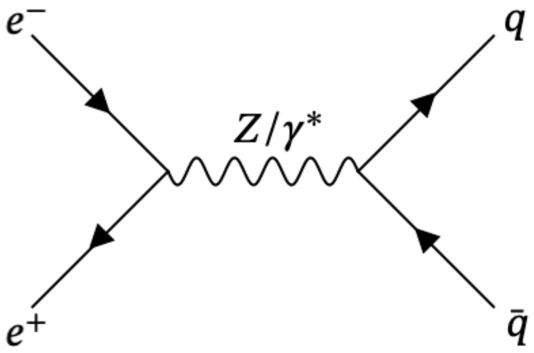
Outline

- **Direct production** (Z/ɣ/Z’) of heavy-quarks (b&c) at high energies.
    - Precision measurement of EW couplings.
- BSM framework: **Gauge-Higgs Unification (GHU)**.
    - Phenomenology of two kinds of models (A & B).
- Physical observables at **ILC250/500**.
    - Hadronic fraction (R_q) and Forward-Backward asymmetry (**A_{FB}**).
- **TPC PID** role in Flavour Tagging & Charge measurement.
- **Discrimination power** for GHU’s Models.

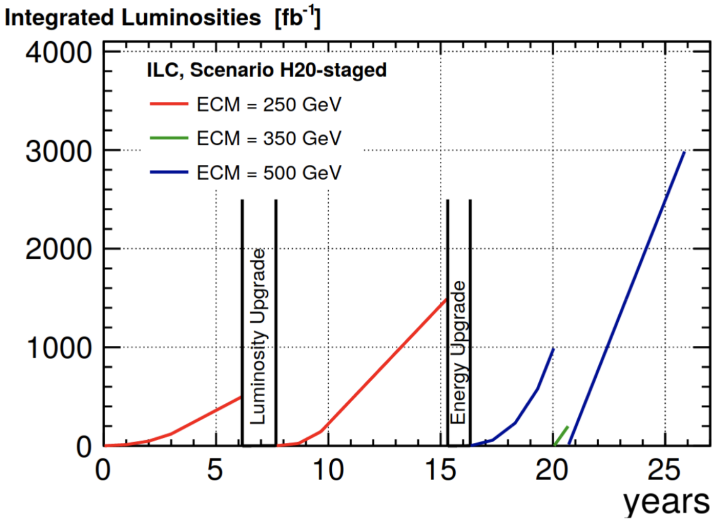


ILC physics program

- The ILC is more than a Higgs factory:
  - It provides access to **all SM particles**.
- It also features polarized beams P(e⁻,e⁺)=(0.8,0.3).
  - Allow us to inspect all 4 helicity amplitudes:

$$\frac{d\sigma^{q\bar{q}}_{XY}}{d\cos\theta}(\cos\theta) \approx \frac{s}{32\pi}\left\{(1+\cos\theta)^2\,|Q_{eXqX}|^2 + (1-\cos\theta)^2\,|Q_{eXqY}|^2\right\}$$

- It can aim for specific processes by adjusting:
  - **Center-of-mass energy**.
  - **Beam polarisation**.
- ILC run plan:
  - 4 different energies: Z-Pole, **250**, **500**, 1000 GeV.
  - 4 different polarisation configurations:
    - sgn(P(e⁻),P(e⁺)) = **(+,-)**, **(-,+)**, (+,+), (-,-)



Luminosity upgrade: 5 Hz to 10 Hz.
Energy upgrade: Extend the linac

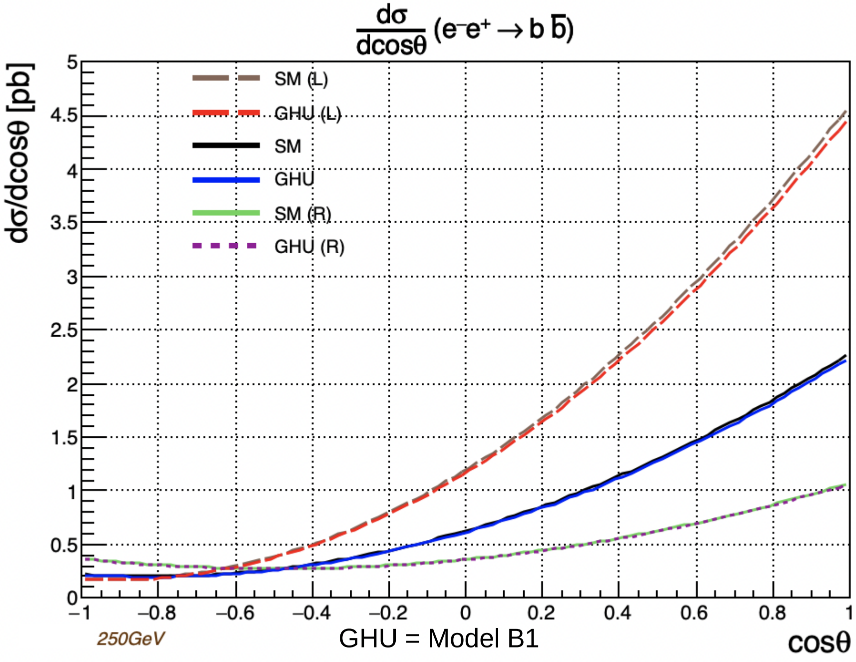
	sgn(P(e$^-$),P(e$^+$))			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	Integrated Luminosity (fb^{-1})			
250 GeV	900	900	100	100
350 GeV	135	45	10	10
500 GeV	1600	1600	400	400

Gauge-Higgs Unification Models

- GHU [Hos. et al] models unify all forces under the same gauge group. It's defined in a 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**, ϕ_H, determines the projection of the 5D fields, fixing all physical effects:
    - **KK-resonances** of Z/ɣ!
      - But m_{kk}~10 TeV, **only indirect measurements**.
    - Effects in **EW couplings/helicity amplitudes**.
    - Deviations from SM **scale with energy**:
      - **It start being noticeable at 250 GeV!**
  - We distinguish **A-Models** and **B-Models**.
    - A-Models are more sensitive to Right-Handed helicity & B-Models to Left-Handed helicity.
    - A-Models (1705.05282) & B-Models (2006.02157).

      [Funatsu, Hatanaka, Hosotani, Orikasa, Yamatsu]

For more details: back-up or poster session!



Projection of couplings and EW mixing angle:

$$\boxed{g_Y^{5\mathrm{D}} = \frac{g_A g_B}{\sqrt{g_A^2 + g_B^2}} \quad \sin\theta_W^0 = \frac{s_\phi}{\sqrt{1+s_\phi^2}}}$$

Observables

- Hadronic fraction (R_q):
  - Quark ID (flavour tagging).
  - Angular measurement *possible*, but not needed.

$$R_q = \frac{\sigma_{e^-e^+\to q\bar{q}}}{\sigma_{hadron}}$$

- Forward-backward asymmetry (A_{FB}):
  - Quark ID + charge measurement.
  - Angular measurement needed.

$$A_{\mathrm{FB}} = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta}{\int_{-1}^1 \frac{d\sigma}{d\cos\theta} d\cos\theta}$$

Normalized & **differential** observables are highly preferred:
Control of systematic uncertainties.

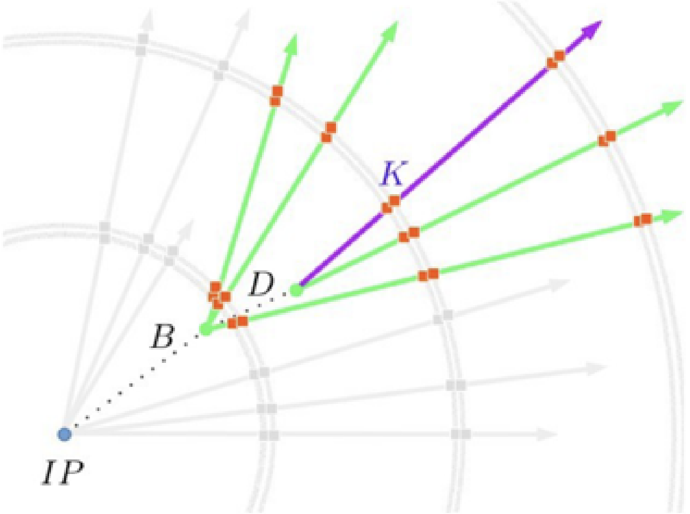
$$A_{FB}^{Exp} = \frac{N_F - N_B}{N_{Total}}$$

$$R_q^{Exp} = \frac{N_q}{N_{hadron}}$$

Up to a total of 16 different measurements.
But this talk **will only explore result on AFB.**

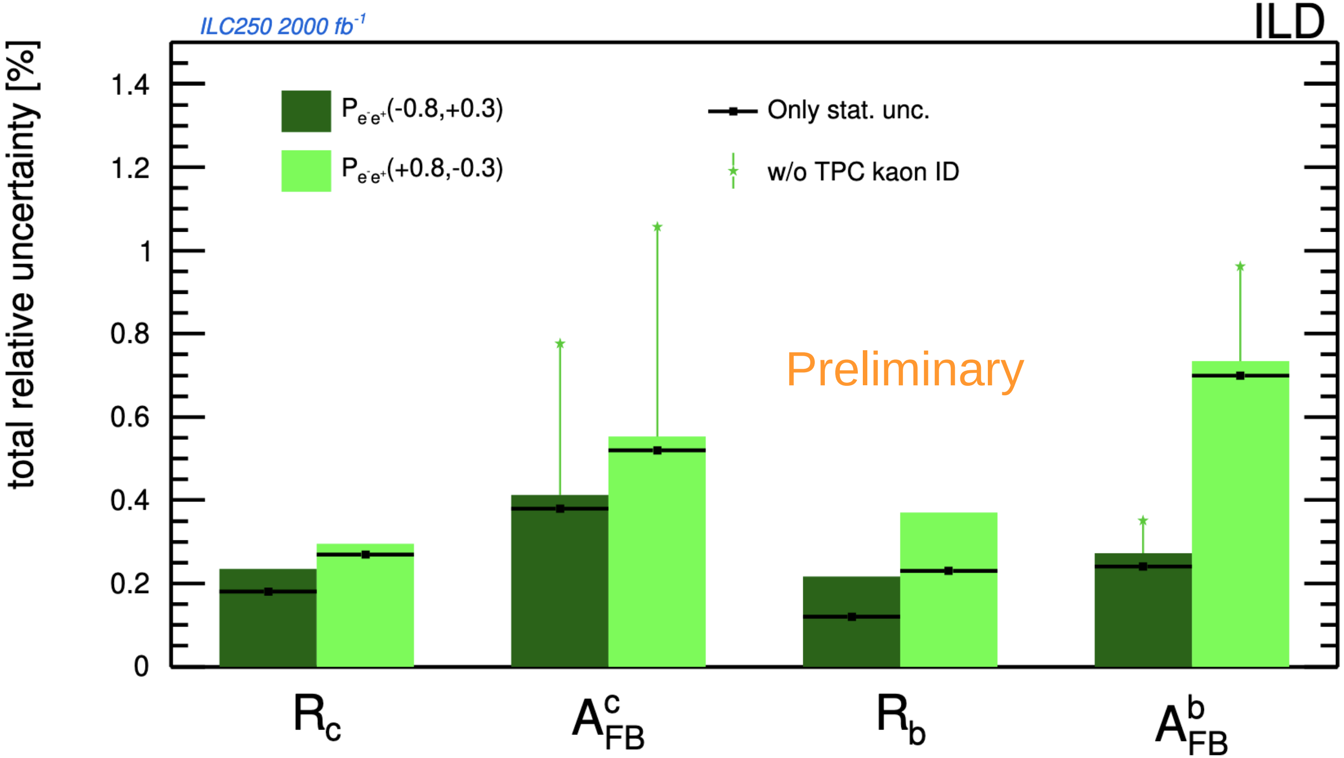
Preselection of $b\bar{b}$ & $c\bar{c}$ signals

- Experimental procedure:
  - Preselection of $q\bar{q}$ events.
    - Removal of backgrounds.
      - Mostly **radiative return**.
        - Up to x10 more data than the signal!
  - Flavour tagging.
    - Using standard ILD Tool: **LCFI+**.
      - Boosted Decision Trees (ROOT TMVA).
  - Jet charge measurement:
    - **VTX method**: Use all secondary tracks.
    - **Kaon method**: Use **TPC's kaon PID**



Double Tag method: *Only* events with 2 opposite-charged identified jets are accepted.

Uncertainties for R_q and A_{FB} (250 GeV)



Full Simulation Study. ILD Note on preparation.

A. Irles, R. Poeschl, F. Richard
(K. Fuji, M. Berggren as ILD PSB Ed. members)

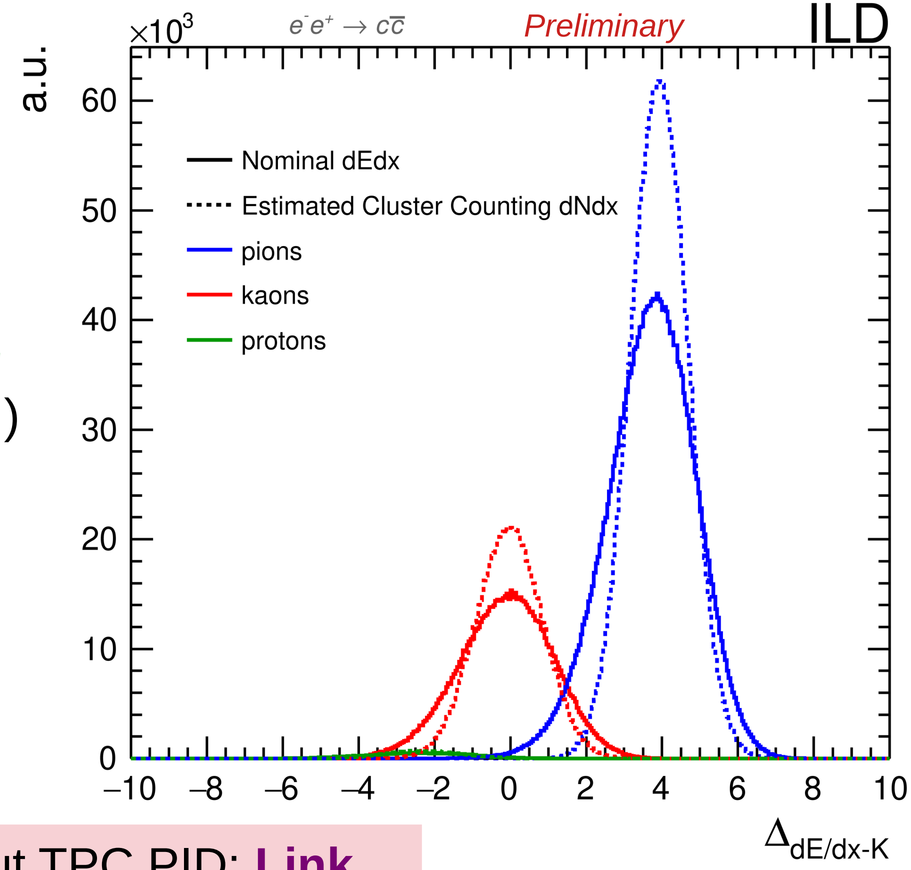
Kaon ID in R_q and A_{FB} (250 GeV)

- Note how:
  - R_q are not affected by Kaon ID, since we only need flavour tagging.
  - A_{FB} highly depends of identifying Kaons for charge measurement. After applying the **double-charge** selection criteria:
    - B-jets: Only ~18% of events survive.
      - Of which ~**40% requires PID**.
    - C-jets: Only ~4% of events survive.
      - Of which ~**90% requires PID!**

Improving the use of TPC PID

- New ways to improve the use of TPC-PID:
  - Include PID in the **Flavour Tagging (LCFI+)**.
    - More details in back-up & poster!
  - Improve the PID performance itself.
    - From traditional dEdx to **cluster counting** method (+35%[1] in K/p separation power!)

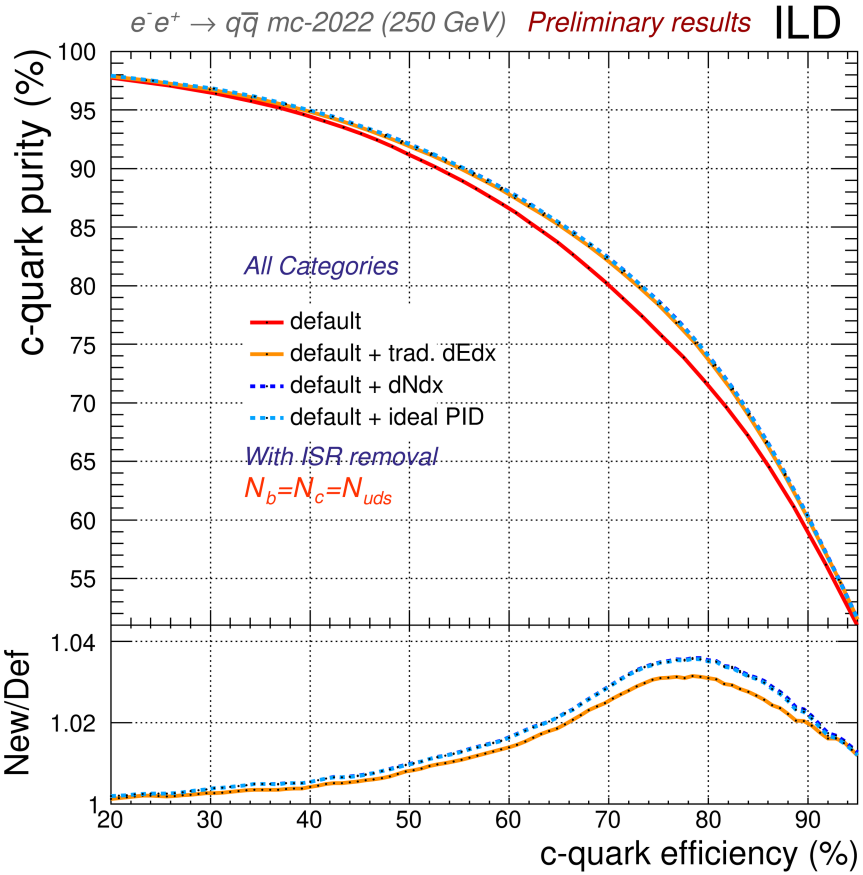
PID information is rewritten by an ILCSOFT processor which estimates the expected improvements we'd have when working with Cluster Counting (dNdx).

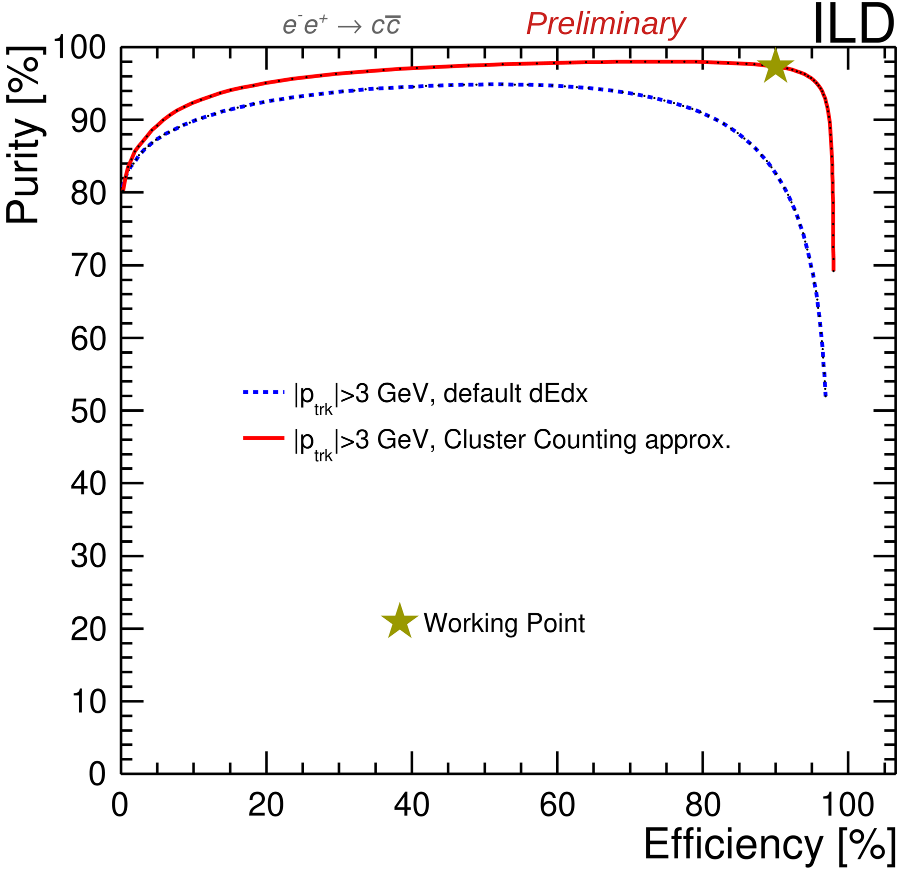


U. Einhaus detailed talk about TPC PID: **Link**

[1] Einhaus U, Krämer U, Malek P. Studies on Particle Identification with dE/dx for the ILD TPC. arXiv:1902.05519. 2019 Feb 14.

Effects of improving the use of PID





Effects in **Flavour Tagging**

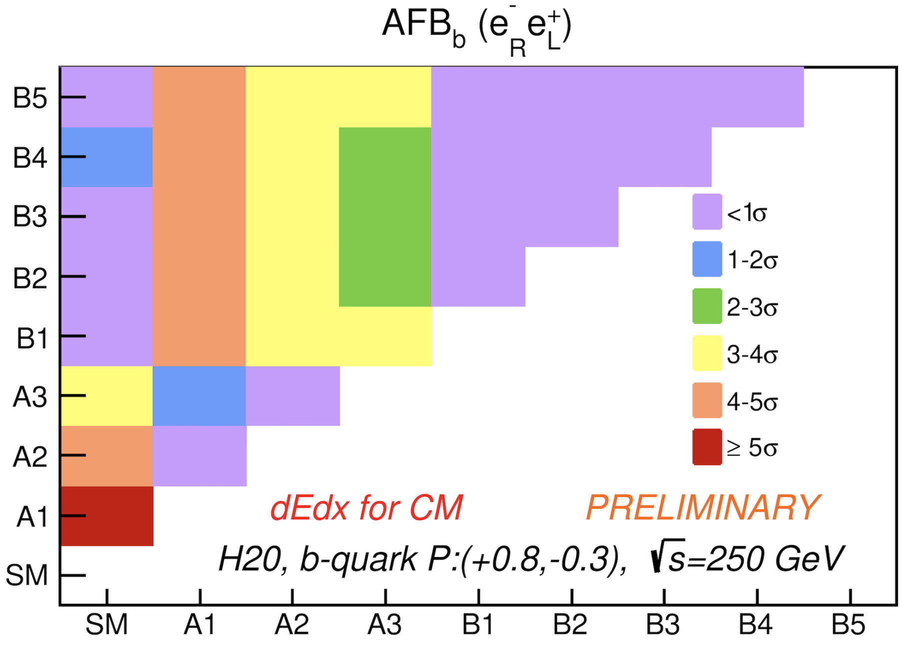
Effects in **Kaon ID** for charge reco.

Discrimination of BSM Models

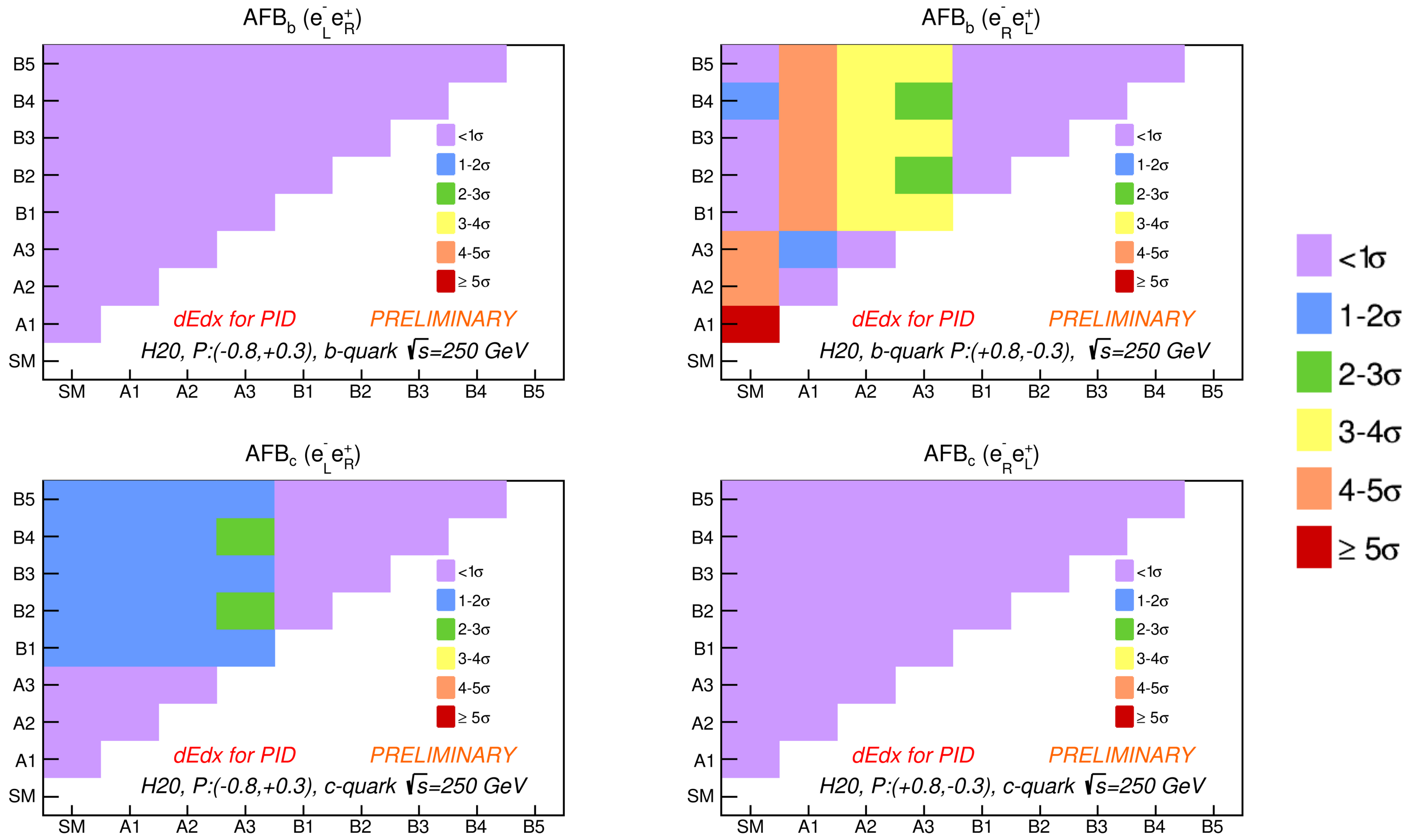
- Assumption: A measurement of one specific model is conducted.
  - Row/Column combination for comparison.

- The uncertainties are considered normally distributed:
  - **Significance in σ**: $d_\sigma = \dfrac{\|\mathrm{AFB}_{\mathrm{test}} - \mathrm{AFB}_{\mathrm{ref}}|}{\Delta \mathrm{AFB}_{\mathrm{ref}}}$
  - P-value: Gaussian at d_σ.

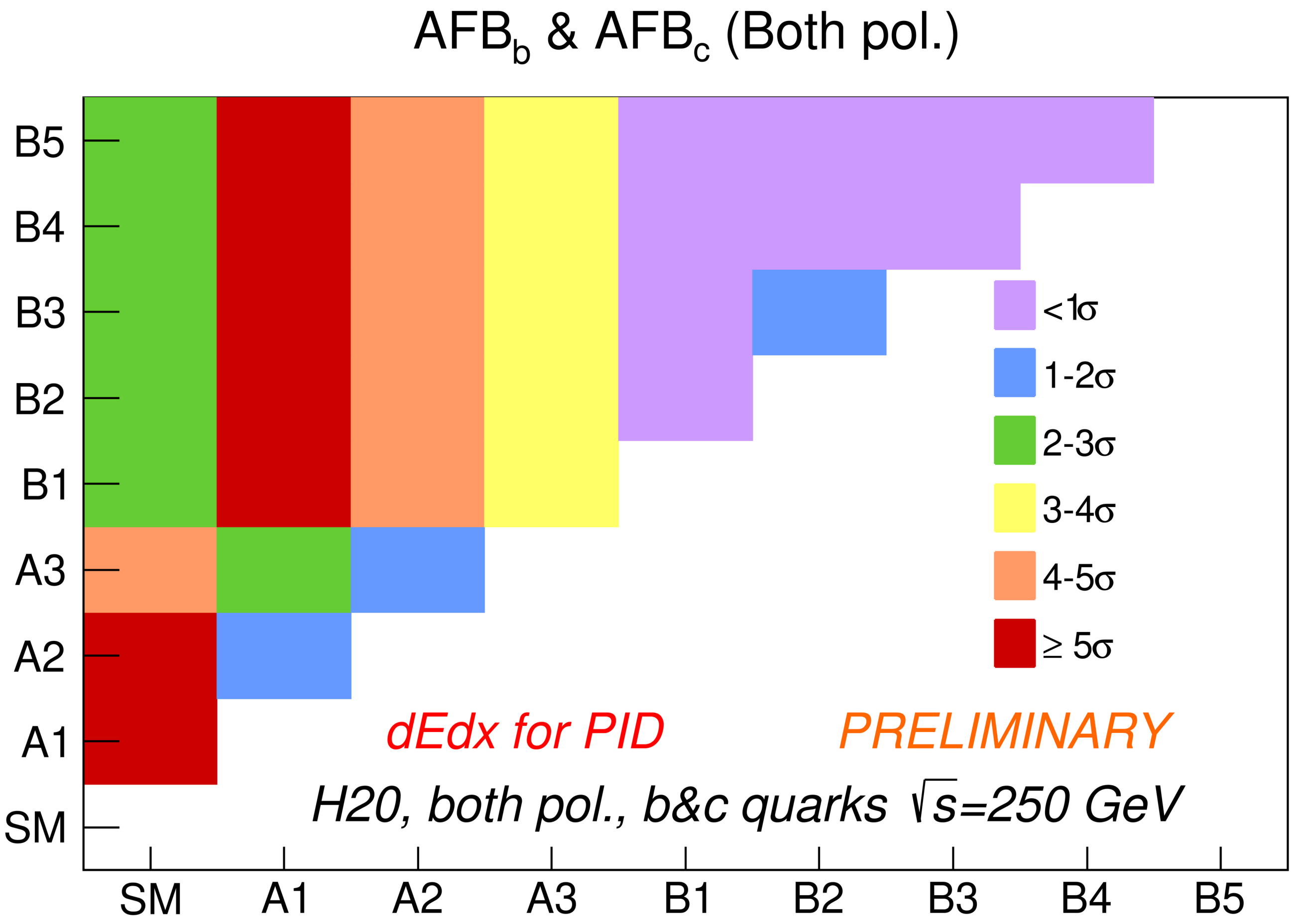
- Combination of multiple measurements is done with a *multivariate gaussian*.
  - Assuming no correlations for A_{FB}.



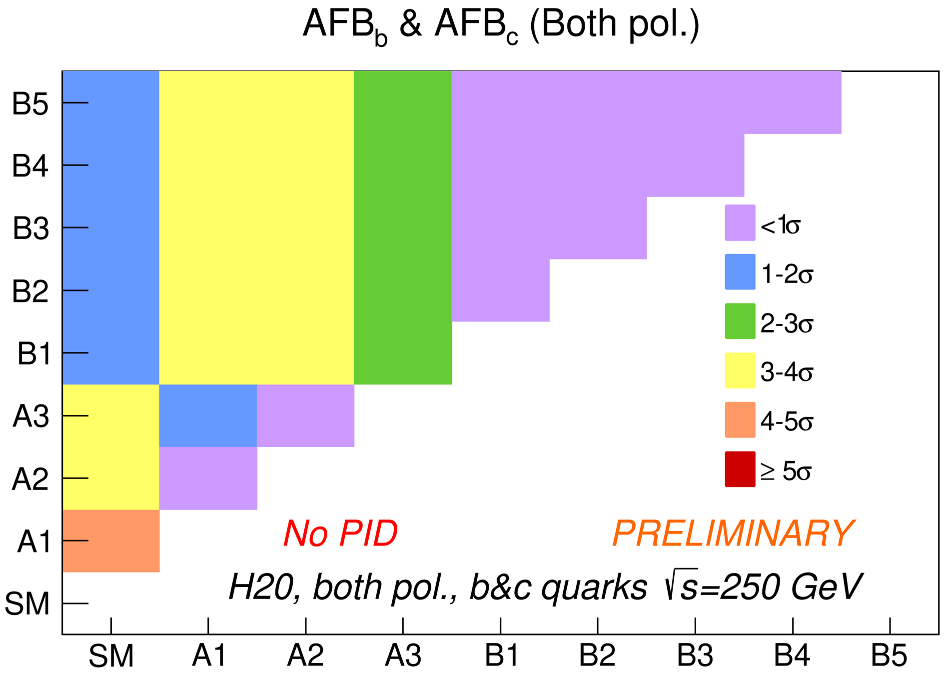
GHU's Models ILC250

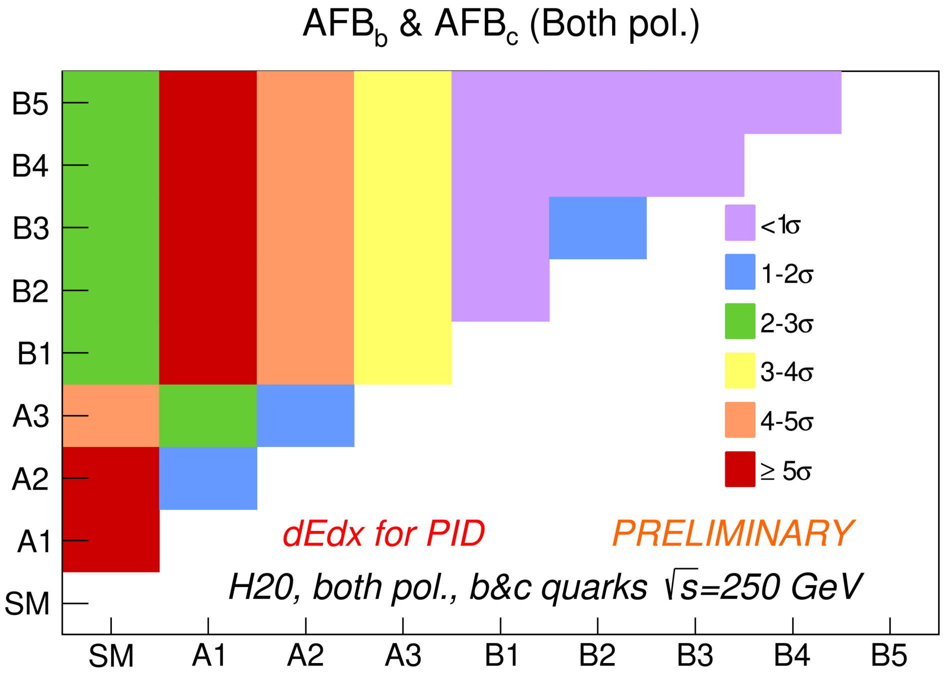


GHU's Models ILC250 (combined)



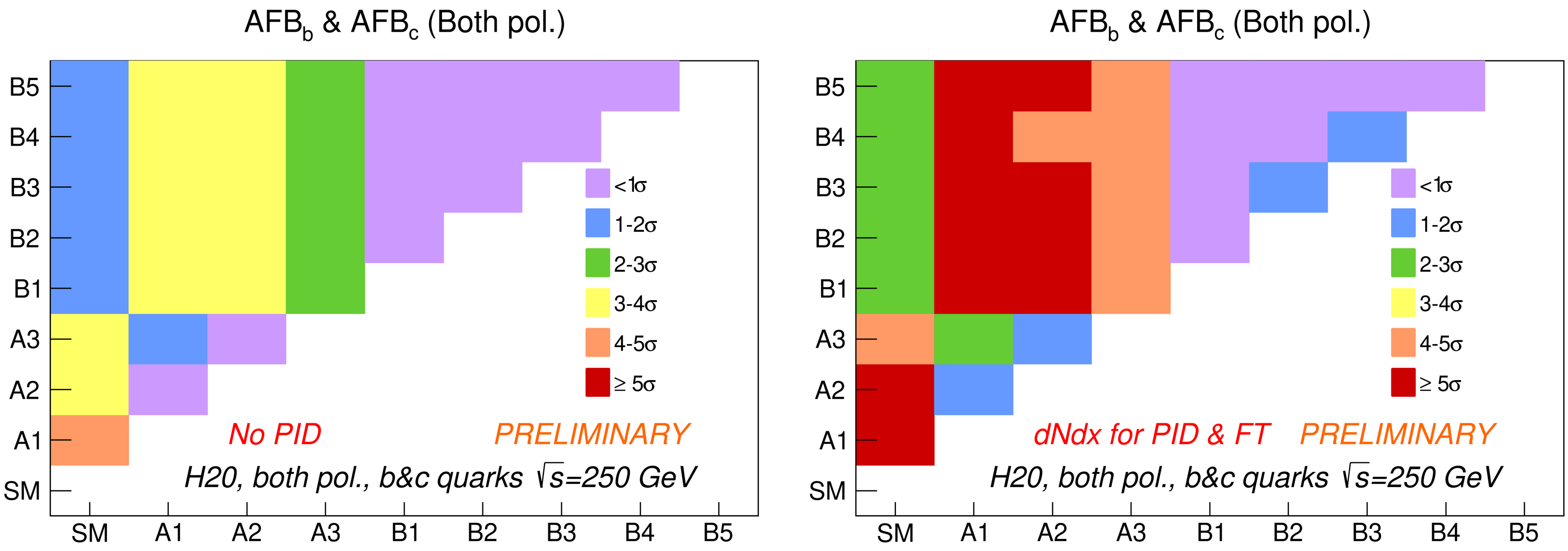
GHU’s Models ILC250 (TPC impact)





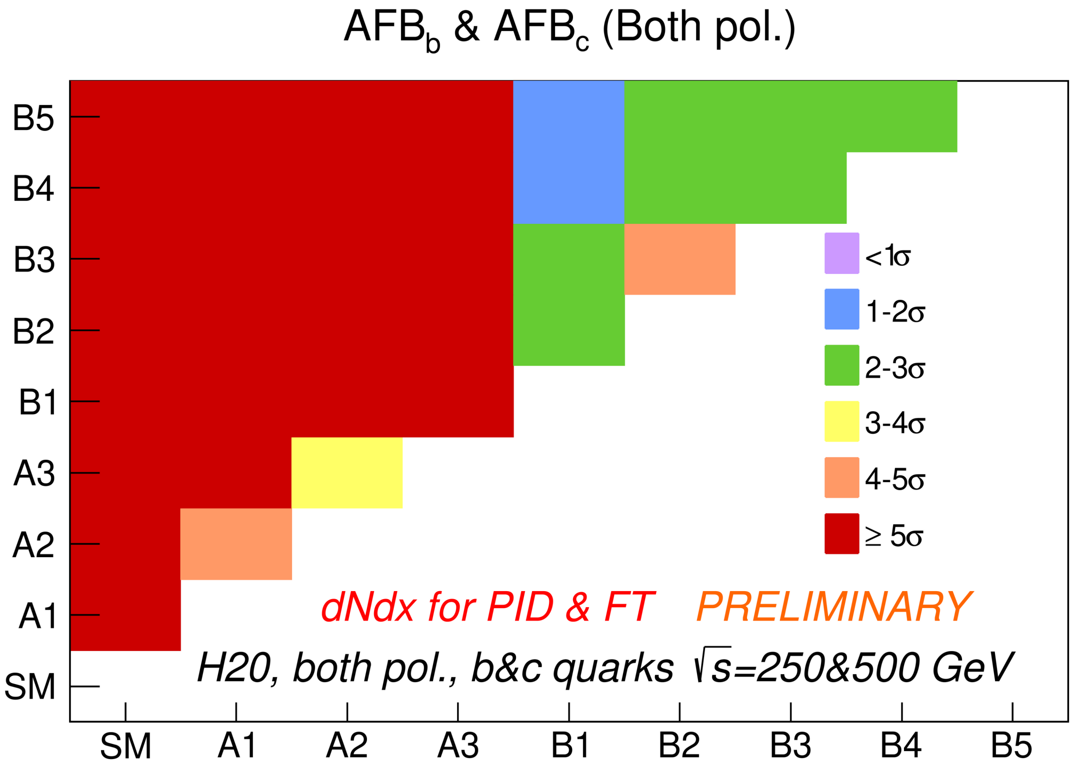
We do **need TPC PID** to discriminate these models!

GHU’s Models ILC250 (TPC impact)



dNdx optimises the use of **TPC PID**

GHU's Models ILC250+500



*The 500 GeV results are an estimation using 2*syst. uncertainties & same preselection ef. than the 250 GeV case*

Accessing **higher energies** is a key factor to discriminate these models!

Summary/Conclusions

- ILC+ILD are powerful tools to discriminate BSM Models thanks to:
    - Polarisation.
    - Energy range.

8 different measurements per energy!

    - **Key role of TPC PID**.
        - Flavour Tagging & jet charge reconstruction.

- There’s still work to do:
    - Finishing computations with results at 500 GeV!
    - R_q and statistical combinations!
    - Study other BSM models?

Thanks for your attention!

BACK-UP

General

Observables

- Differential Cross-Section:
  - General case with polarisation dependence:

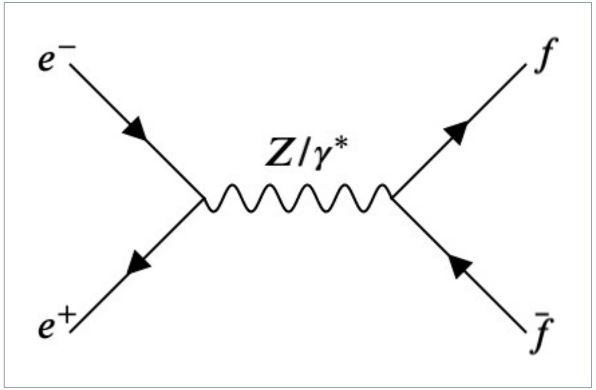
$$\frac{d\sigma^{f\bar{f}}}{d\cos\theta}(P_{e^-},P_{e^+},\cos\theta) = (1-P_{e^-}P_{e^+})\frac{1}{4}\left\{(1-P_{eff})\frac{d\sigma^{f\bar{f}}_{LR}}{d\cos\theta}(\cos\theta)+(1+P_{eff})\frac{d\sigma^{f\bar{f}}_{RL}}{d\cos\theta}(\cos\theta)\right\}$$

$$\boxed{P_{\text{eff}} \equiv \frac{P_{e^-}-P_{e^+}}{1-P_{e^-}P_{e^+}}}$$

  - Polarization contributions:

$$\frac{d\sigma^{f\bar{f}}_{LR}}{d\cos\theta}(\cos\theta) \simeq \frac{s}{32\pi}\left\{(1+\cos\theta)^2\left|Q_{e_L f_L}\right|^2+(1-\cos\theta)^2\left|Q_{e_L f_R}\right|^2\right\}$$

$$\frac{d\sigma^{f\bar{f}}_{RL}}{d\cos\theta}(\cos\theta) \simeq \frac{s}{32\pi}\left\{(1+\cos\theta)^2\left|Q_{e_R f_R}\right|^2+(1-\cos\theta)^2\left|Q_{e_R f_L}\right|^2\right\}$$

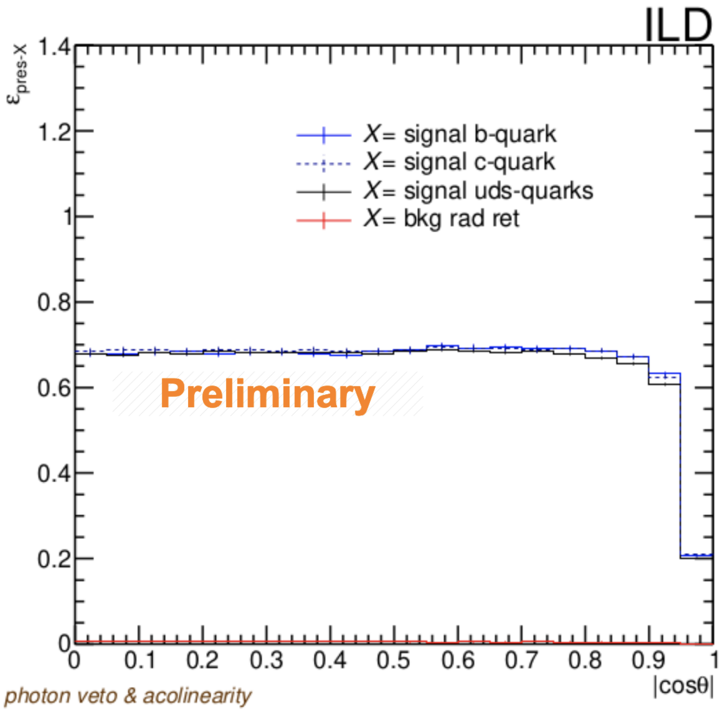


- Helicity amplitudes from the s-channel (may include BSM mediators):
  - They could only be inspected by using polarisation.

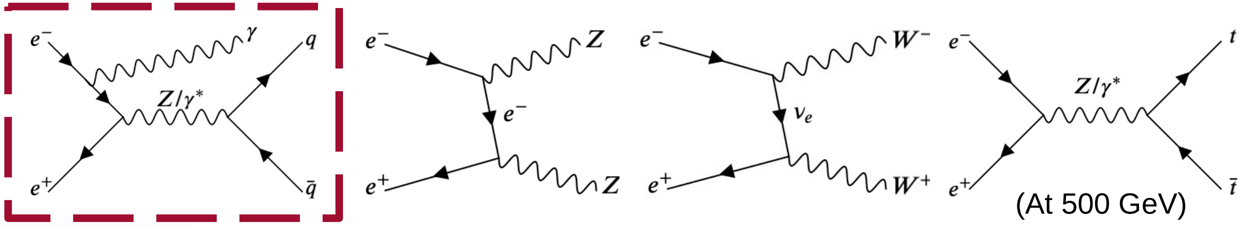
$$Q_{e_X f_Y} = \sum_i \frac{g^X_{V_i e}\, g^Y_{V_i f}}{(s-m^2_{V_i})+i m_{V_i}\Gamma_{V_i}}$$

Preselection of q$\bar{q}$ signals

- ILCSOFT cluster the pfos in jets (VLC algorithm):
  - The algorithm packs together the PFOs into two back-to-back jets.
  - Most of the data is background! (~x10).
    - Most of the background is **radiative return (γq$\bar{q}$)**.
  - Most of the backgrounds (ZZ, WW, ISR, tt) are removed with topological, kinematical and energetic cuts.
    - And additional cut by identifying photon pfos in the detector is used for ISR.
      - PFA detector!



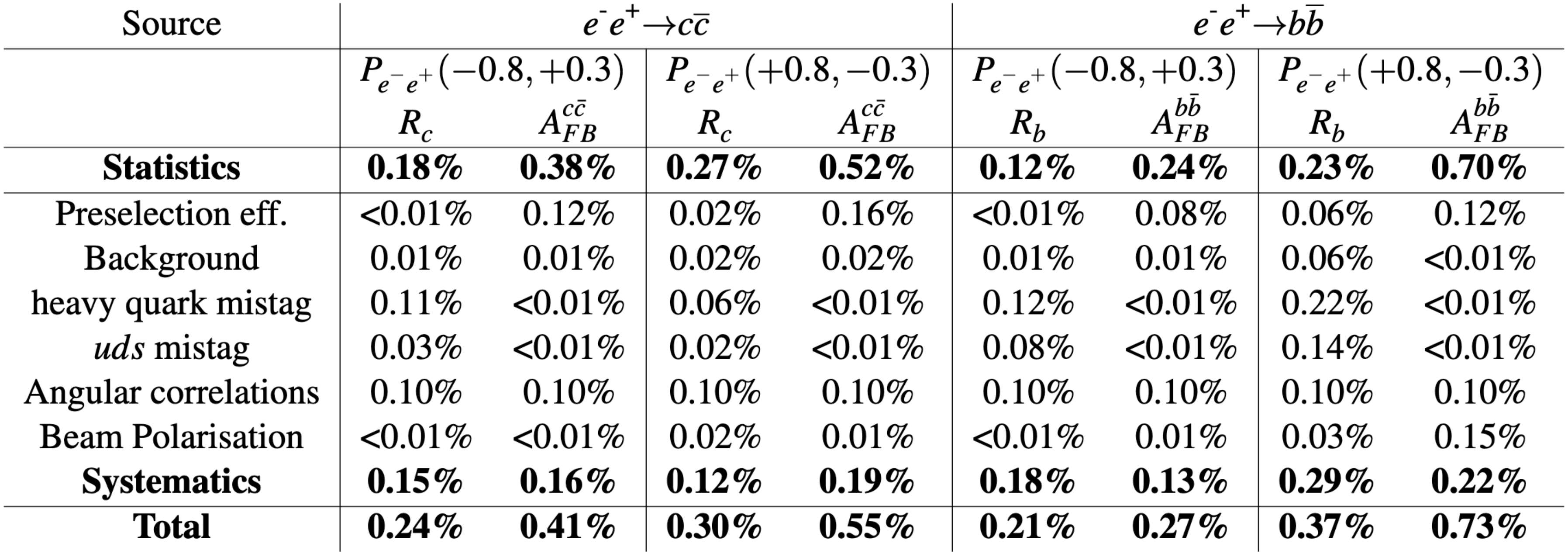
photon veto & acolinearity & K_{reco} & m_{j1j1} & y_{23} cuts



(At 500 GeV)

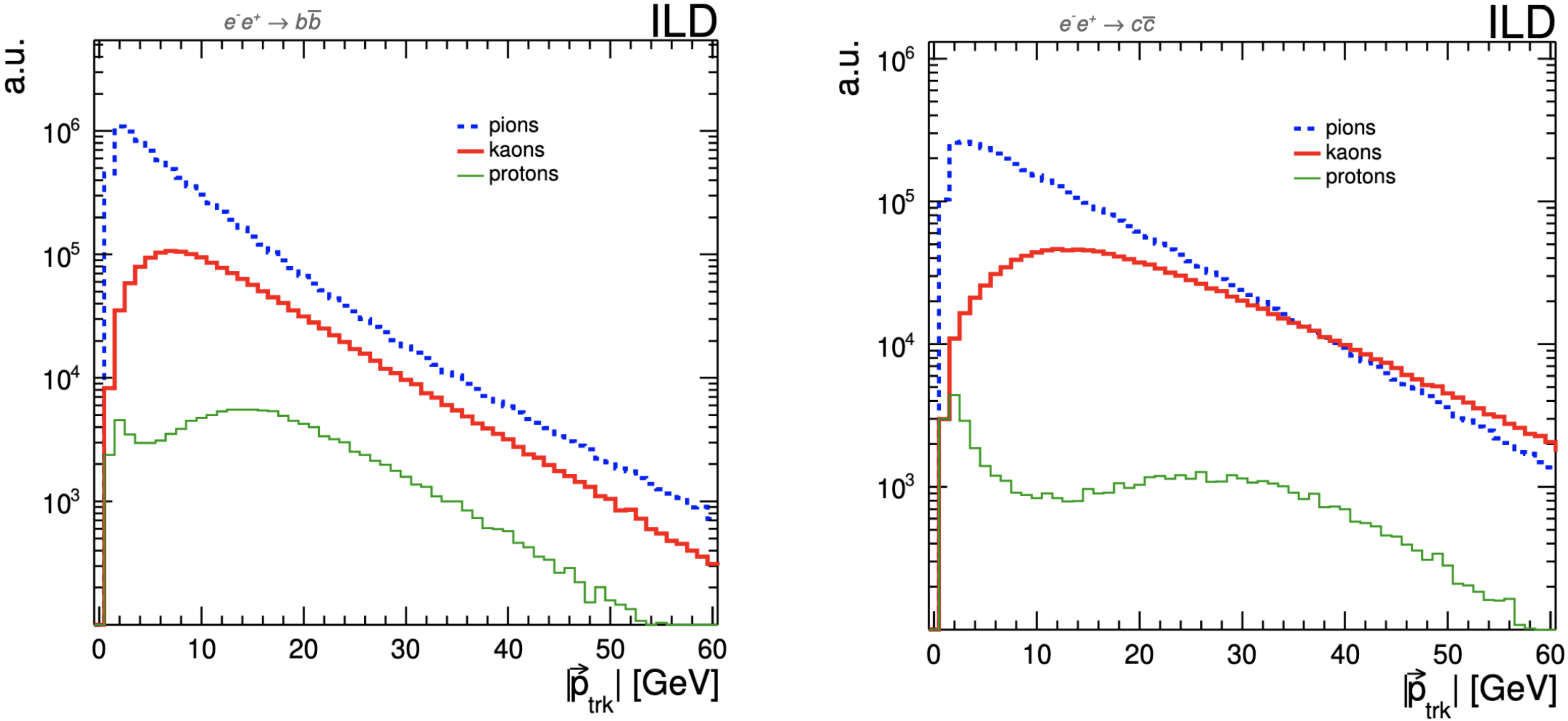
Systematical uncertainties (250 GeV)

Preliminary

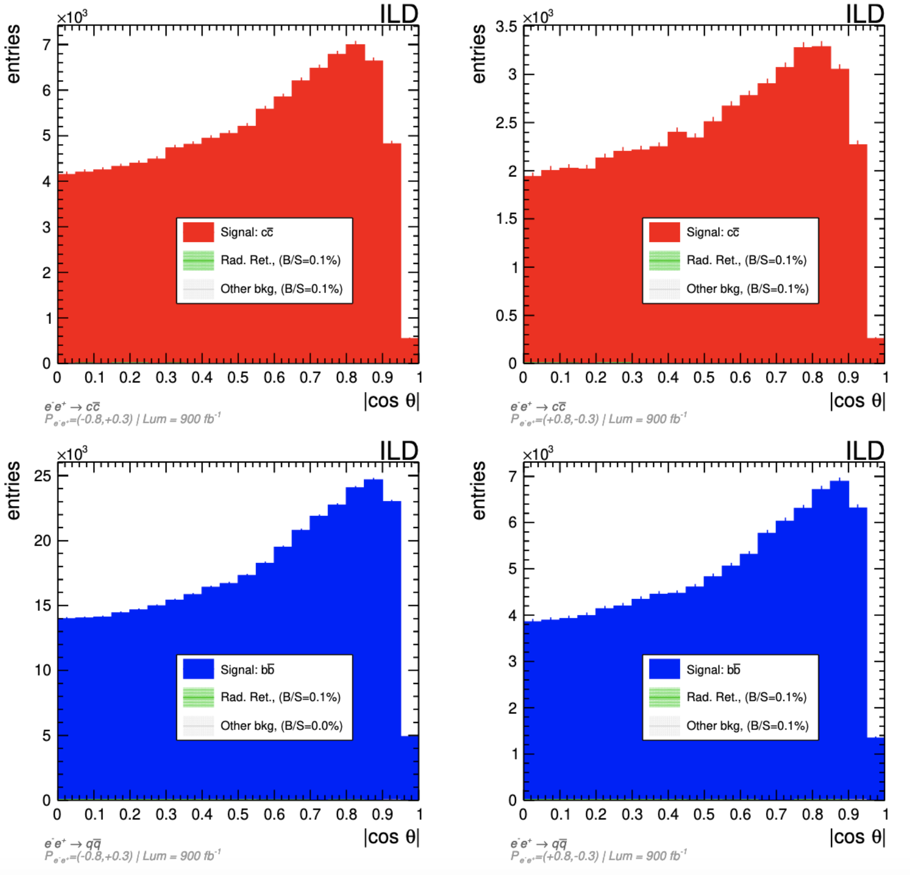


Source	$e^- e^+ \to c\bar{c}$				$e^- e^+ \to b\bar{b}$			
	$P_{e^-e^+}(-0.8,+0.3)$		$P_{e^-e^+}(+0.8,-0.3)$		$P_{e^-e^+}(-0.8,+0.3)$		$P_{e^-e^+}(+0.8,-0.3)$	
	R_c	$A_{FB}^{c\bar{c}}$	R_c	$A_{FB}^{c\bar{c}}$	R_b	$A_{FB}^{b\bar{b}}$	R_b	$A_{FB}^{b\bar{b}}$
Statistics	**0.18%**	**0.38%**	**0.27%**	**0.52%**	**0.12%**	**0.24%**	**0.23%**	**0.70%**
Preselection eff.	<0.01%	0.12%	0.02%	0.16%	<0.01%	0.08%	0.06%	0.12%
Background	0.01%	0.01%	0.02%	0.02%	0.01%	0.01%	0.06%	<0.01%
heavy quark mistag	0.11%	<0.01%	0.06%	<0.01%	0.12%	<0.01%	0.22%	<0.01%
uds mistag	0.03%	<0.01%	0.02%	<0.01%	0.08%	<0.01%	0.14%	<0.01%
Angular correlations	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%
Beam Polarisation	<0.01%	<0.01%	0.02%	0.01%	<0.01%	0.01%	0.03%	0.15%
Systematics	**0.15%**	**0.16%**	**0.12%**	**0.19%**	**0.18%**	**0.13%**	**0.29%**	**0.22%**
Total	**0.24%**	**0.41%**	**0.30%**	**0.55%**	**0.21%**	**0.27%**	**0.37%**	**0.73%**

Kinematics of secondary tracks



Selection efficiency for A_{FB}



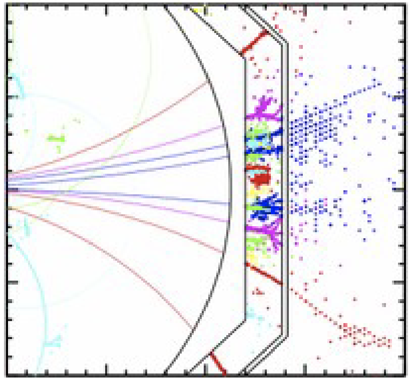
b-quarks & c-quarks after applying the double-charge method to them

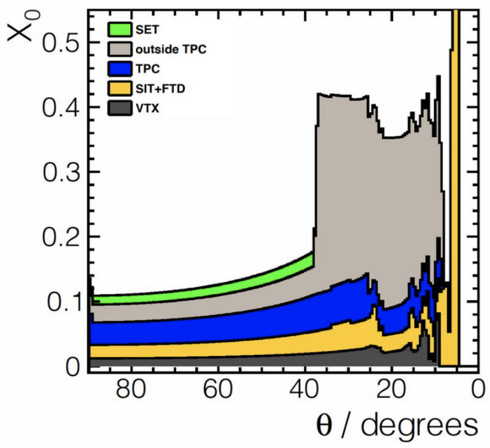
b-quarks & c-quarks Signals are close to:

- Background-free
- uncorrelated

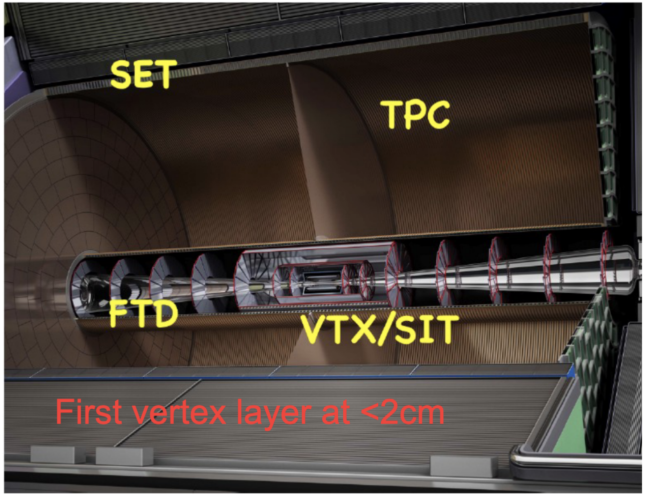
ILD overview

- ILD: International Large Detector.
  - Excellent resolution:
    - Beam IP constraining capability.
    - Tracking efficiency (>99%).
    - Vertexing.
      - Secondary vtcs and flavour tagging!
  - Compact and hermetic high granularity calorimetry system ($>10^8$ cells!).
  - Optimized for Particle Flow Concept, i.e., single particle reconstruction.





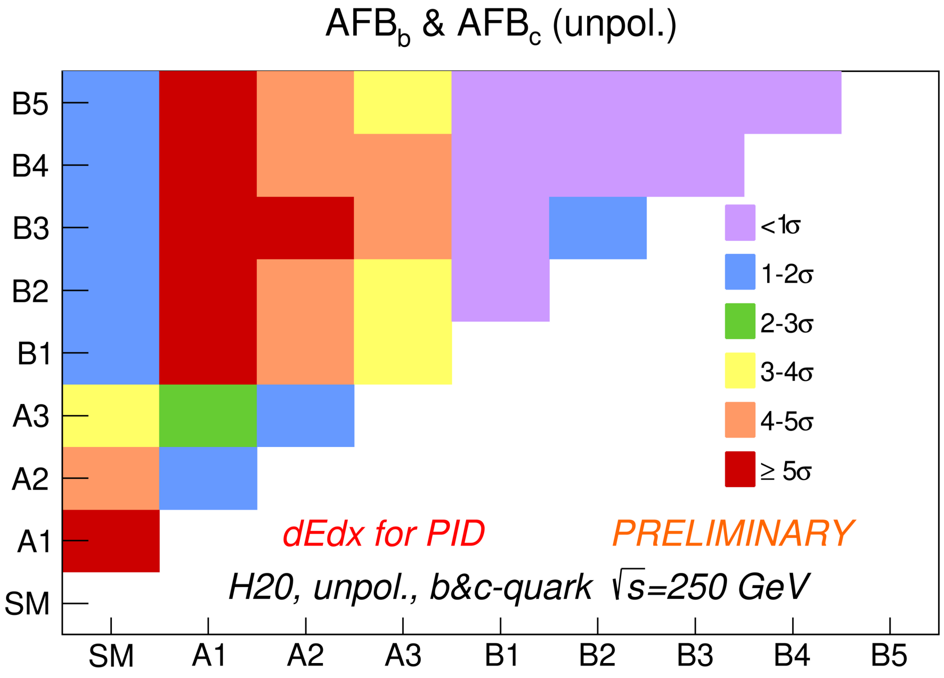
ILD design



First vertex layer at <2cm

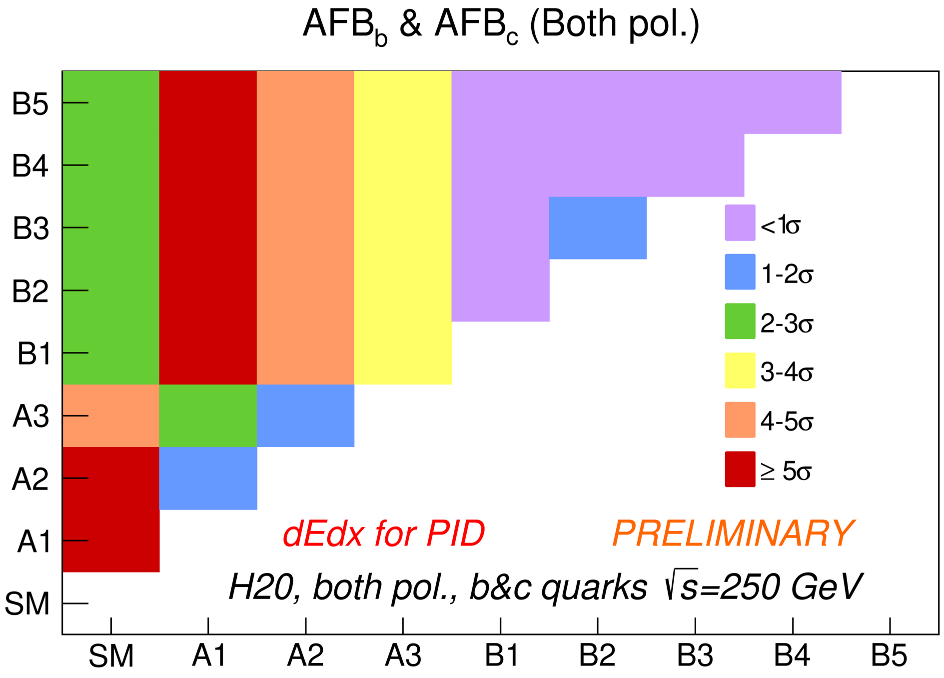
ILD: Interim Design Report.
ArXiv:1003.01116

GHU’s Models ILC250 (Polarisation)



AFB_b & AFB_c (unpol.)

	SM	A1	A2	A3	B1	B2	B3	B4	B5
B5	1-2σ	≥ 5σ	4-5σ	3-4σ	<1σ	<1σ	<1σ	<1σ	
B4	1-2σ	≥ 5σ	4-5σ	4-5σ	<1σ	<1σ	<1σ		
B3	1-2σ	≥ 5σ	≥ 5σ	4-5σ	<1σ	1-2σ			
B2	1-2σ	≥ 5σ	4-5σ	3-4σ	<1σ				
B1	1-2σ	≥ 5σ	4-5σ	3-4σ					
A3	3-4σ	2-3σ	1-2σ						
A2	4-5σ	1-2σ							
A1	≥ 5σ								
SM									

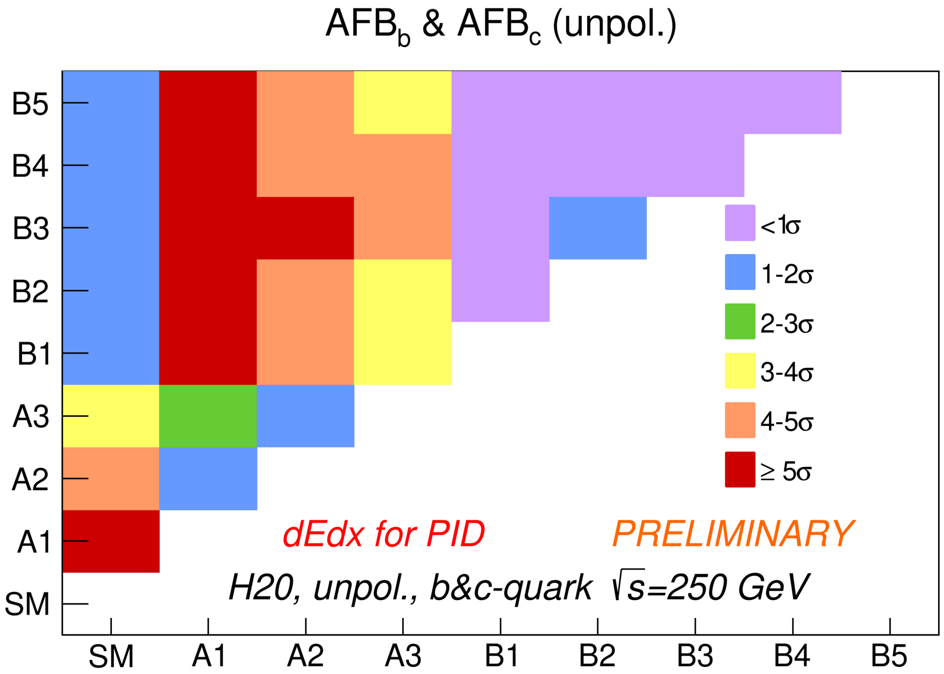


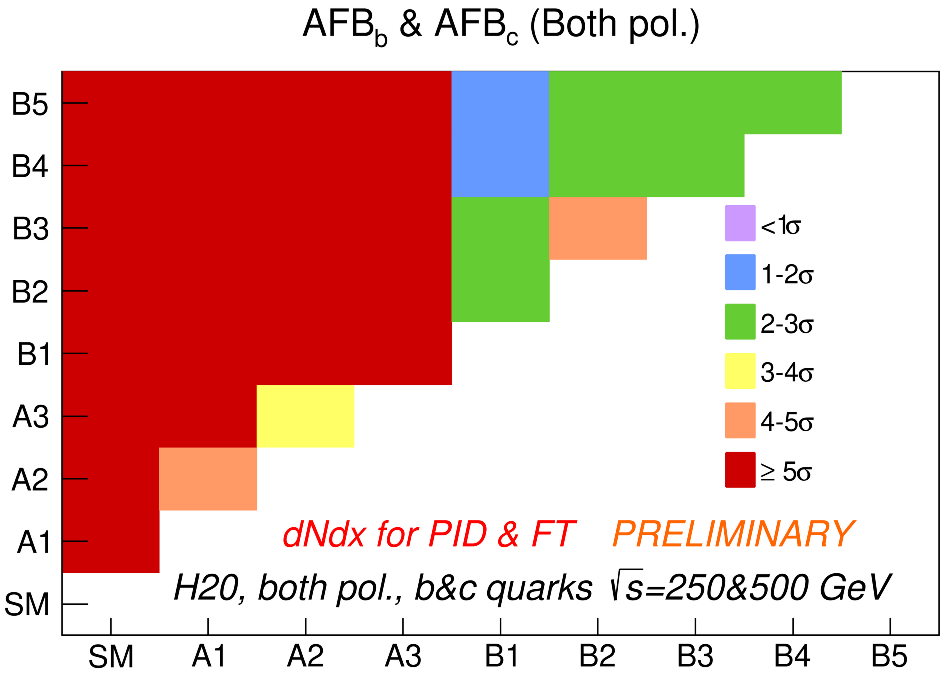
AFB_b & AFB_c (Both pol.)

	SM	A1	A2	A3	B1	B2	B3	B4	B5
B5	2-3σ	≥ 5σ	4-5σ	3-4σ	<1σ	<1σ	<1σ	<1σ	
B4	2-3σ	≥ 5σ	4-5σ	3-4σ	<1σ	<1σ	<1σ		
B3	2-3σ	≥ 5σ	4-5σ	3-4σ	<1σ	1-2σ			
B2	2-3σ	≥ 5σ	4-5σ	3-4σ	<1σ				
B1	2-3σ	≥ 5σ	4-5σ	3-4σ					
A3	4-5σ	2-3σ	1-2σ						
A2	≥ 5σ	1-2σ							
A1	≥ 5σ								
SM									

Effects of polarised beams at 250 GeV

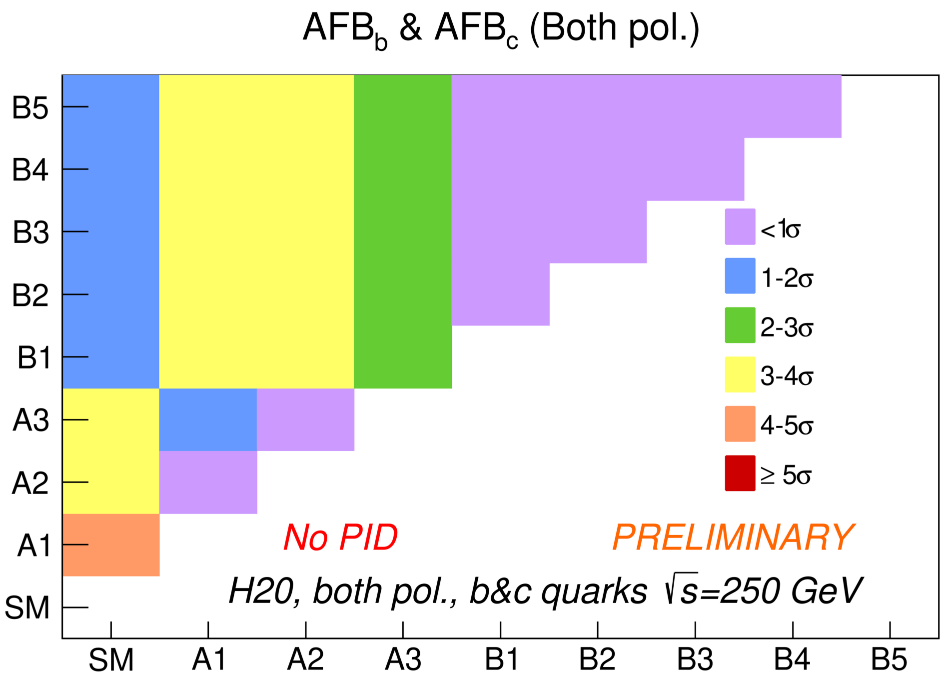
GHU's Models ILC250/500 (Pol.)

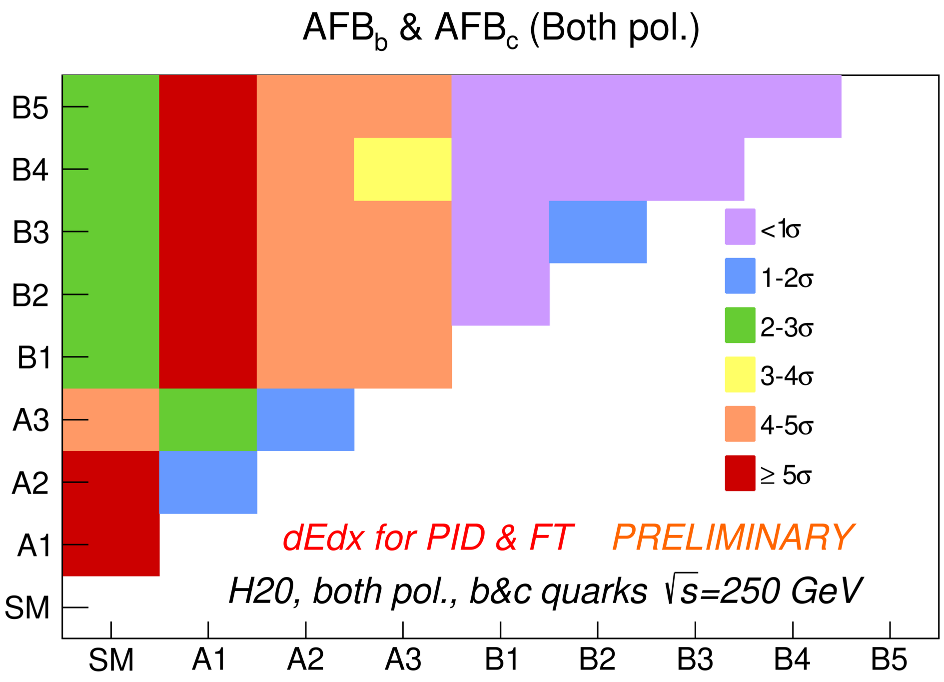




Effects of polarised beams

GHU’s Models ILC250 (TPC impact)



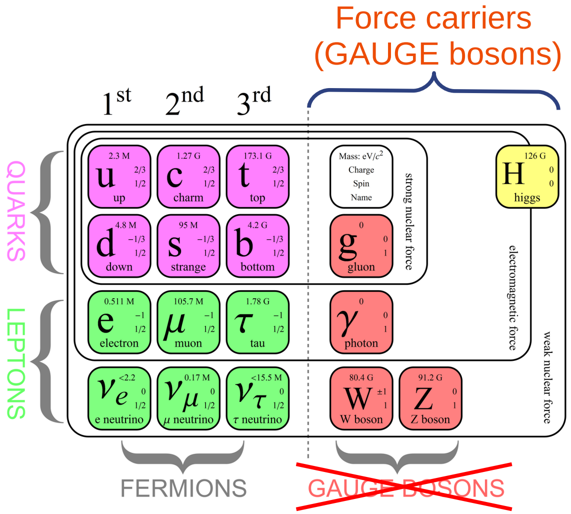


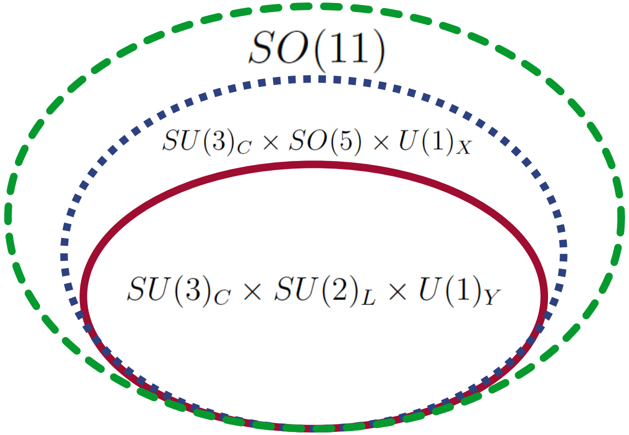
dEdx optimises the use of **TPC PID**

Hosotani’s Models

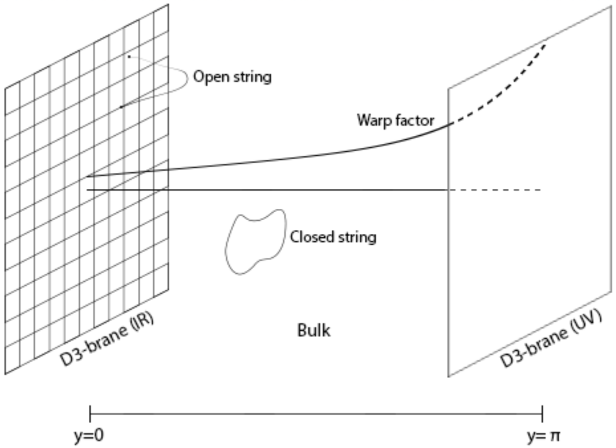
Gauge-Higgs Unification (GHU) Models

- In the Hosotani Models the GHU unify all the force carriers under a single gauge group by using an extra physical dimension (Randall-Sundrum metric):





$$ds^2 = g_{MN}dx^M dx^N = e^{-2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2,$$



- The breaking pattern is way more complex than in the SM and features the Hosotani's mechanism.
  - Most of the fields are localized in the bulk and we feel the IR-projections.
  - We distinguish **A-Models** (GHU) and **B-Models** (GHU+GUT).

Projection of couplings and EW mixing angle:

$$g_Y^{5D} = \frac{g_A g_B}{\sqrt{g_A^2 + g_B^2}} \qquad \sin\theta_W^0 = \frac{s_\phi}{\sqrt{1+s_\phi^2}}$$

Gauge-Higgs Unification (GHU) Models

- The metric of the warped Randall-Sundrum space-time:

$$ds^2 = g_{MN} dx^M dx^N = e^{-2\sigma(y)} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2,$$

- This is inspired by conformal symmetry, a.k.a. “scale symmetry”; used in cosmology, string theory and holography.
  - Conformal coordinates:

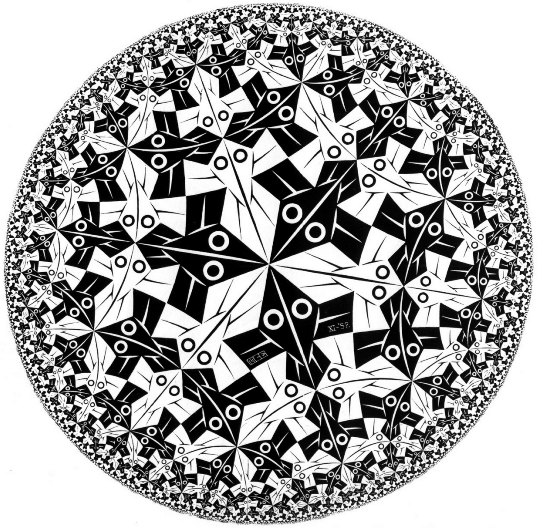
$$z = e^{ky}$$

  - The metric in conformal coordinates:

$$ds^2 = \frac{1}{z^2}\left(\eta_{\mu\nu} dx^\mu dx^\nu + \frac{dz^2}{k^2}\right)$$

Extra-dimension (+1D)

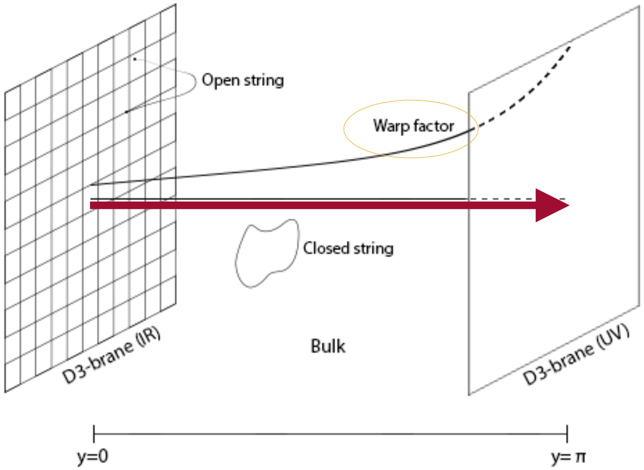
Minkowski space-time (4D)



M. C. Escher “Circle Limit 1”. Example of conformal symmetry with hyperbolic scaling

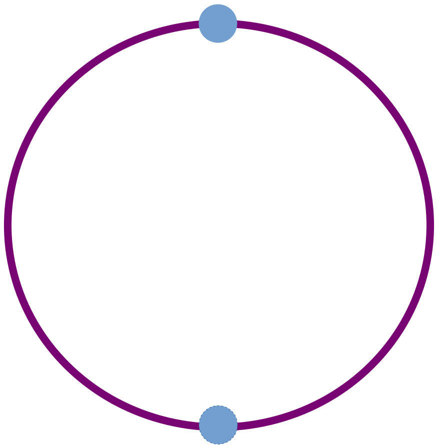
Gauge-Higgs Unification (GHU) Models

- How the Randall-Sundrum space-time works:



$$ds^2 = g_{MN}dx^M dx^N = \overbrace{e^{-2\sigma(y)}}^{\text{warping}}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2,$$

5h dimension compactified in a ring-shaped, two branes at opposite points, orbifold b.c. in both parts of the circle

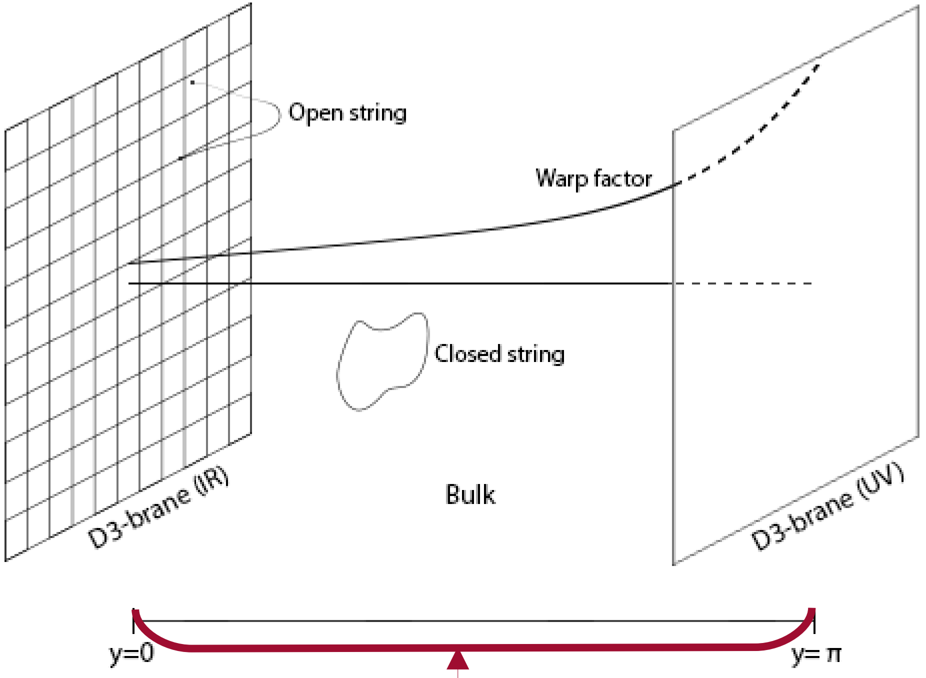


This side is symmetric to → ← this other side

This was proposed as a way to explain why gravity is so much weaker that the rest of the forces: gravitons (closed strings) leak into the extra-dimension

Gauge-Higgs Unification (GHU) Models

- Kaluza-Klein resonances:



Normal modes over this interval (fifth component)

KK-resonances!

Gauge-Higgs Unification (GHU) Models

- How the Hosotani's Models work:
  - Most of the fields are localized in the bulk and the effects in our brane are projections
  - The original group symmetry is in 5 dimensions
    - The breaking pattern is way more complex than in the SM and features the Hosotani's mechanism

$$
\begin{aligned}
& SU(3)_C \times SO(5) \times U(1)_X \\
& \xrightarrow[BC]{} SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \quad \text{at } y = 0, L \\
& \xrightarrow[\langle\Phi\rangle]{} SU(3)_C \times SU(2)_L \times U(1)_Y \quad \text{by the VEV } \langle \Phi_{(\mathbf{1},\mathbf{4})} \rangle \neq 0 \text{ at } y = 0 \\
& \xrightarrow[\theta_H]{} SU(3)_C \times U(1)_{EM} \quad \text{by the Hosotani mechanism,}
\end{aligned}
$$

Remember we will we working with two different kind of models!

	B-model	A-model
Quark Lepton	$(\mathbf{3},\mathbf{4})_{\frac{1}{6}}$ $(\mathbf{3},\mathbf{1})^{+}_{-\frac{1}{3}}$ $(\mathbf{3},\mathbf{1})^{-}_{-\frac{1}{3}}$ $(\mathbf{1},\mathbf{4})_{-\frac{1}{2}}$	$(\mathbf{3},\mathbf{5})_{\frac{2}{3}}$ $(\mathbf{3},\mathbf{5})_{-\frac{1}{3}}$ $(\mathbf{1},\mathbf{5})_{0}$ $(\mathbf{1},\mathbf{5})_{-1}$
Dark fermion	$(\mathbf{3},\mathbf{4})_{\frac{1}{6}}$ $(\mathbf{1},\mathbf{5})^{+}_{0}$ $(\mathbf{1},\mathbf{5})^{-}_{0}$	$(\mathbf{1},\mathbf{4})_{\frac{1}{2}}$
Brane fermion	$(\mathbf{1},\mathbf{1})_{0}$	$(\mathbf{3},[\mathbf{2},\mathbf{1}])_{\frac{7}{6},\frac{1}{6},-\frac{5}{6}}$ $(\mathbf{1},[\mathbf{2},\mathbf{1}])_{\frac{1}{2},-\frac{1}{2},-\frac{3}{2}}$
Brane scalar	$(\mathbf{1},\mathbf{4})_{\frac{1}{2}}$	$(\mathbf{1},[\mathbf{1},\mathbf{2}])_{\frac{1}{2}}$

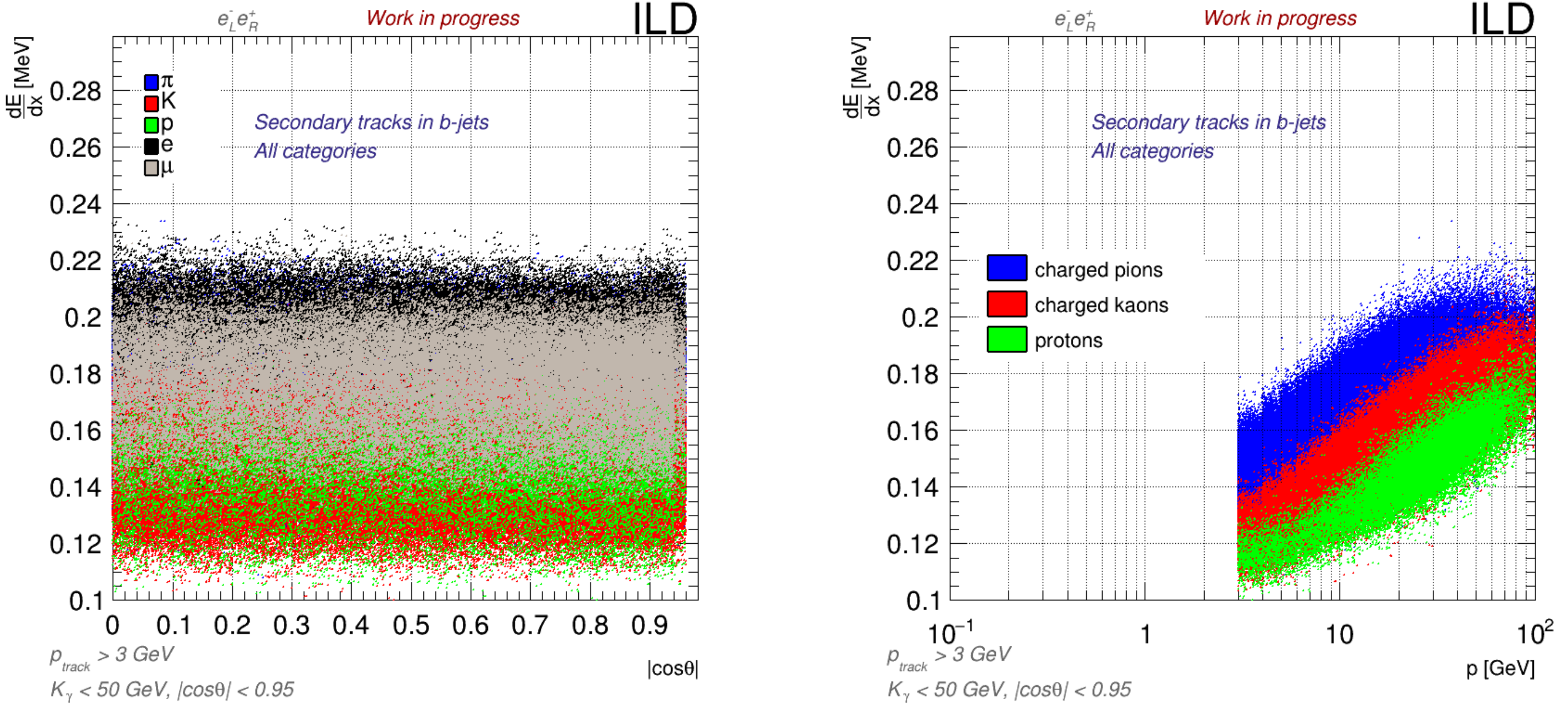
Field content in the group representation

Projection of couplings and EW mixing angle:

$$
\boxed{g_Y^{5\mathrm{D}} = \frac{g_A g_B}{\sqrt{g_A^2 + g_B^2}} \qquad \sin\theta_W^0 = \frac{s_\phi}{\sqrt{1+s_\phi^2}}}
$$

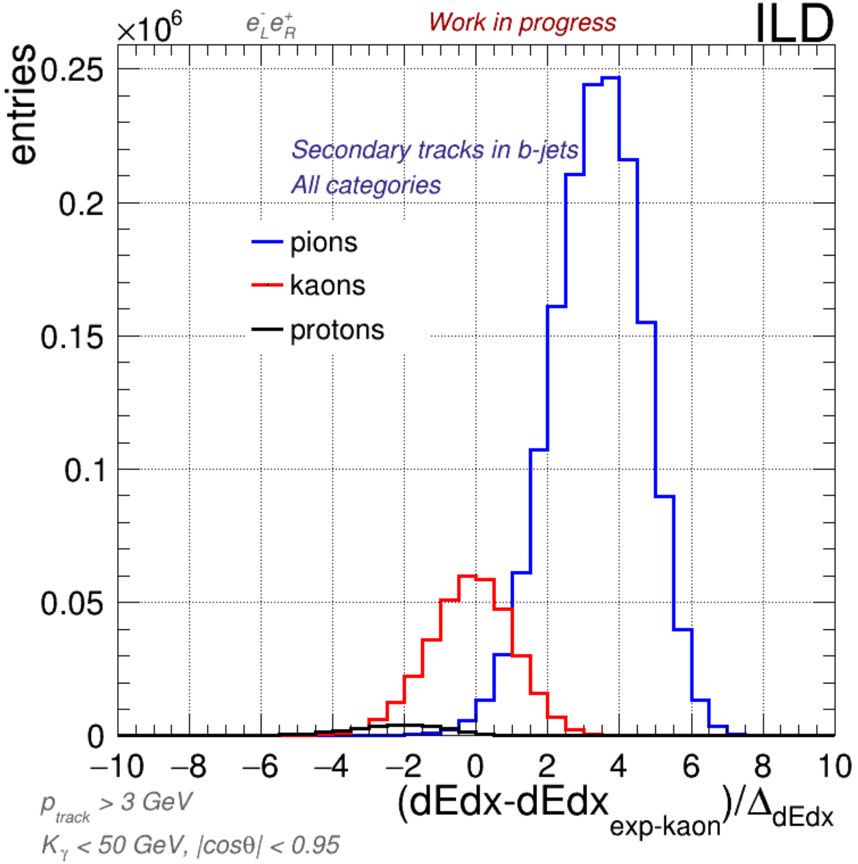
Adding dEdx in LCFI+

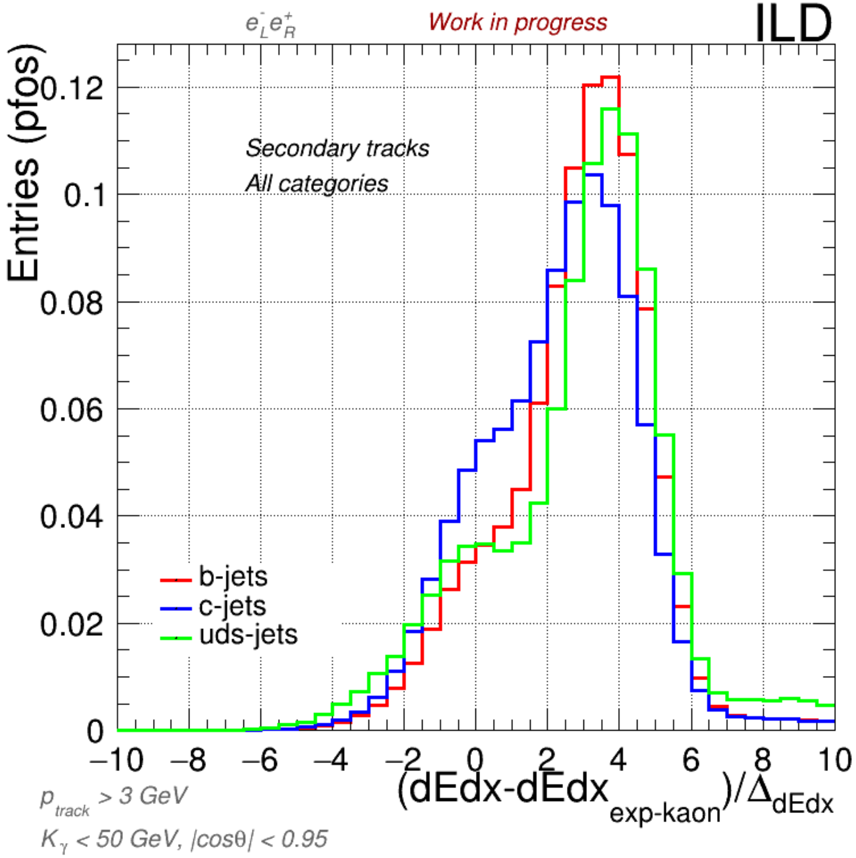
dEdx – Preselection of pfos



Adjusting this points to the Bethe-Bloch formula: Estimate PID

dEdx – KDS for different quark flavours





We repeat this also with Pions and Protons.

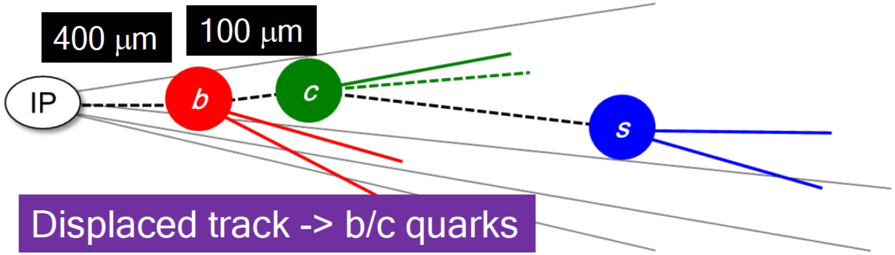
We build 3 variables NKaonSec, NPionSec & NProtonSec and add them to the FT!

Flavour tagging: LCFI+

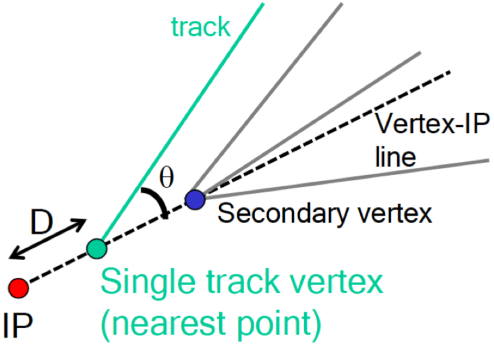
- Vertex finder:
  - Reconstruct collinear or close-to-collinear vertexes by merging particle tracks from the event information.
  - Distance ($\tau_q \cdot c$) from the IP is key for b and c quark ID: Displaced vertexes.
  - We also encounter single track vertexes: pseudo-vertexes.

- Jet Clustering & vertex refiner:
  - Use the vertexing information.
  - Different algorithms could be used (k_T, Durham, **VLC**, etc.).
  - In our case, we expect two back-to-back jets with ISR.

- Flavour tagging:
  - TMVA (BDT based).
  - 3-class classifier b/c/uds.



Displaced track -> b/c quarks



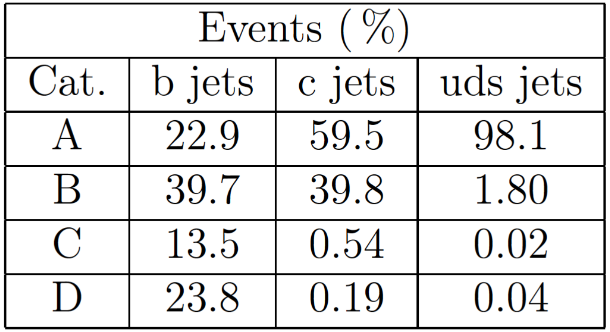
Single track vertex (nearest point)

arXiv:1506.08371

Events for each category

With ISR removal

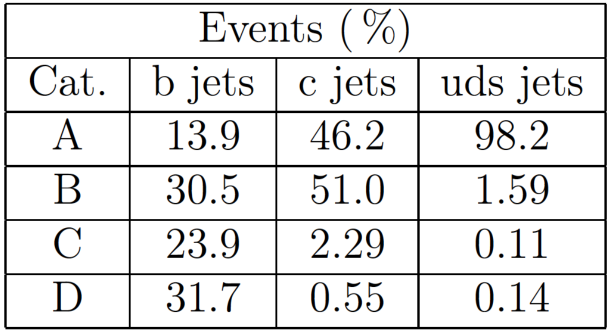
Z-Pole (LCFI+ paper[1])



Events (%)			
Cat.	b jets	c jets	uds jets
A	22.9	59.5	98.1
B	39.7	39.8	1.80
C	13.5	0.54	0.02
D	23.8	0.19	0.04

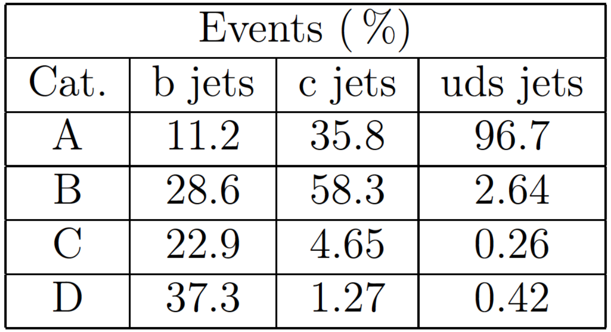
1. LCFIPlus: A Framework for Jet Analysis in Linear Collider Studies

250 GeV samples

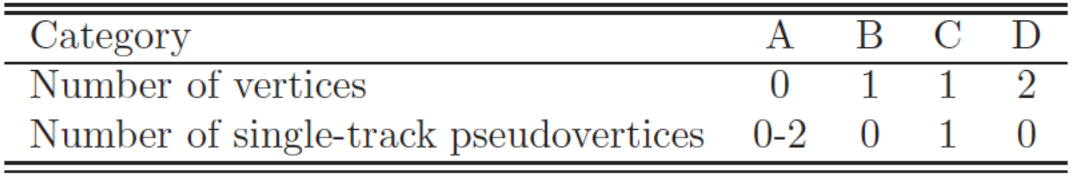


Events (%)			
Cat.	b jets	c jets	uds jets
A	13.9	46.2	98.2
B	30.5	51.0	1.59
C	23.9	2.29	0.11
D	31.7	0.55	0.14

500 GeV samples



Events (%)			
Cat.	b jets	c jets	uds jets
A	11.2	35.8	96.7
B	28.6	58.3	2.64
C	22.9	4.65	0.26
D	37.3	1.27	0.42



Category	A	B	C	D
Number of vertices	0	1	1	2
Number of single-track pseudovertices	0-2	0	1	0

Re-training flavor tagging (coding)

TrackNtuple.cc+TrackProb.C

Prepare track info: D0/Z0/vertexing tolerance, etc.

MakeNtuple.cc

Creates the Ntuples used for the training process.
(It needs the track info for many of them.)

TrainMVA.cc

Run the TMVA with the BDTs for each category.
Creates the weight files for b/c-tag.

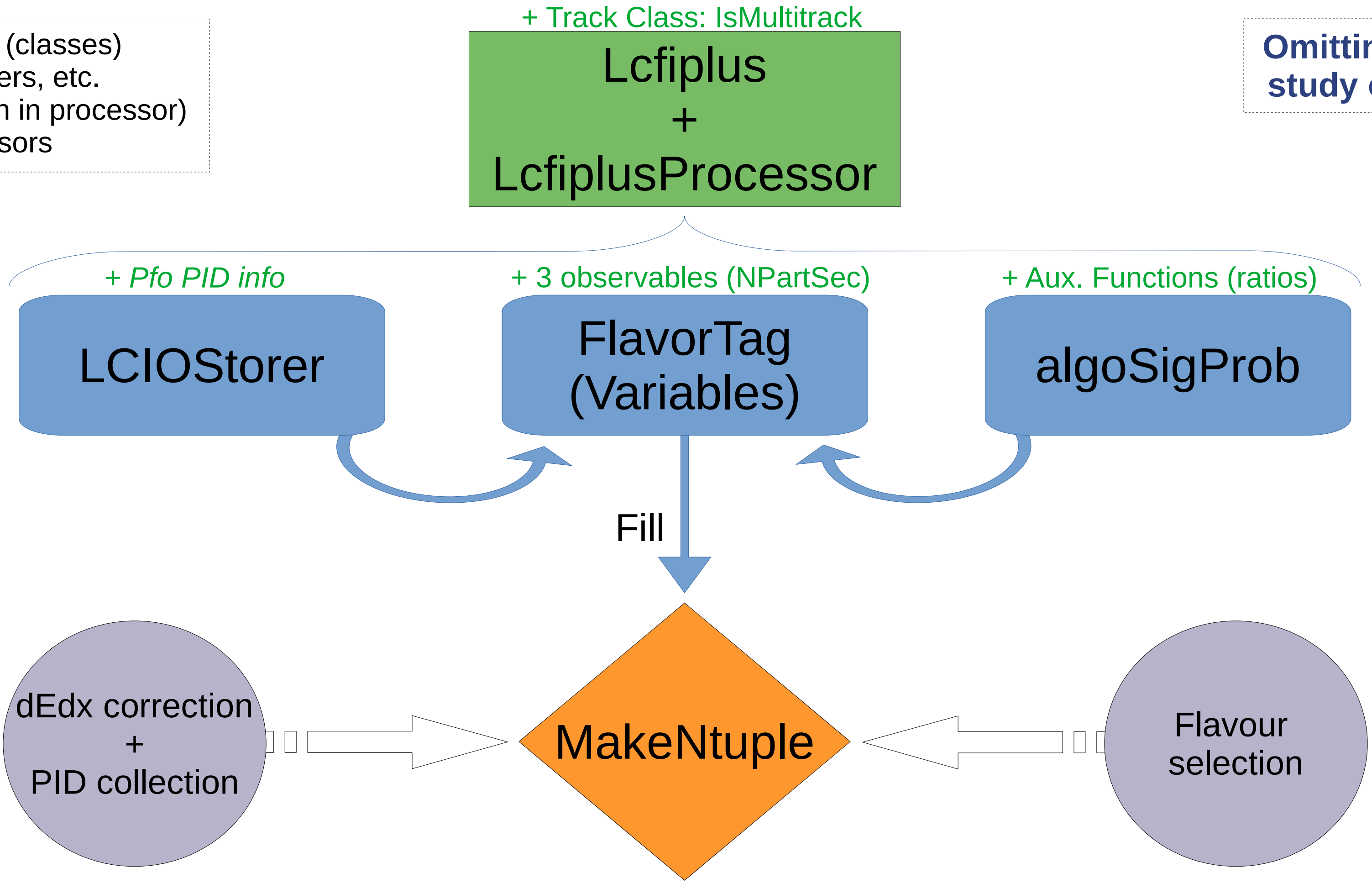
To introduce dEdx in the training process we need to:

1. Load it into the Ntuples when we run MakeNtuple.cc
2. Re-Train to get new weights.
3. Check that this training is optimal:
   3.1 **Particle Swarm Optimization** + Statistical tests (KS & AD)

LCFI+ MakeNtuple Workflow (+dEdx)

- 🟩 Main definitions (classes)
- 🟦 Functions, readers, etc.
- 🟧 Algorithm (to run in processor)
- 🟪 External processors

Omitting parts I didn't study or interact with



+ Track Class: IsMultitrack

Lcfiplus
+
LcfiplusProcessor

+ *Pfo PID info*

LCIOStorer

+ 3 observables (NPartSec)

FlavorTag
(Variables)

+ Aux. Functions (ratios)

algoSigProb

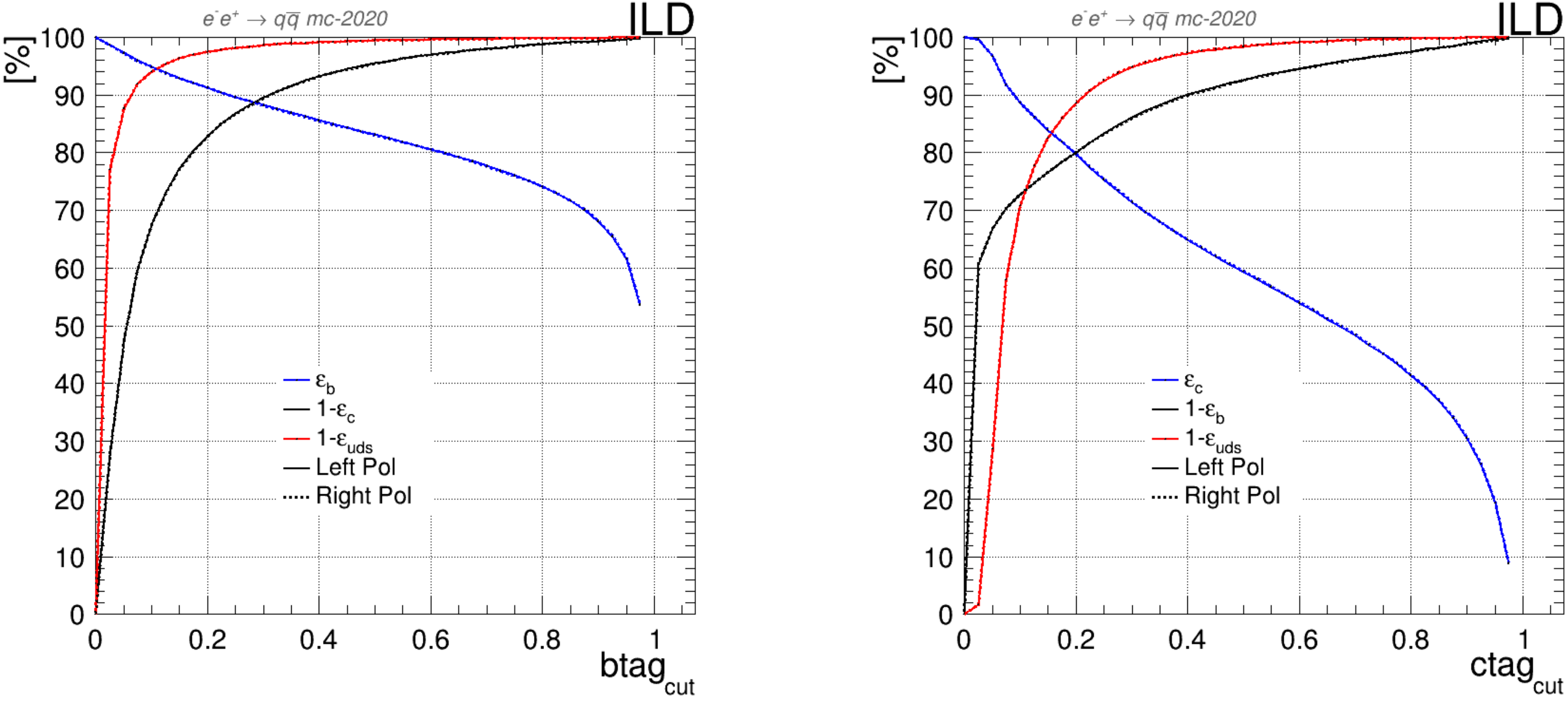
Fill

dEdx correction
+
PID collection

MakeNtuple

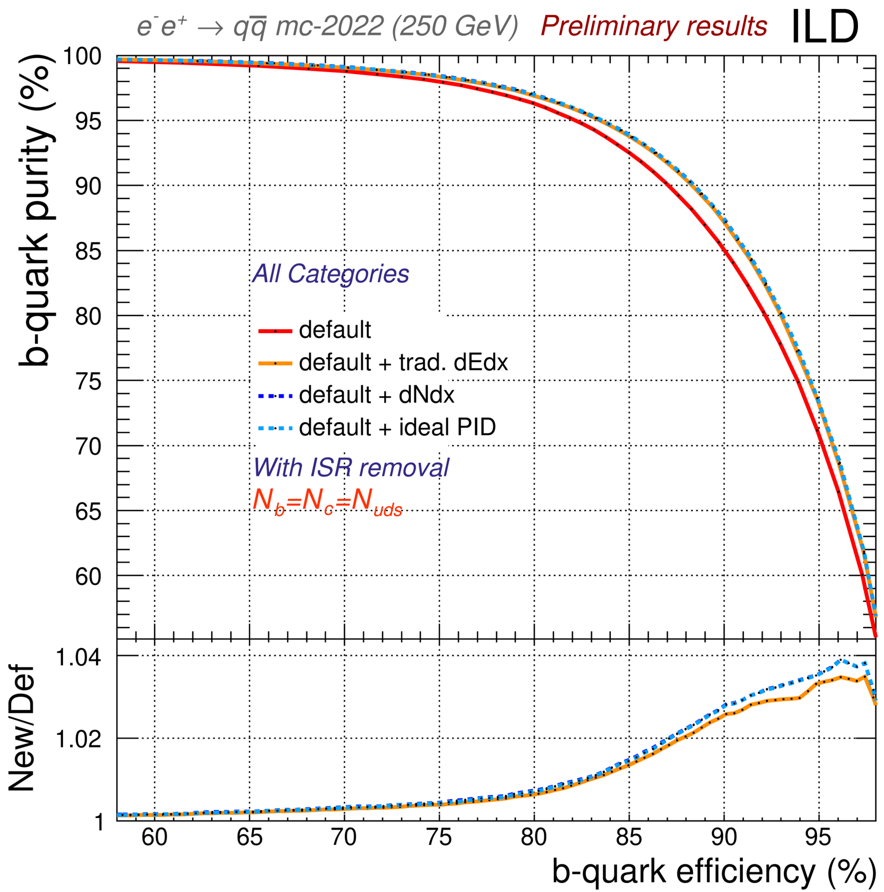
Flavour
selection

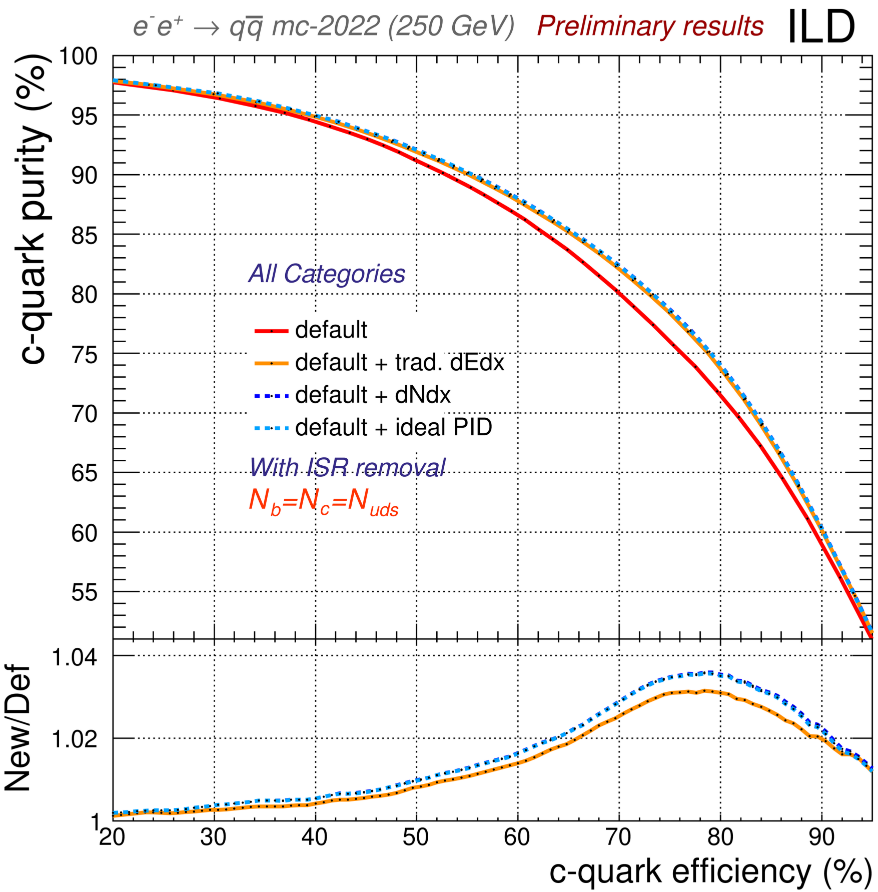
Flavour tagging (250GeV)



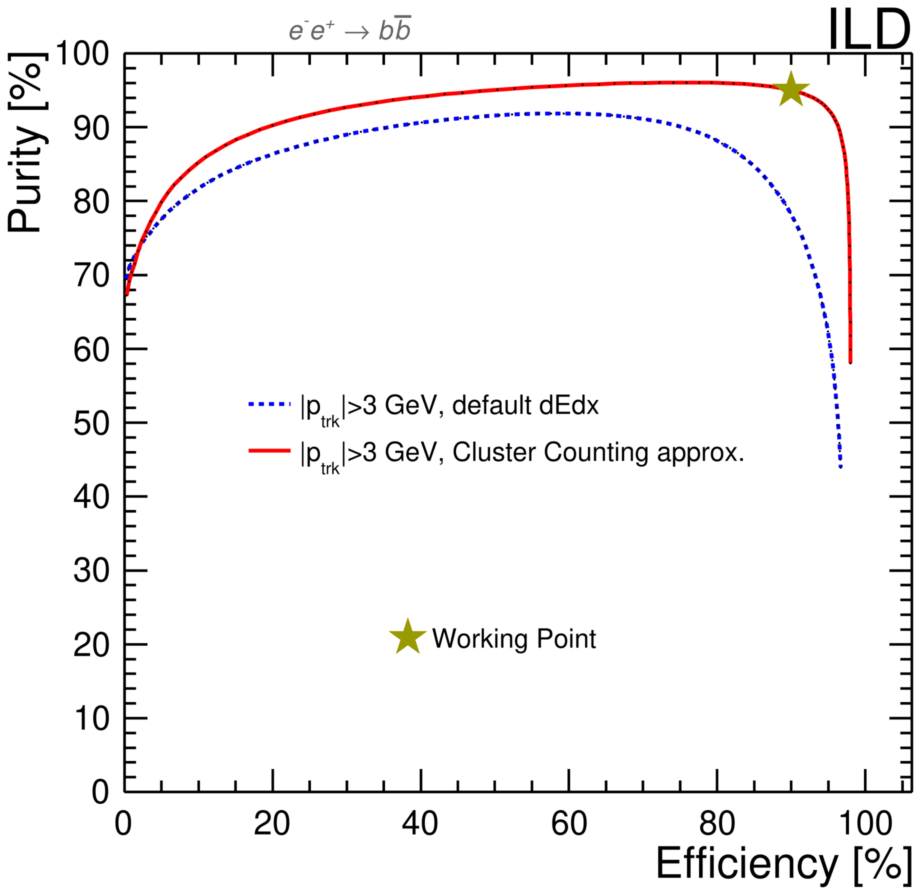
Nominal values of Flavour tagging at 250 GeV, without adding dEdx information.

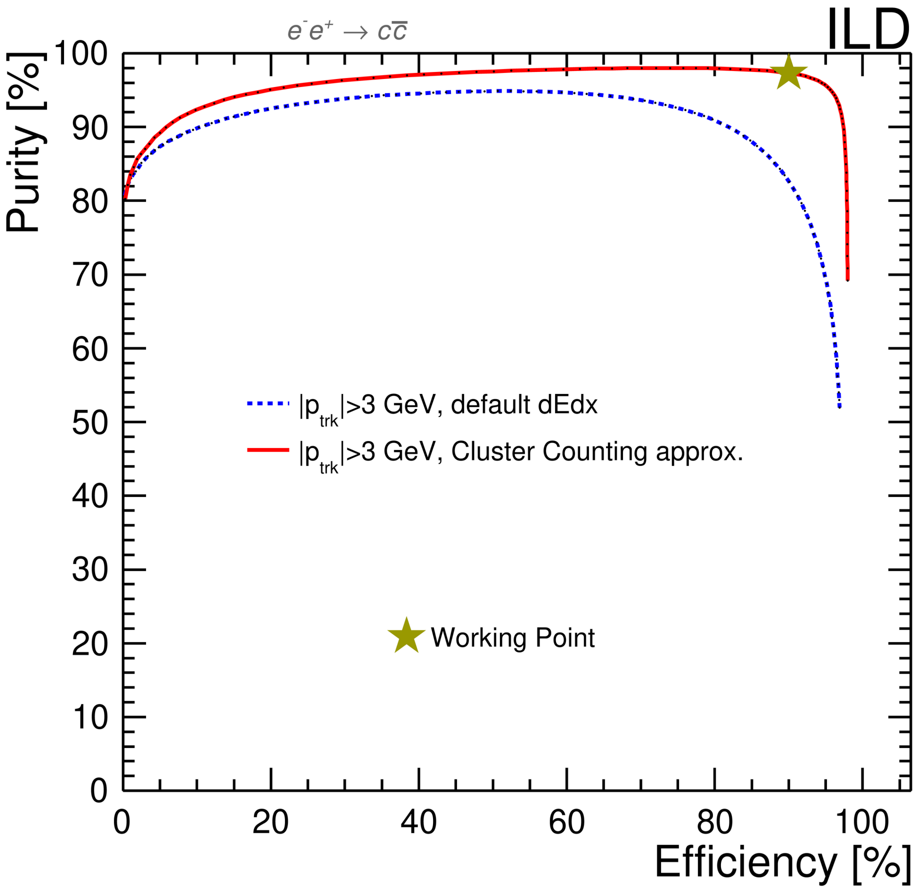
Effects of dNdx in Flavour Tagging (250 GeV)





Effects of dNdx in charge measurement (250 GeV)





Particle Swarm Optimization

Boosted Decision Trees (BDT) - TMVA

- We are already working with these Gradient Boosted Decision trees using ROOT's Toolkit for MultiVariate data Analysis (TMVA). We use the following parameters:
  - BoostType=Grad.
  - NTrees.
  - Shrinkage.
  - UseBaggedBoost:BaggedSampleFraction.
    - Bagging: A new sampling is performed before each step (removes biases).
  - NCuts (binning used when sampling).
  - MaxDepth (Nº of leaves).

The Particle Swarm Algorithm optimizes the use of *these parameters*

We used all but the orange ones, which are method definitions

PSO - Overview

- Particle Swarm Optimization is a Gradient-free, bio-inspired, stochastic, population-based algorithm to optimize any kind of process towards a certain goal:
    - No maths involved in the optimization (no gradients or loss functions!).
    - It just try configurations and saves the *best-performing one*.
        - It mimics how animals look for resources, by trial and error.
- How it works:
    - We have N “particles” (in our case: configurations of the BDT). Then:
        1) The BDT runs with the configuration of the particle.
        2) When finished, each particle gets a performance score.
           -We define a Function Of Merit (FOM) for this scoring
        3) We track each particle’s best configuration and the best global one.
        4) The particles move to a new configuration (next slide).

For each iteration

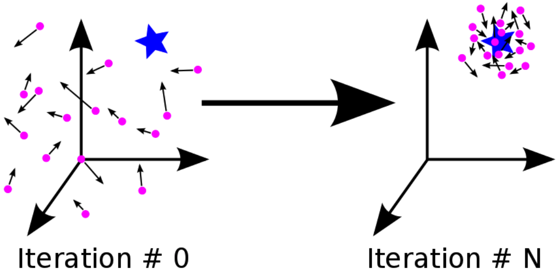
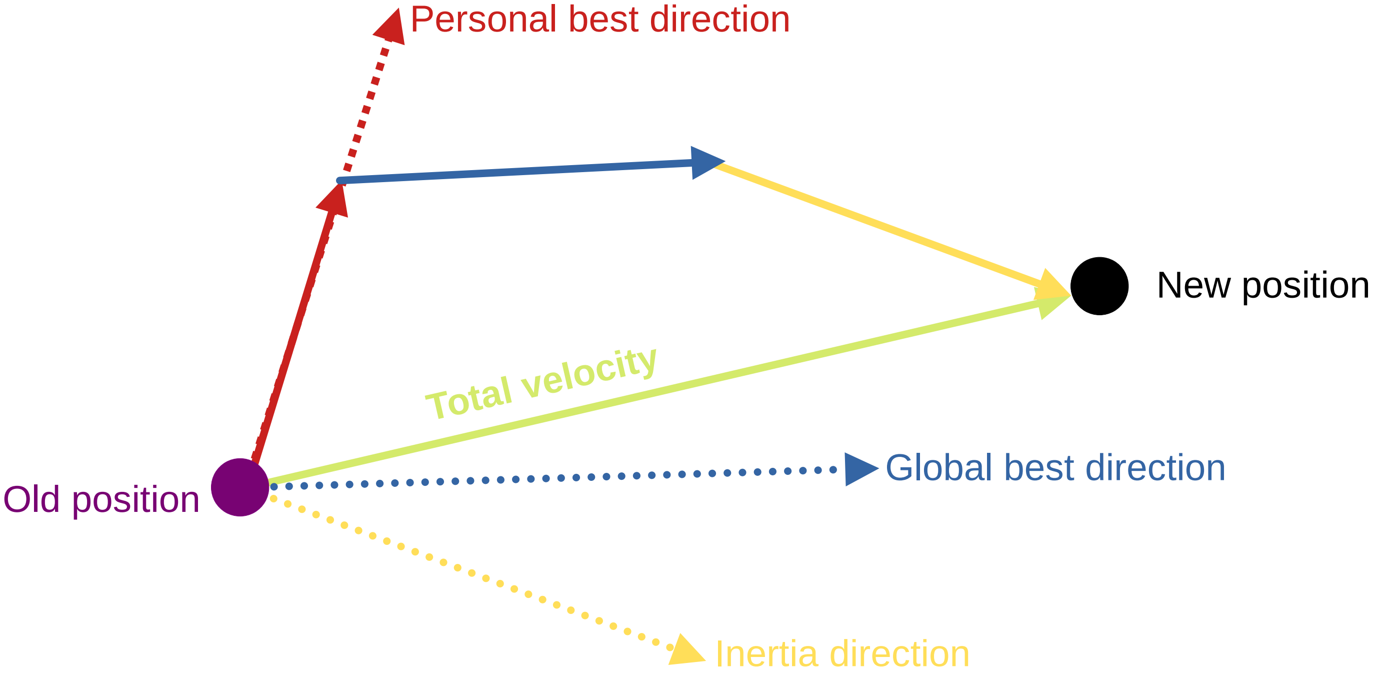


Image taken from a website

PSO - Overview

Position: $\overrightarrow{X_i^{t+1}} = \overrightarrow{X_i^t} + \overrightarrow{V_i^{t+1}}$

Velocity: $\overrightarrow{V_i^{t+1}} = w\overrightarrow{V_i^t} + c_1 r_1 \left(\overrightarrow{P_i^t} - \overrightarrow{X_i^t}\right) + c_2 r_2 \left(\overrightarrow{G^t} - \overrightarrow{X_i^t}\right)$



PSO – Adaptation to FT in LCFI+

- We need:
  - A 3-class classifier (b quarks, c quarks, uds quarks).
  - We also want to avoid overfitting:
    - Kolmogorov-Smirnov test
    - Anderson-Darling test

Control biased test scores. (more info in back-up)

  - We need a FOM adapted to 3 different classes.
  - Important remark: A final check is **always needed**:

Trial and error can go wrong sometimes!

PSO – Function Of Merit (FOM)

- The FOM being used is the averaged value of the Integral of the Receiver Operating Characteristic curve for each of the 3 data classes.
    - Considering the target class as signal and the others as background.

- Our FOM is simply:

$$\text{FOM} = (\text{AUC}[b_{\text{quark}}] + \text{AUC}[c_{\text{quark}}] + \text{AUC}[uds_{\text{quarks}}]) / 3,$$

where AUC = ”Area Under Curve” (ROC Integral).