Prospects for Gauge-Higgs Unification models in $e^+e^- \to q\bar{q}$ production ILC250/500 at ILD using PID capabilities

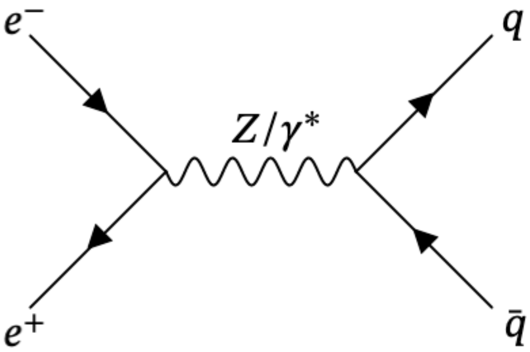
ILD Software & Analysis meeting

2/08/23

Jesús P. Márquez Hernández

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.

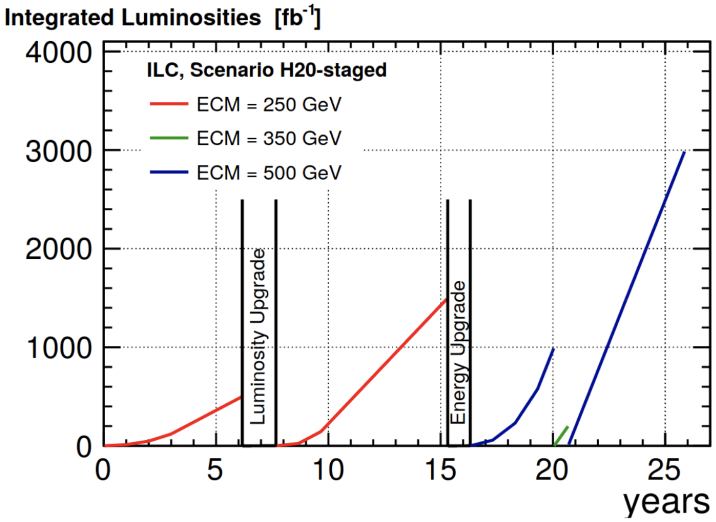


ILC physics program

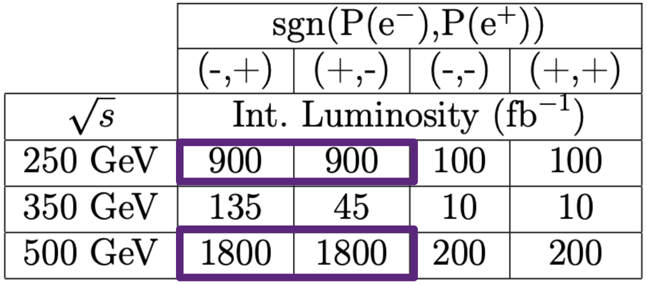
- The ILC is more than a Higgs factory:
    - It provides access to **all SM particles**.
- It also features polarized beams $P(e^-,e^+)=(0.8,0.3)$.
    - Allow us to inspect all 4 helicity amplitudes:

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

- 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:
        - $\mathrm{sgn}(P(e^-),P(e^+))$ = **(+,-)**, **(-,+)**, (+,+), (-,-)



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

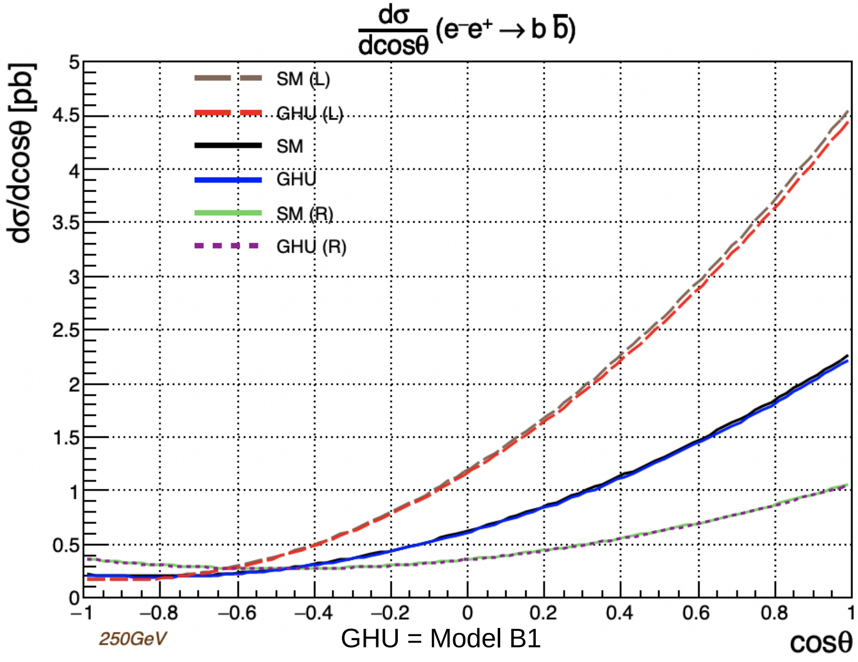


	$\mathrm{sgn}(P(e^-),P(e^+))$			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	Int. Luminosity (fb^{-1})			
250 GeV	900	900	100	100
350 GeV	135	45	10	10
500 GeV	1800	1800	200	200

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]



Projection of couplings and EW mixing angle:

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

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.

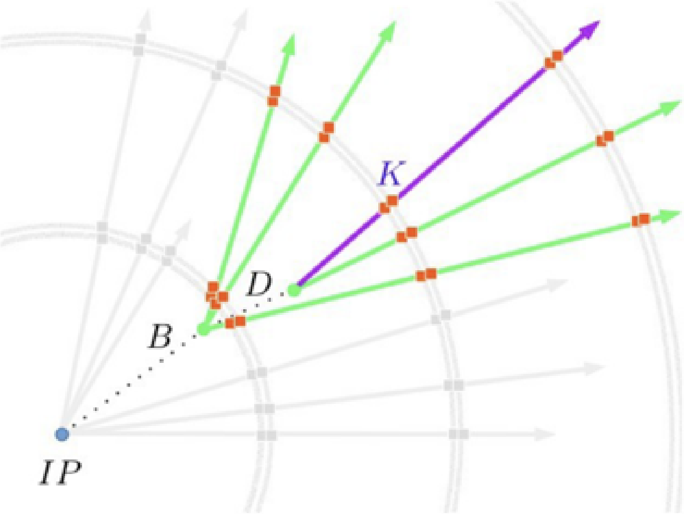
$$A_{FB}^{Exp} = \frac{N_F - N_B}{N_{Total}}$$

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

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

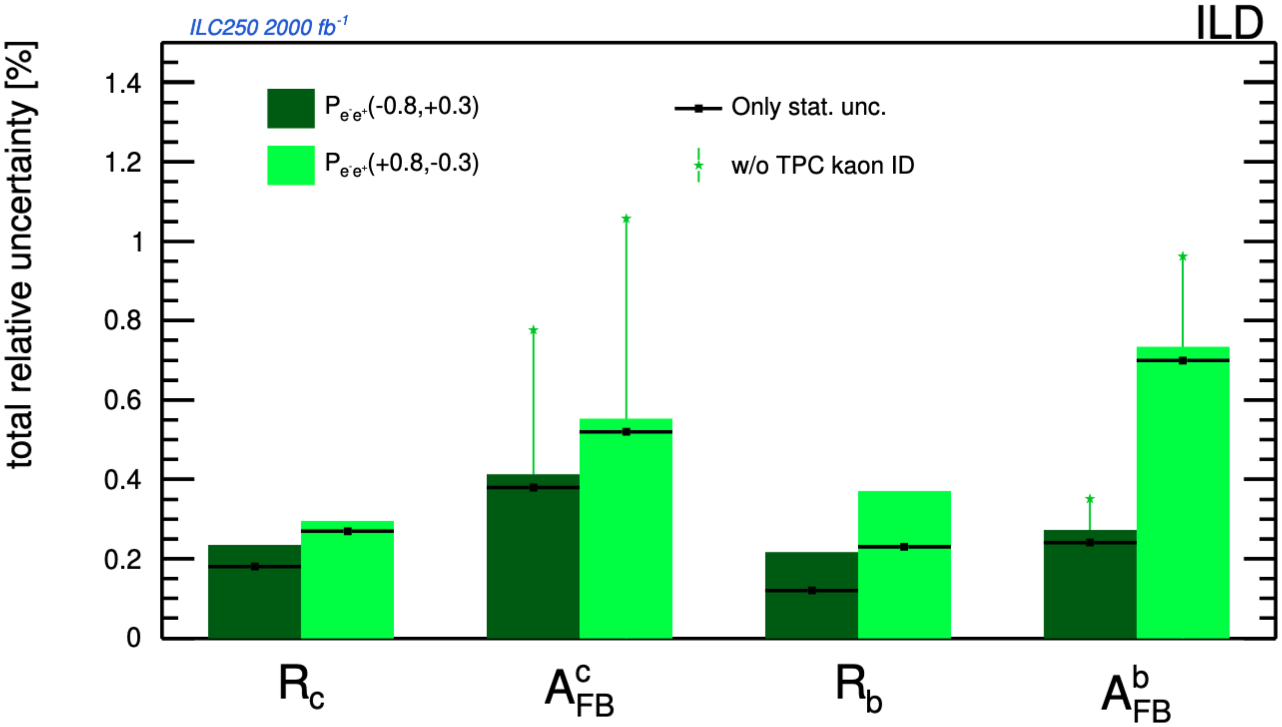
Preselection of $b\bar{b}$ & $c\bar{c}$ signals

- 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.

Previous work for R_q and A_{FB} (250 GeV)



Full Simulation Study. Public ILD Note (2306.11413)

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

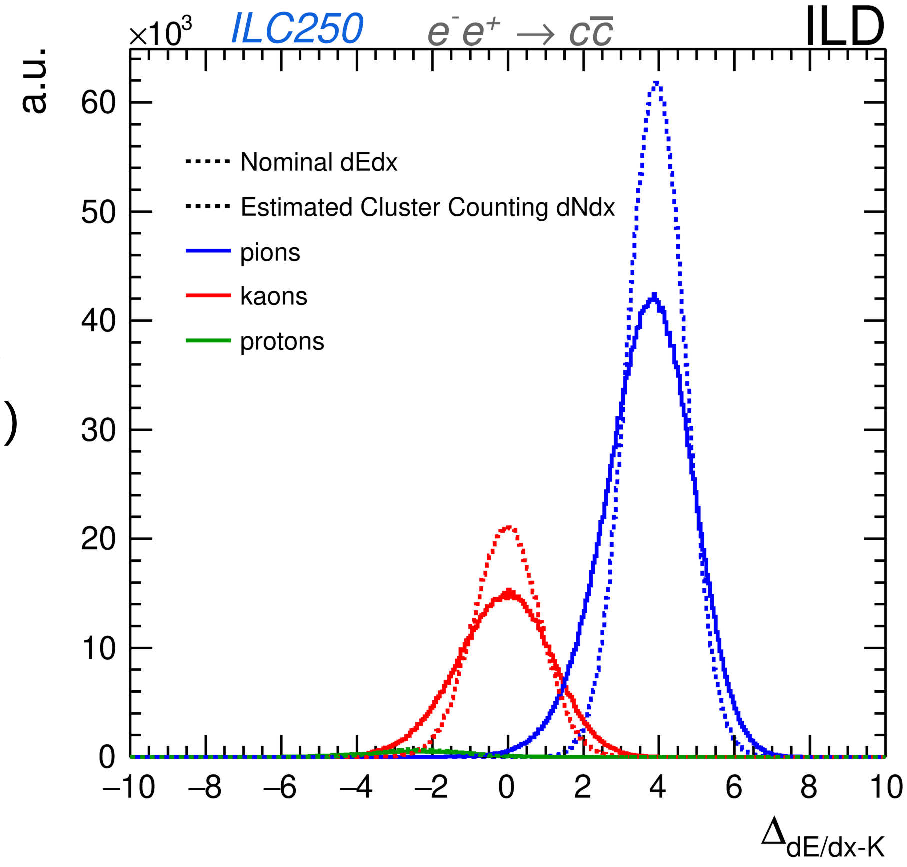
Kaon ID in R_q and A_{FB} (250 GeV)

- 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).



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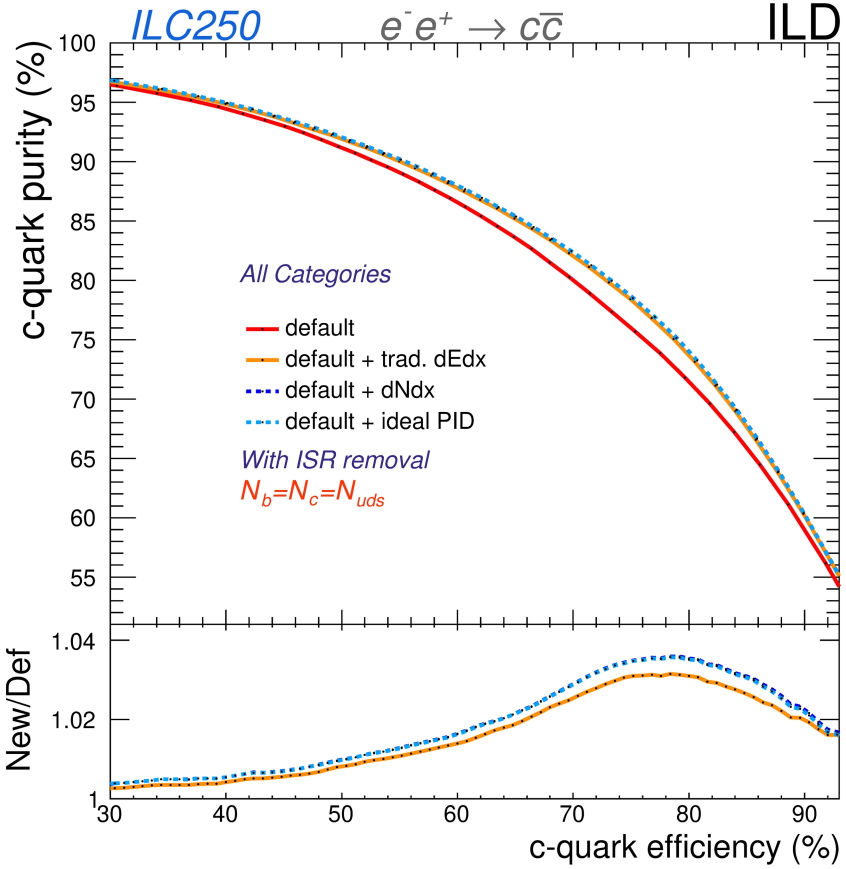
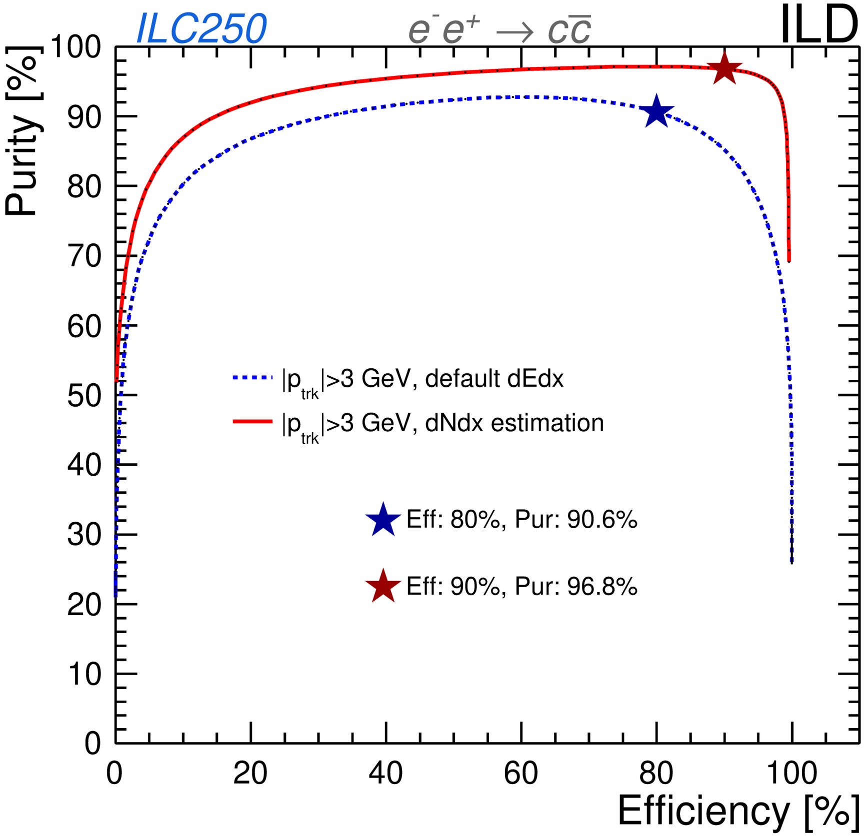
[1] Y. Aoki et al., Double hit separation and dE/dx resolution of a time projection chamber with GEM readout, JINST 17 11 (2022) P11027, arXiv: 2205.12160 [physics.ins-det]

Effects of improving the use of PID

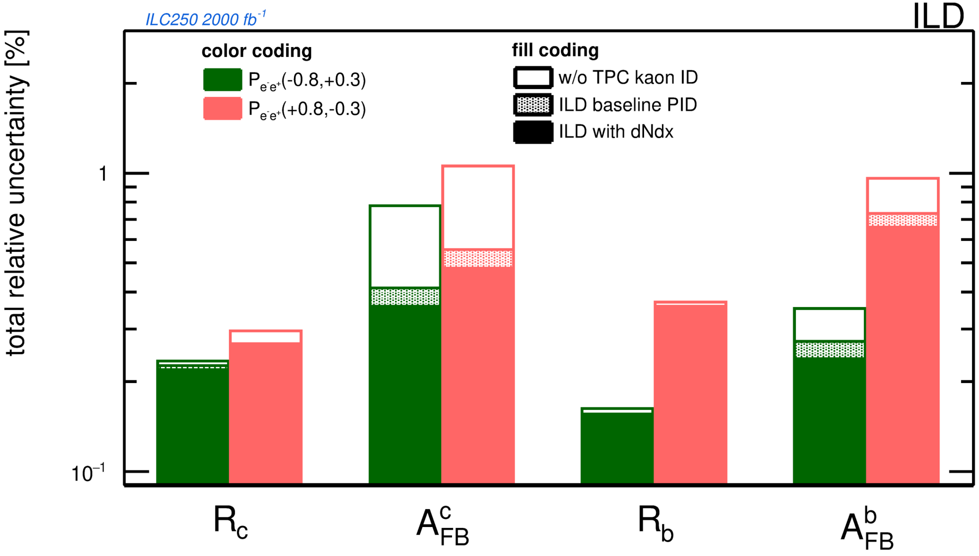


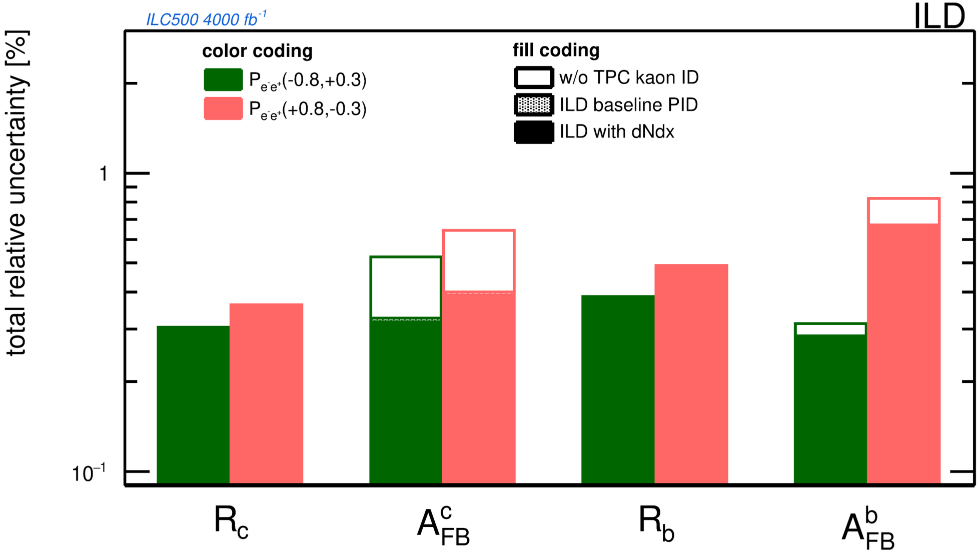
Effects in **Flavour Tagging**



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

Uncertainties for R_q and A_{FB} (250 & 500 GeV)



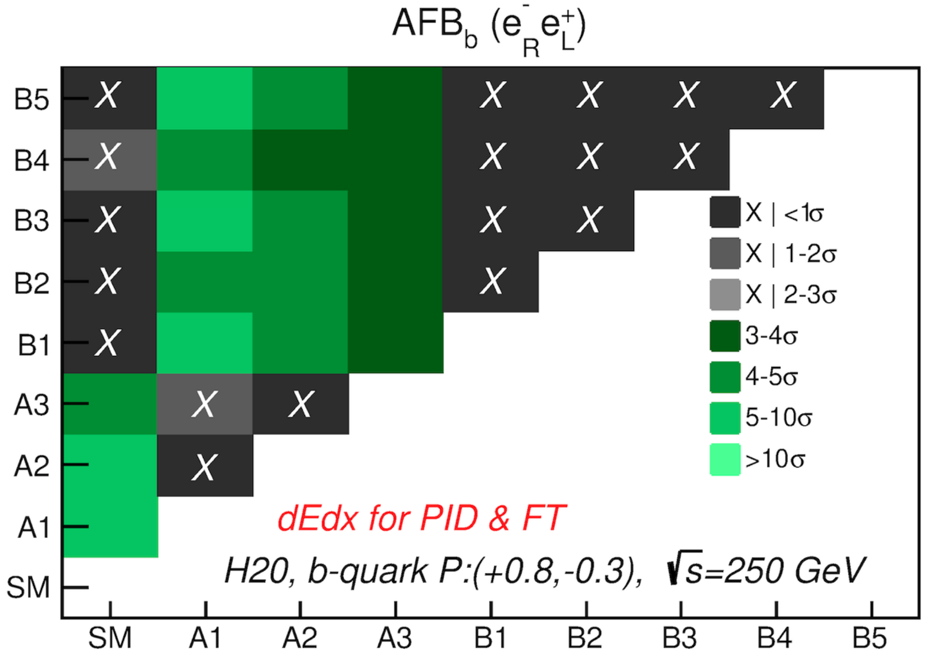


Full Simulation Studies. Proceedings for LCWS2023: arXiv 2307.14888

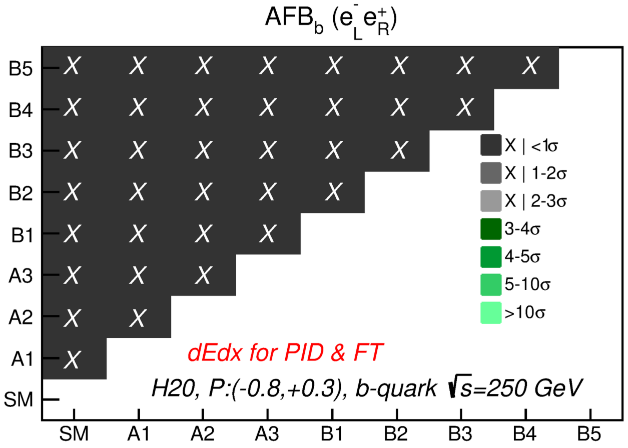
A. Irles, J. P. Márquez | Reviewed by A. Ruiz (as ILD PSB Ed. member)

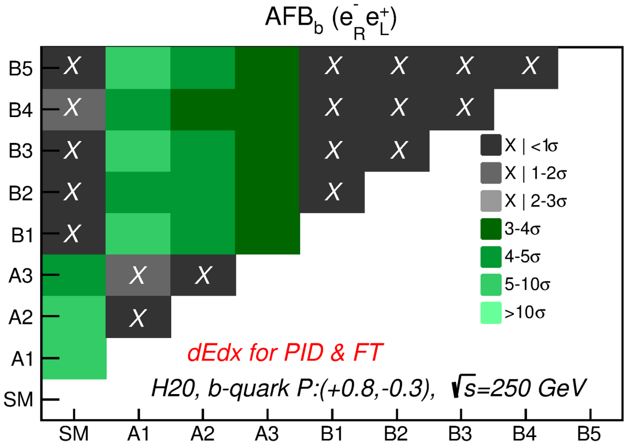
Discrimination of BSM Models

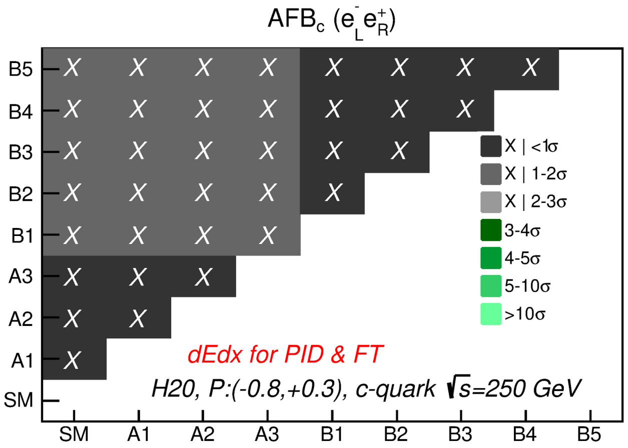
- Assumption: A measurement of one specific model is conducted.
    - Row/Column combination for comparison.
- The uncertainties are considered normally distributed:
    - **Significance in σ**: $\mathrm{d}_\sigma = \dfrac{\|\mathrm{AFB}_{\mathrm{test}} - \mathrm{AFB}_{\mathrm{ref}}\|}{\Delta_{\mathrm{AFB}_{\mathrm{ref}}}}$
    - P-value: Gaussian at d_σ.
- Combination of multiple measurements is done with a *multivariate gaussian*.
    - Assuming no correlations for A_{FB}.

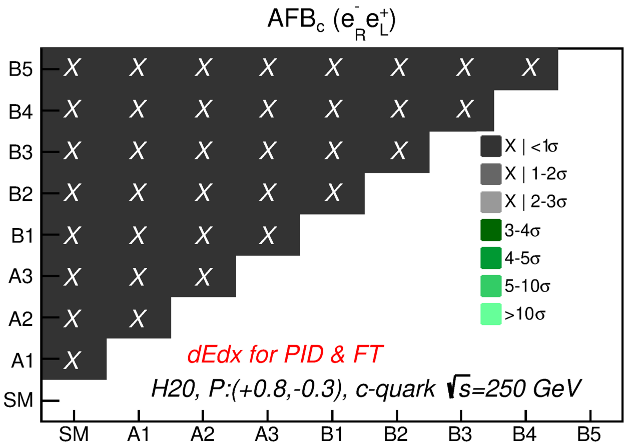


GHU’s Models ILC250



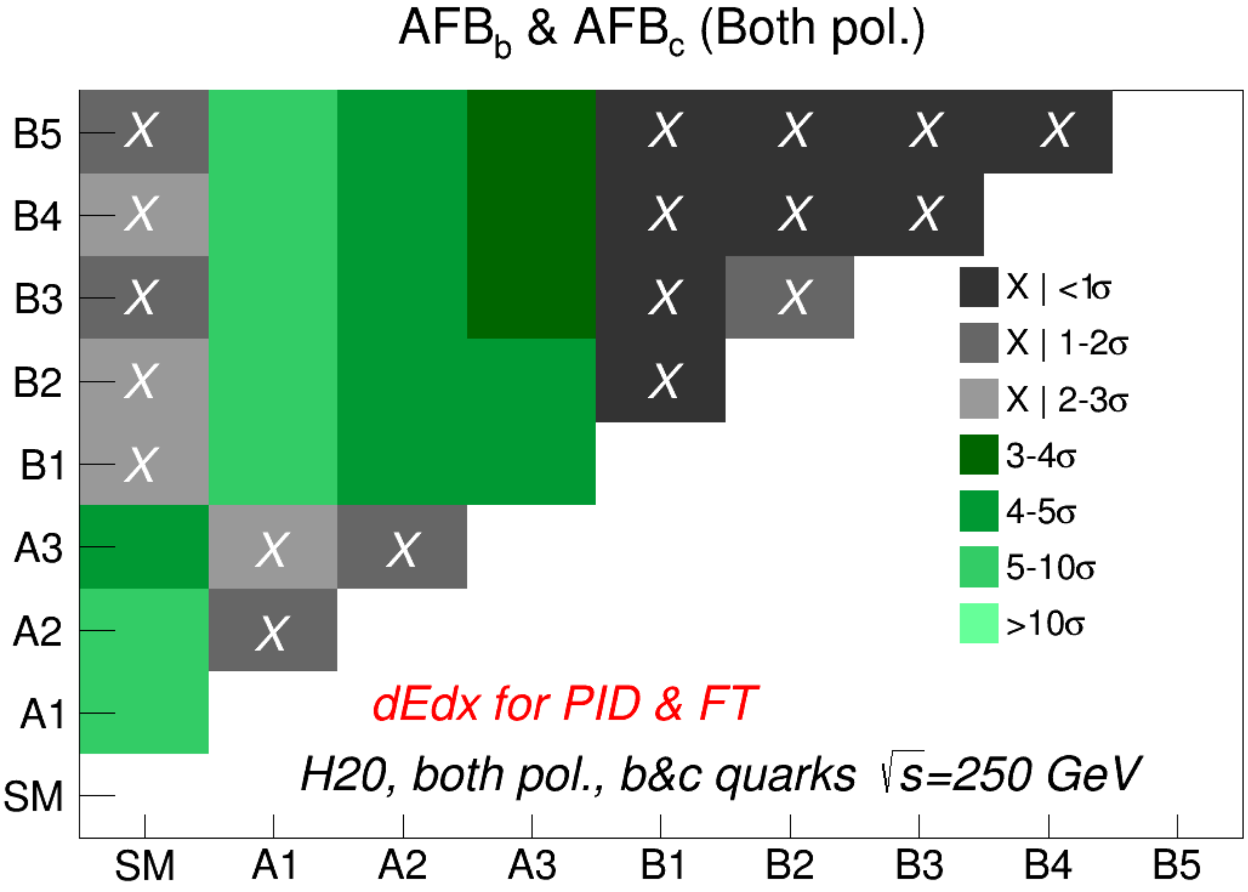




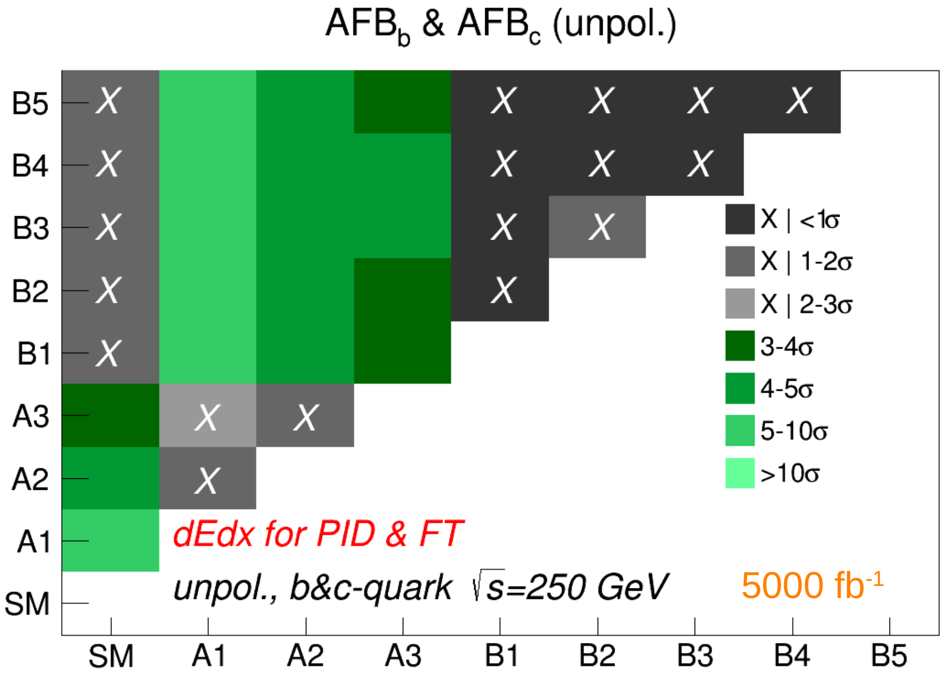


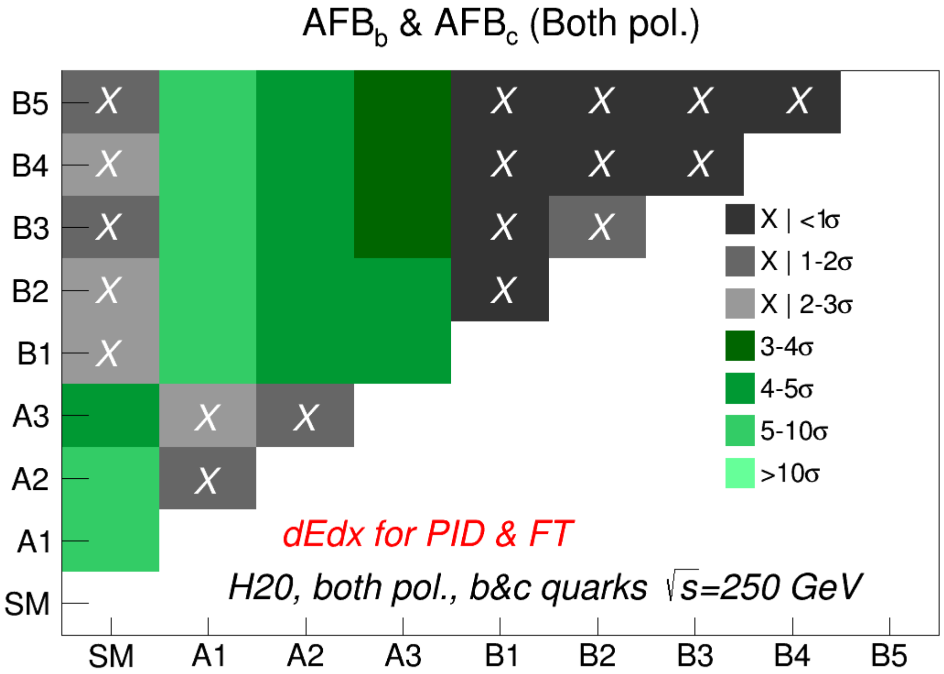
⬛ X | <1σ
⬛ X | 1-2σ
⬛ X | 2-3σ
🟩 3-4σ
🟩 4-5σ
🟩 5-10σ
🟩 >10σ

GHU's Models ILC250 (combined)



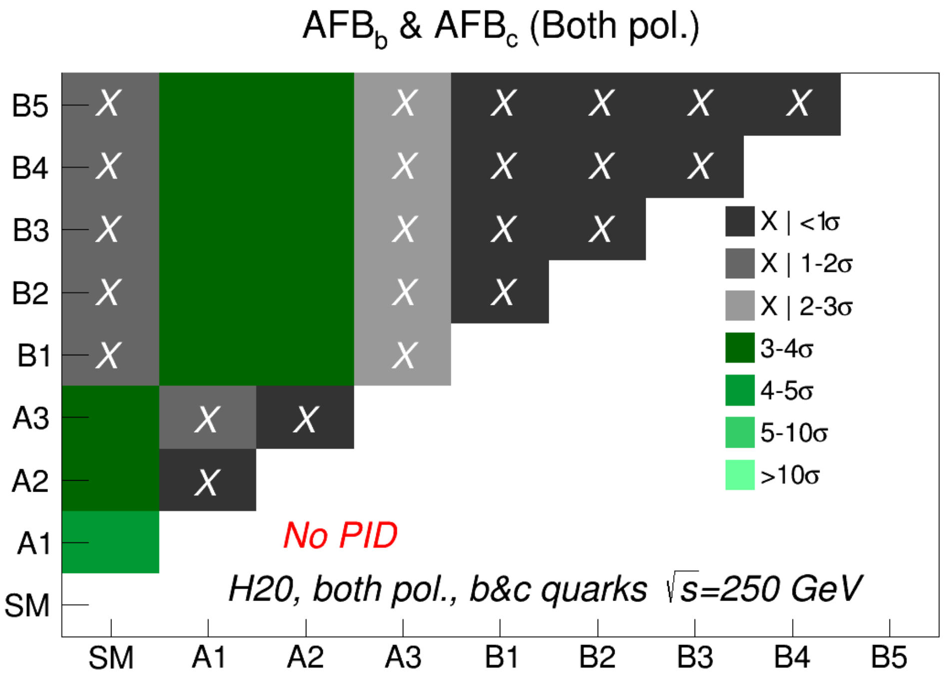
GHU’s Models ILC250 (Polarisation)

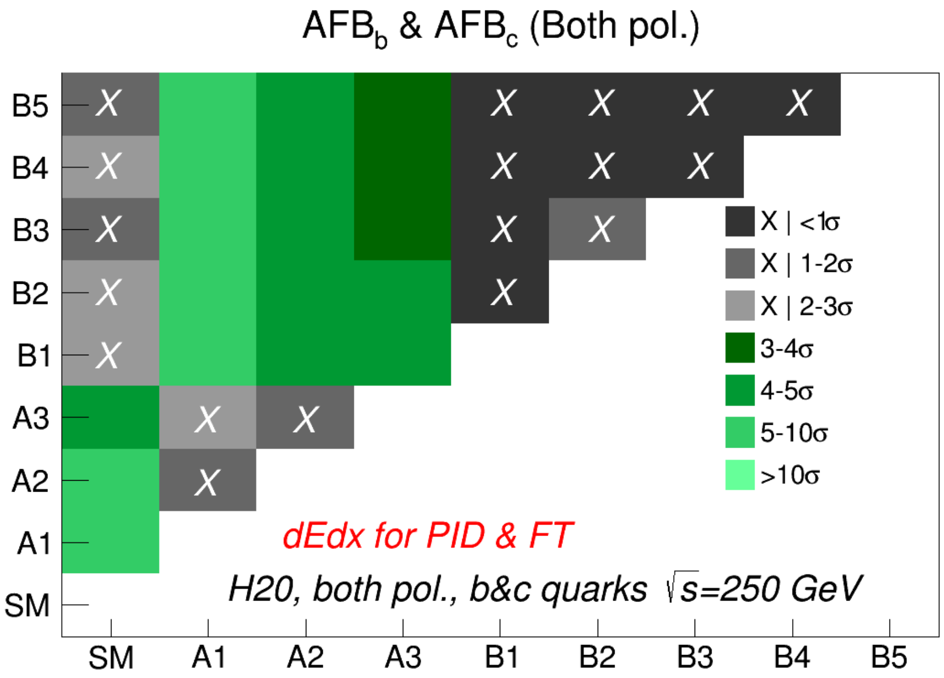

AFB$_b$ & AFB$_c$ (unpol.)


AFB$_b$ & AFB$_c$ (Both pol.)

Effects of polarised beams at 250 GeV

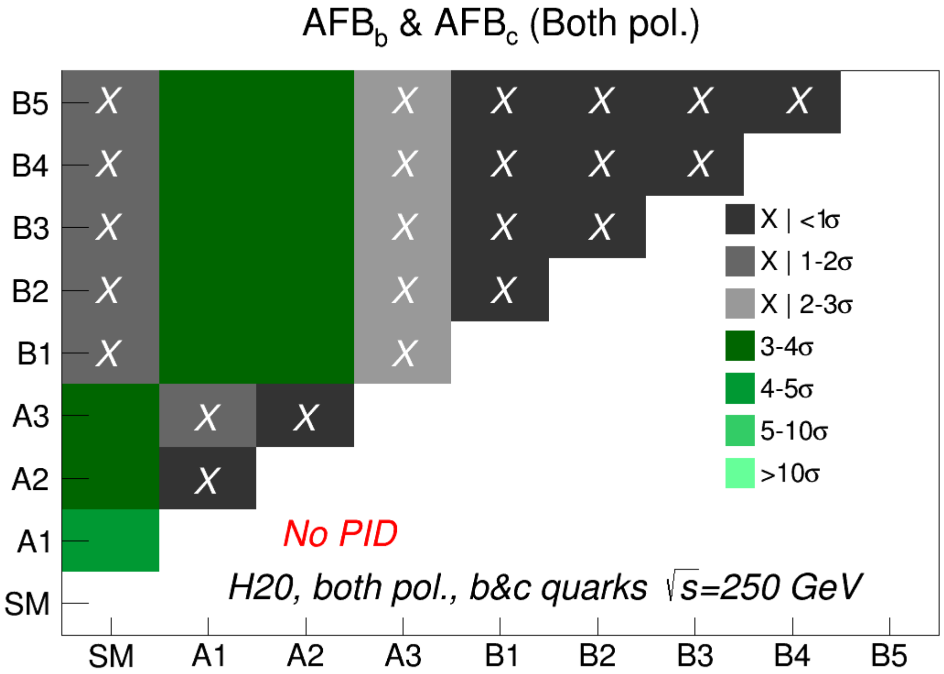
GHU’s Models ILC250 (TPC impact)

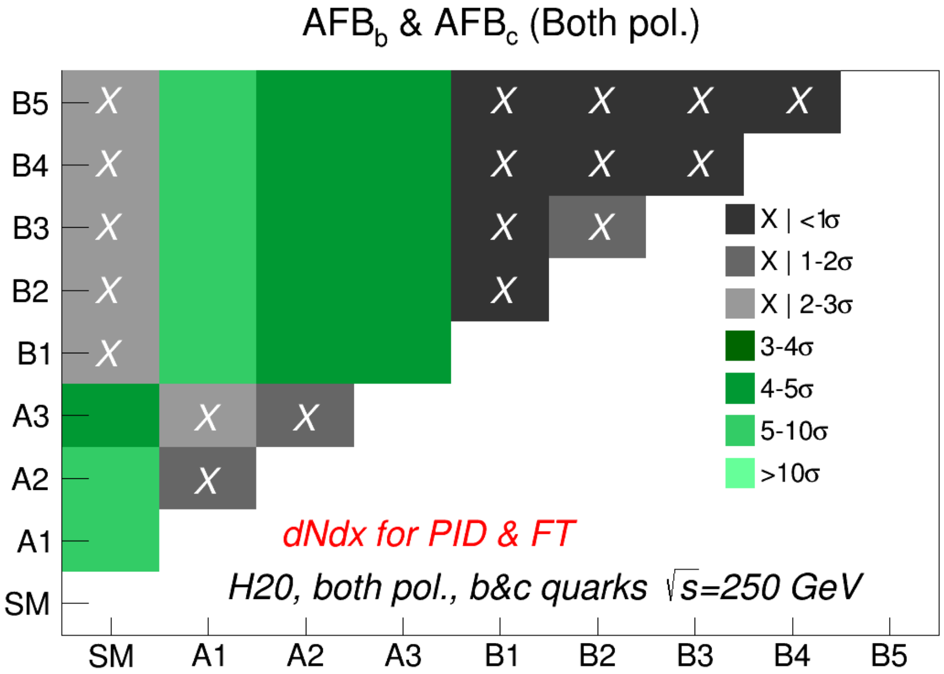




We do **need TPC PID** to discriminate these models

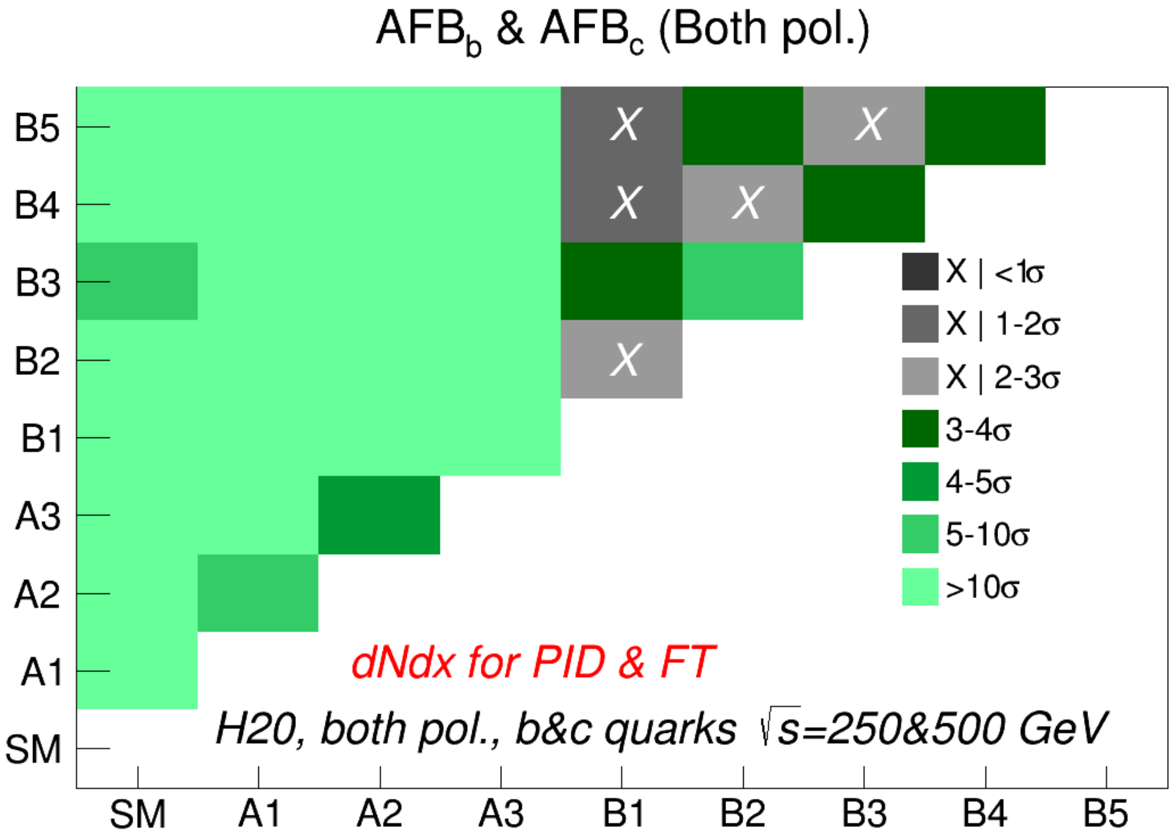
GHU’s Models ILC250 (TPC+dNdx impact)





Using **dNdx** optimises the use of the TPC

GHU’s Models ILC250+500



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.

Up to 8 different measurements per energy!

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

- There's still work to do:
  - More than H20: Giga-Z? 1 TeV?
  - R_q and statistical combinations!
  - What about other BSM models?

Thanks for your attention!

BACK-UP

General

Observables

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

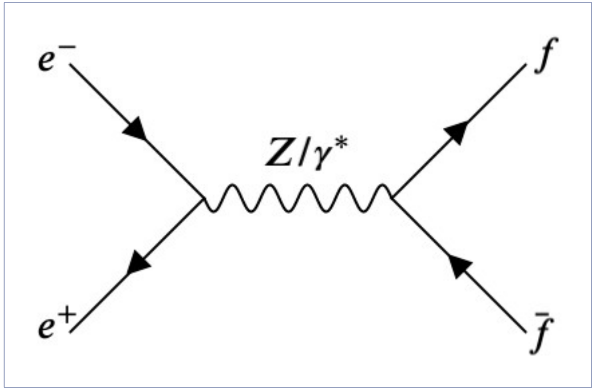
$$\frac{d\sigma^{f\bar f}}{d\cos\theta}(P_{e^-},P_{e^+},\cos\theta)=(1-P_{e^-}P_{e^+})\frac{1}{4}\left\{(1-P_{eff})\frac{d\sigma^{f\bar f}_{LR}}{d\cos\theta}(\cos\theta)+(1+P_{eff})\frac{d\sigma^{f\bar f}_{RL}}{d\cos\theta}(\cos\theta)\right\}$$

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

  - Polarization contributions:

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

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

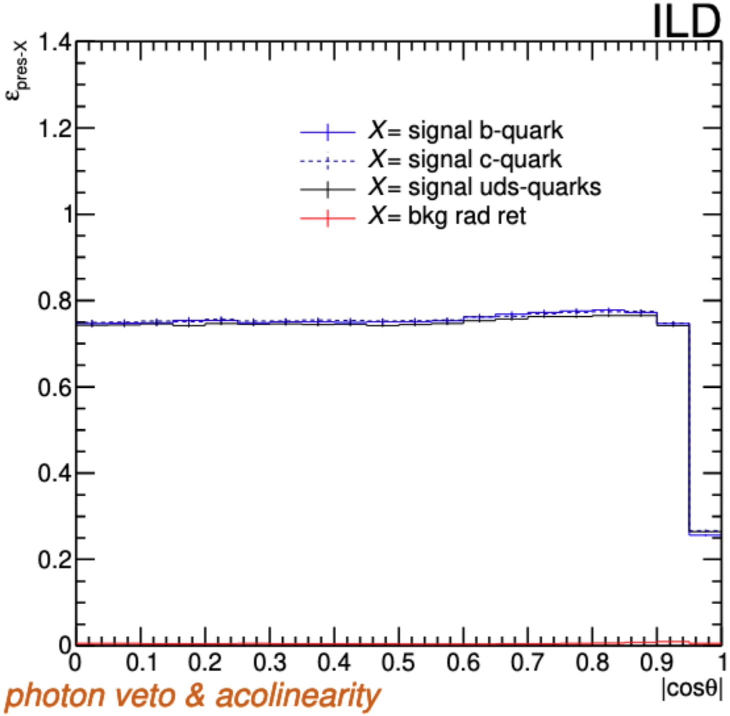


- Helicity amplitudes from the s-channel (may include BSM mediators):
  - They could only be inspected by using polarisation.

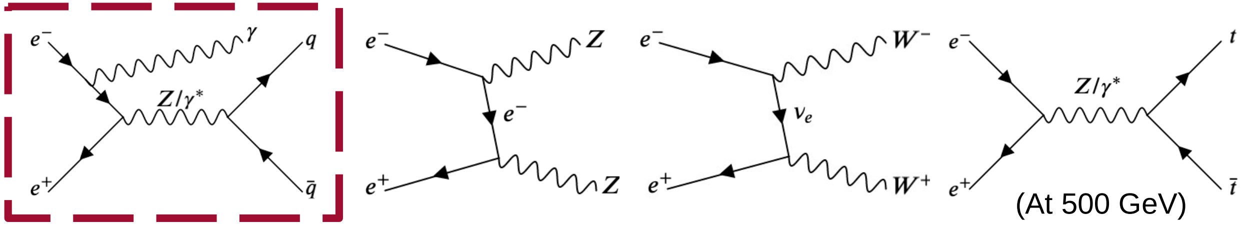
$$Q_{\mathrm{ex}\,f_Y}=\sum_i\frac{g^X_{V_ie}\,g^Y_{V_if}}{(s-m^2_{V_i})+im_{V_i}\Gamma_{V_i}}$$

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 ($\gamma q\bar{q}$)**.
  - 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!

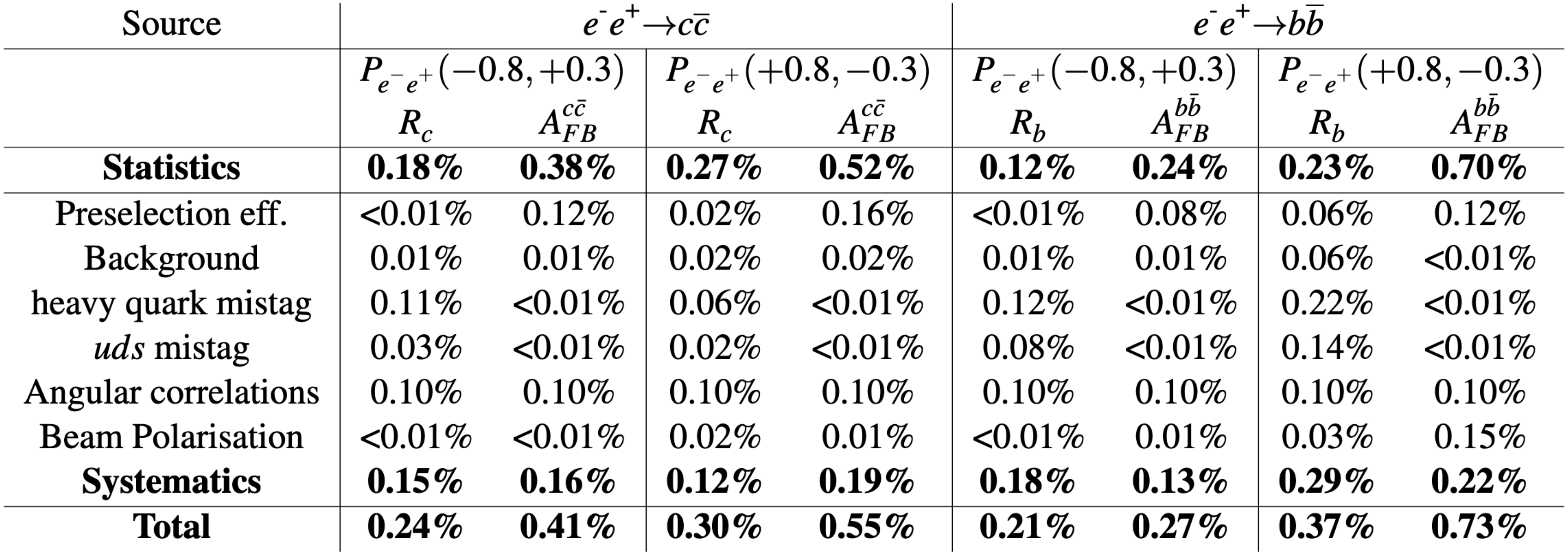


photon veto & acolinearity & m_{jj} & y_{23} cuts



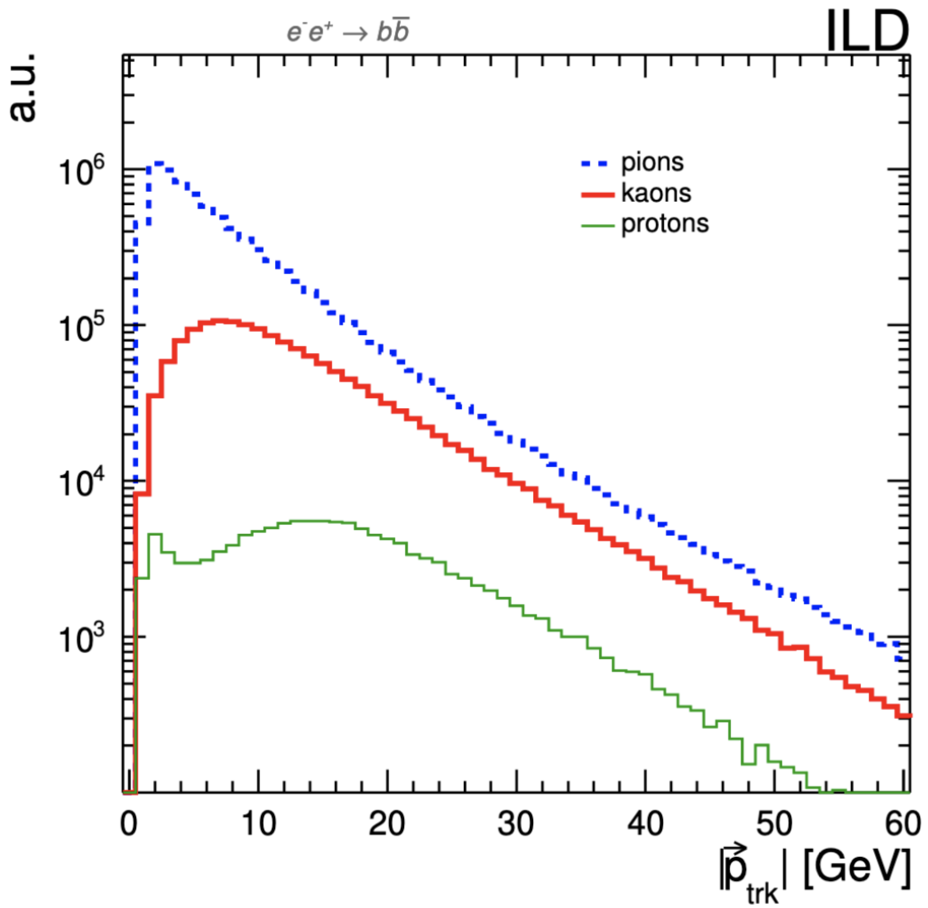
(At 500 GeV)

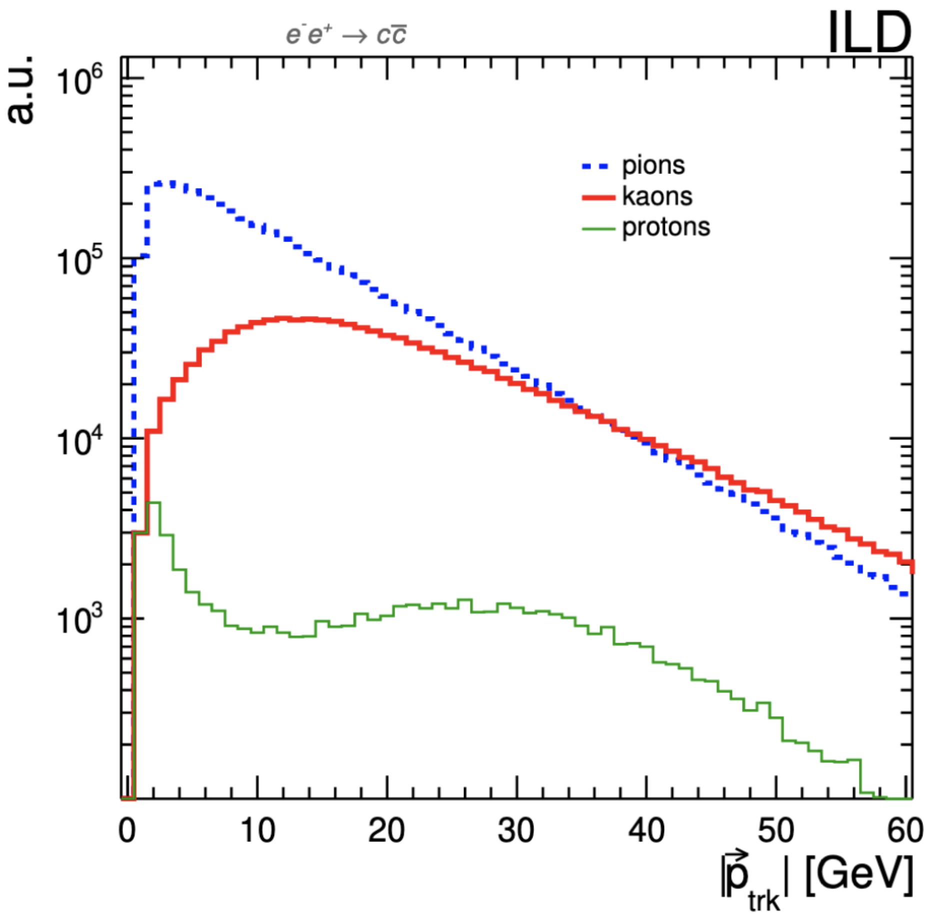
Systematical uncertainties (250 GeV)



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%**

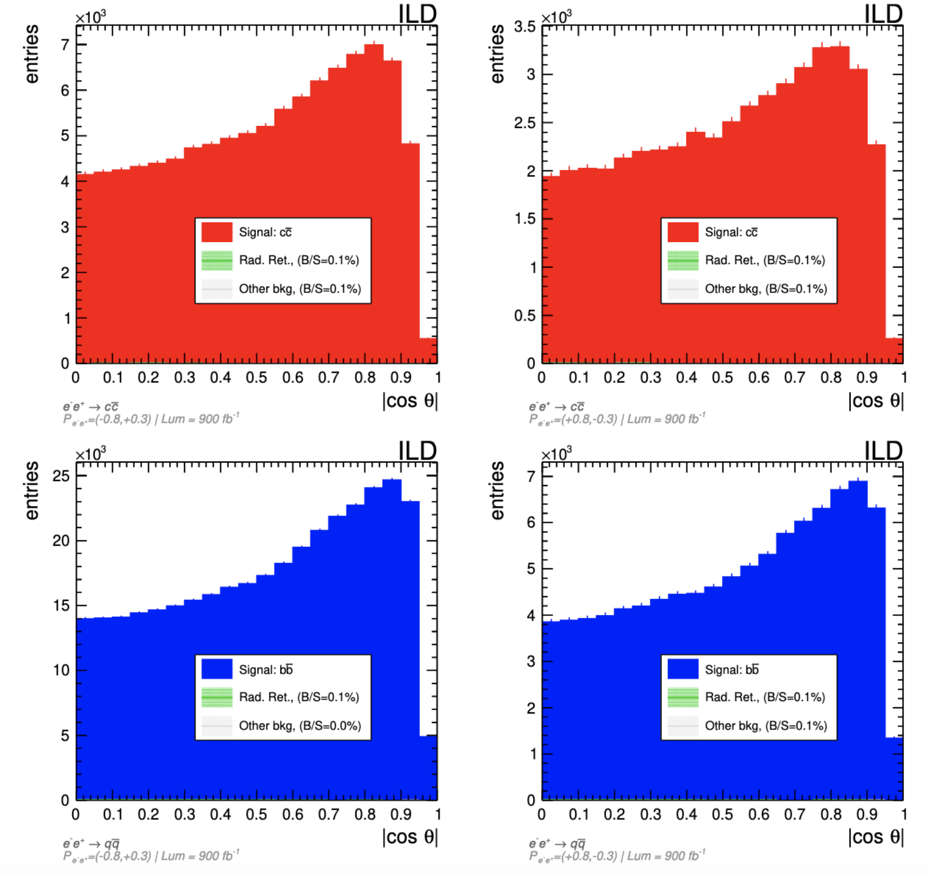
Kinematics of secondary tracks





Selection efficiency for A_{FB}

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

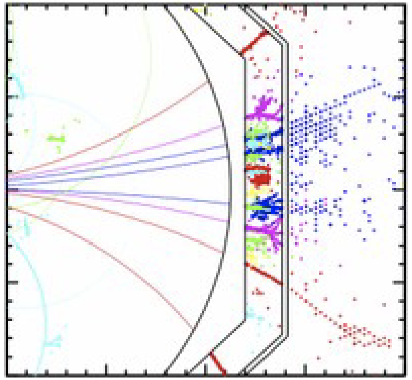


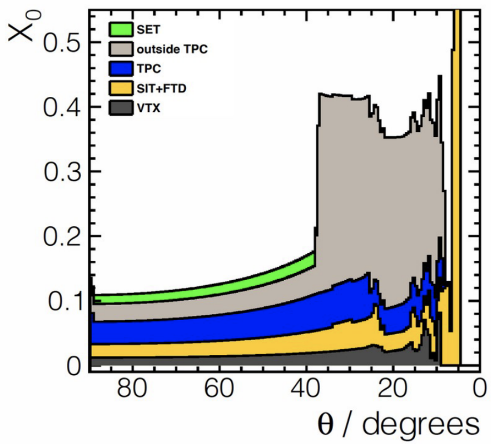
b-quarks & c-quarks Signals are close to:

- Background-free
- uncorrelated

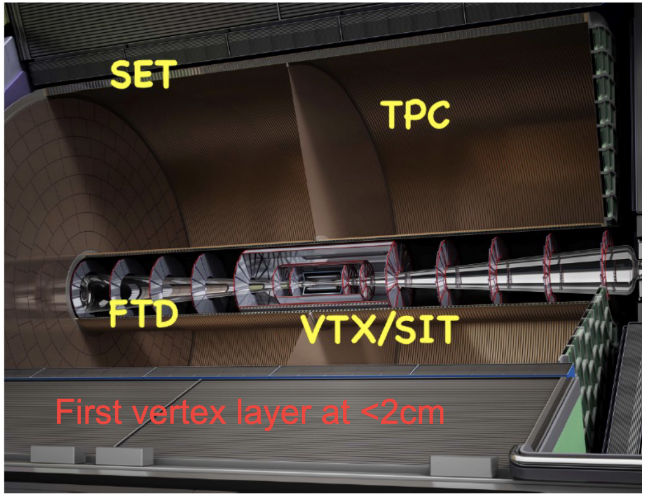
ILD overview

- 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

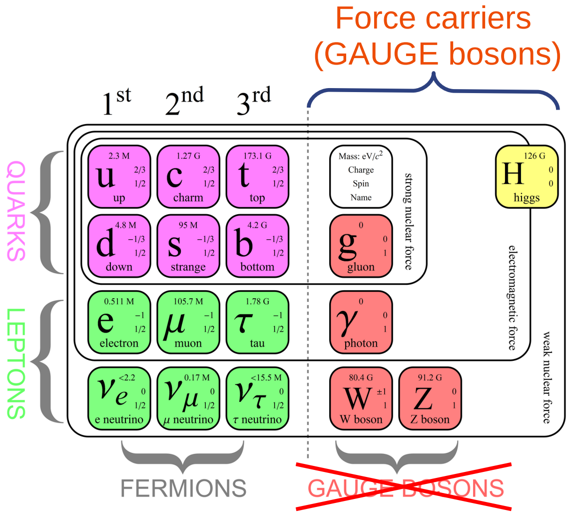


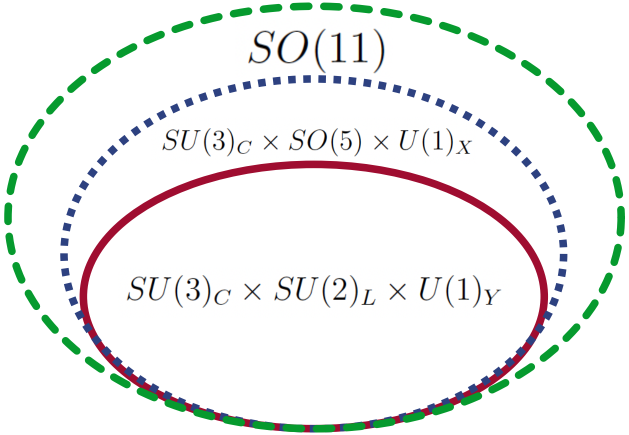
ILD: Interim Design Report.
ArXiv:1003.01116

Hosotani’s Models

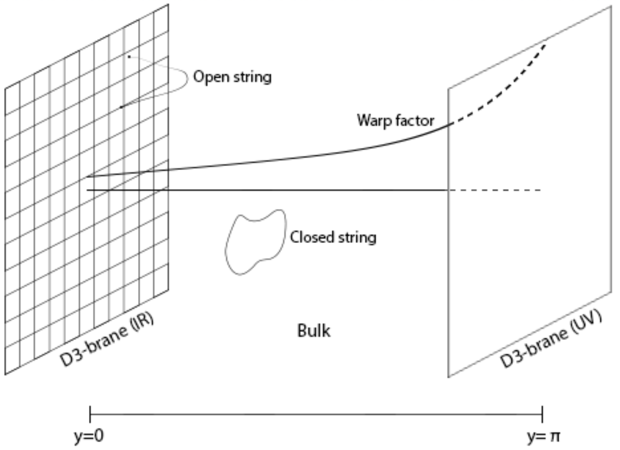
Gauge-Higgs Unification (GHU) Models

- 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:

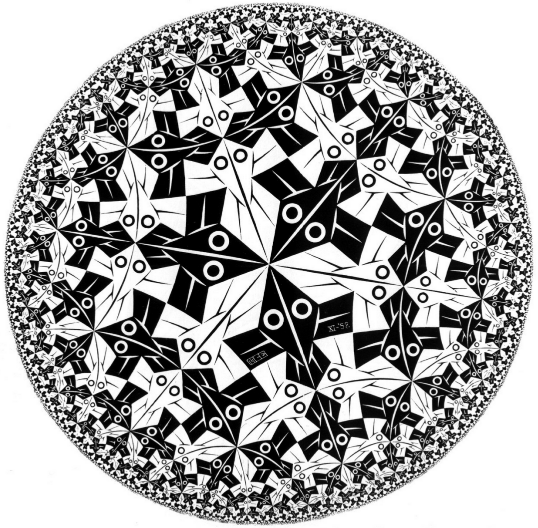
$$z = e^{ky}$$

    - 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)

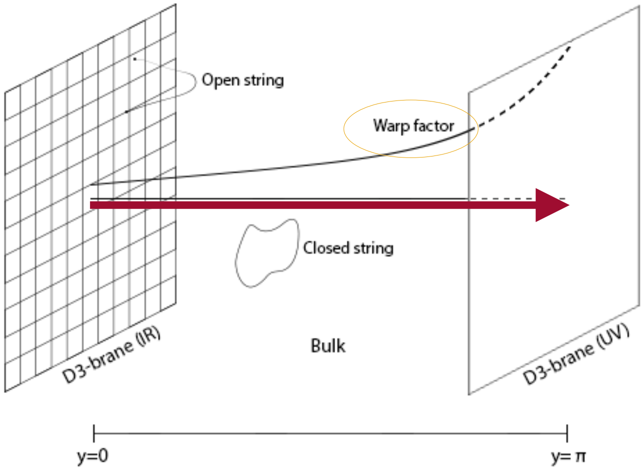
Minkowski space-time (4D)



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

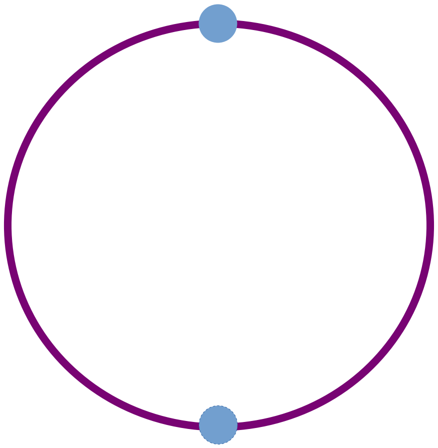
Gauge-Higgs Unification (GHU) Models

- 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

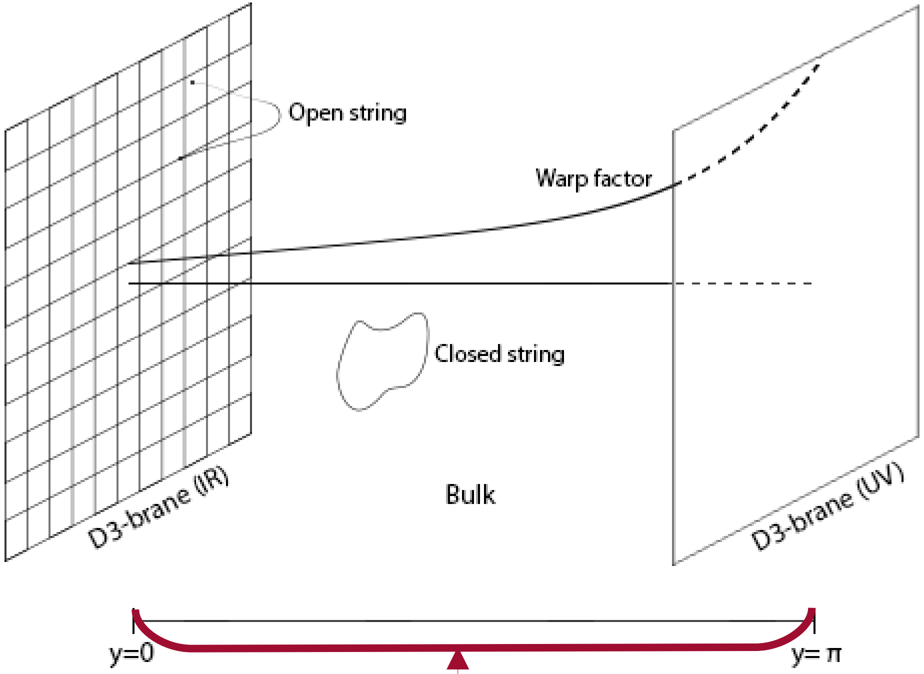


This side is symmetric to → ← this other side

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

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

$$\underset{BC}{\rightarrow} \; SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \quad \text{at } y = 0, L$$

$$\underset{\langle\Phi\rangle}{\rightarrow} \; SU(3)_C \times SU(2)_L \times U(1)_Y \quad \text{by the VEV } \langle\Phi_{(\mathbf{1},\mathbf{4})}\rangle \neq 0 \text{ at } y = 0$$

$$\underset{\theta_H}{\rightarrow} \; SU(3)_C \times U(1)_{EM} \qquad \text{by the Hosotani mechanism,}$$

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	$(\mathbf{1},\mathbf{4})_{\frac{1}{2}}$	$(\mathbf{1},[\mathbf{1},\mathbf{2}])_{\frac{1}{2}}$

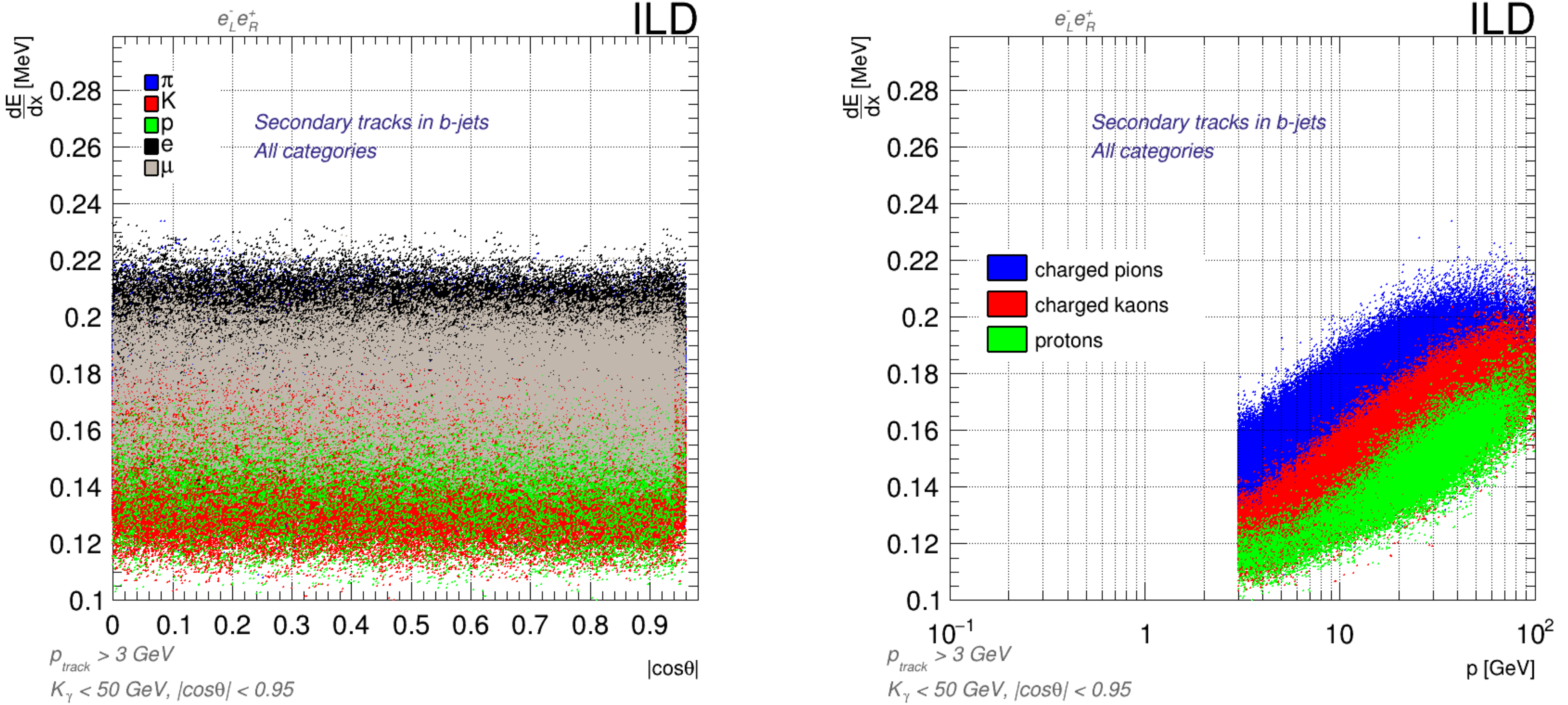
Field content in the group representation

Projection of couplings and EW mixing angle:

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

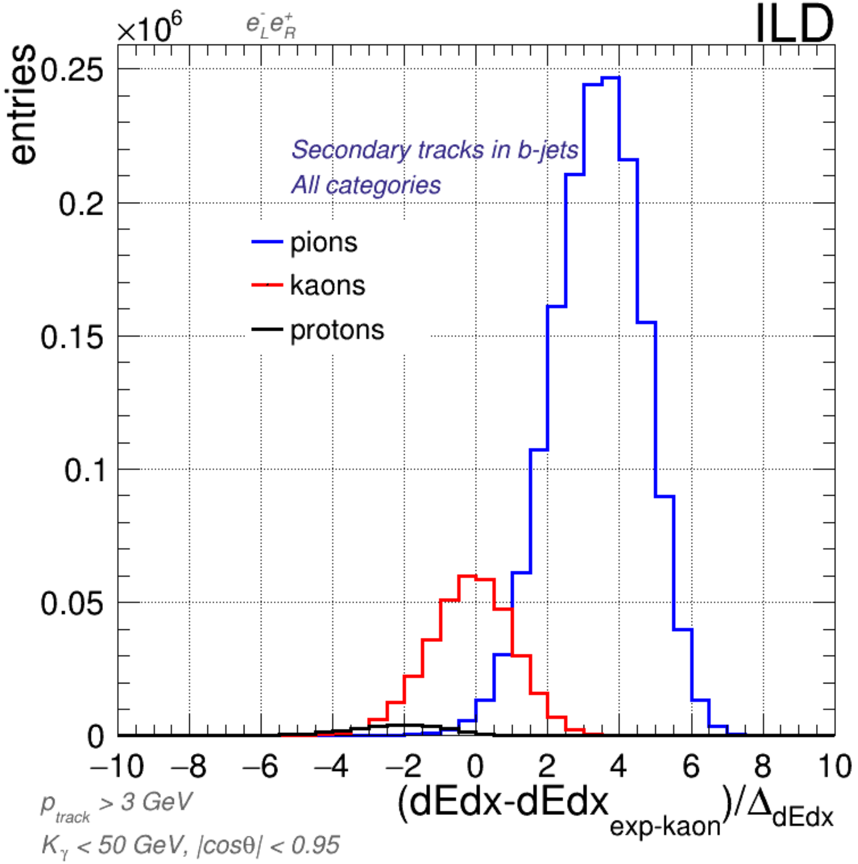
Adding dEdx in LCFI+

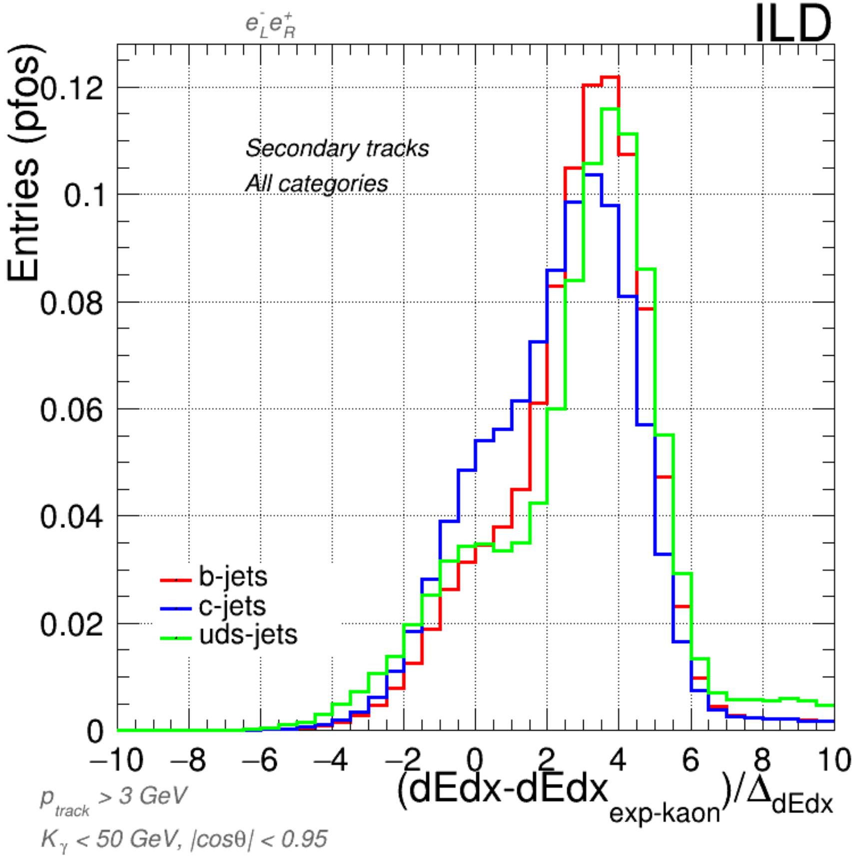
dEdx – Preselection of pfos



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

dEdx – KDS for different quark flavours





We repeat this also with Pions and Protons.

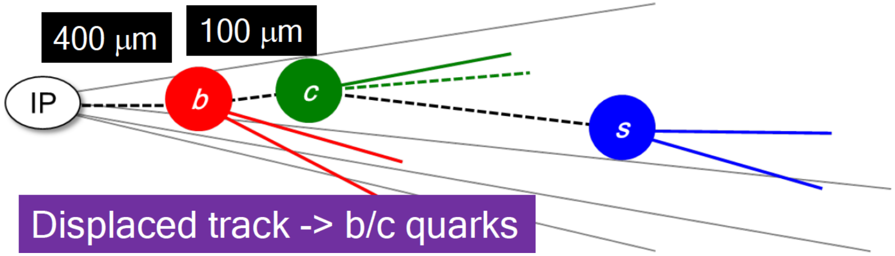
We build 3 variables NKaonSec, NPionSec & NProtonSec and add them to the FT!

Flavour tagging: LCFI+

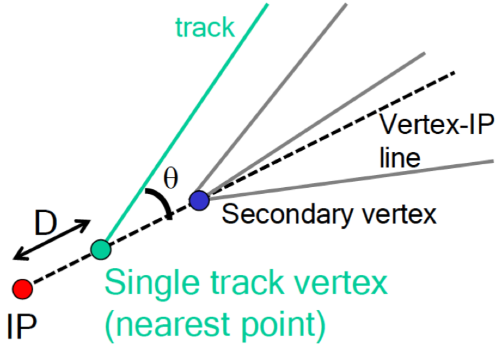
- Vertex finder:
  - Reconstruct collinear or close-to-collinear vertexes by merging particle tracks from the event information.
  - Distance ($\tau_q \cdot c$) from the IP is key for b and c quark ID: Displaced vertexes.
  - We also encounter single track vertexes: pseudo-vertexes.

- 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



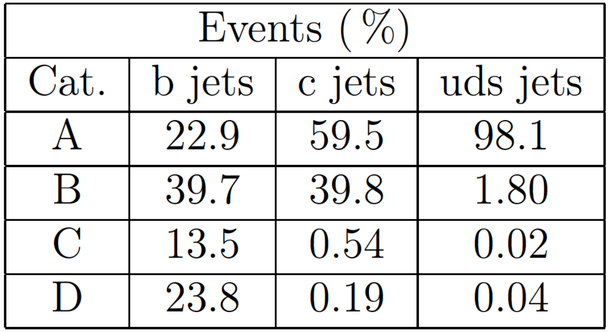
Single track vertex (nearest point)

arXiv:1506.08371

Events for each category

With ISR removal

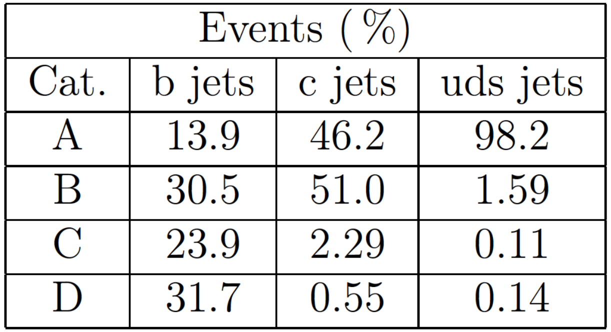
Z-Pole (LCFI+ paper[1])



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

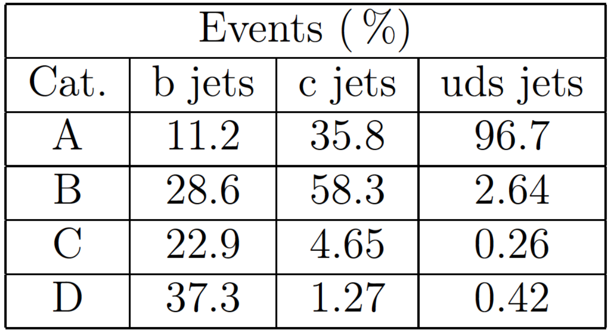
1. LCFIPlus: A Framework for Jet Analysis in Linear Collider Studies

250 GeV samples

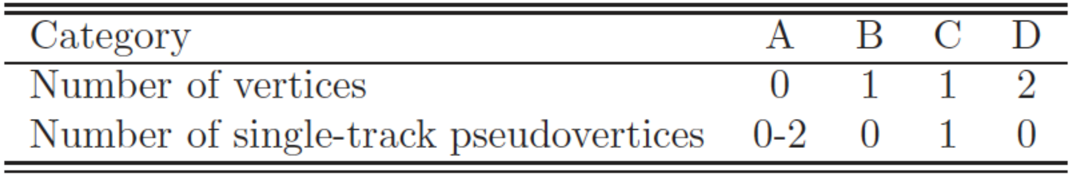


Events (%)			
Cat.	b jets	c jets	uds jets
A	13.9	46.2	98.2
B	30.5	51.0	1.59
C	23.9	2.29	0.11
D	31.7	0.55	0.14

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.

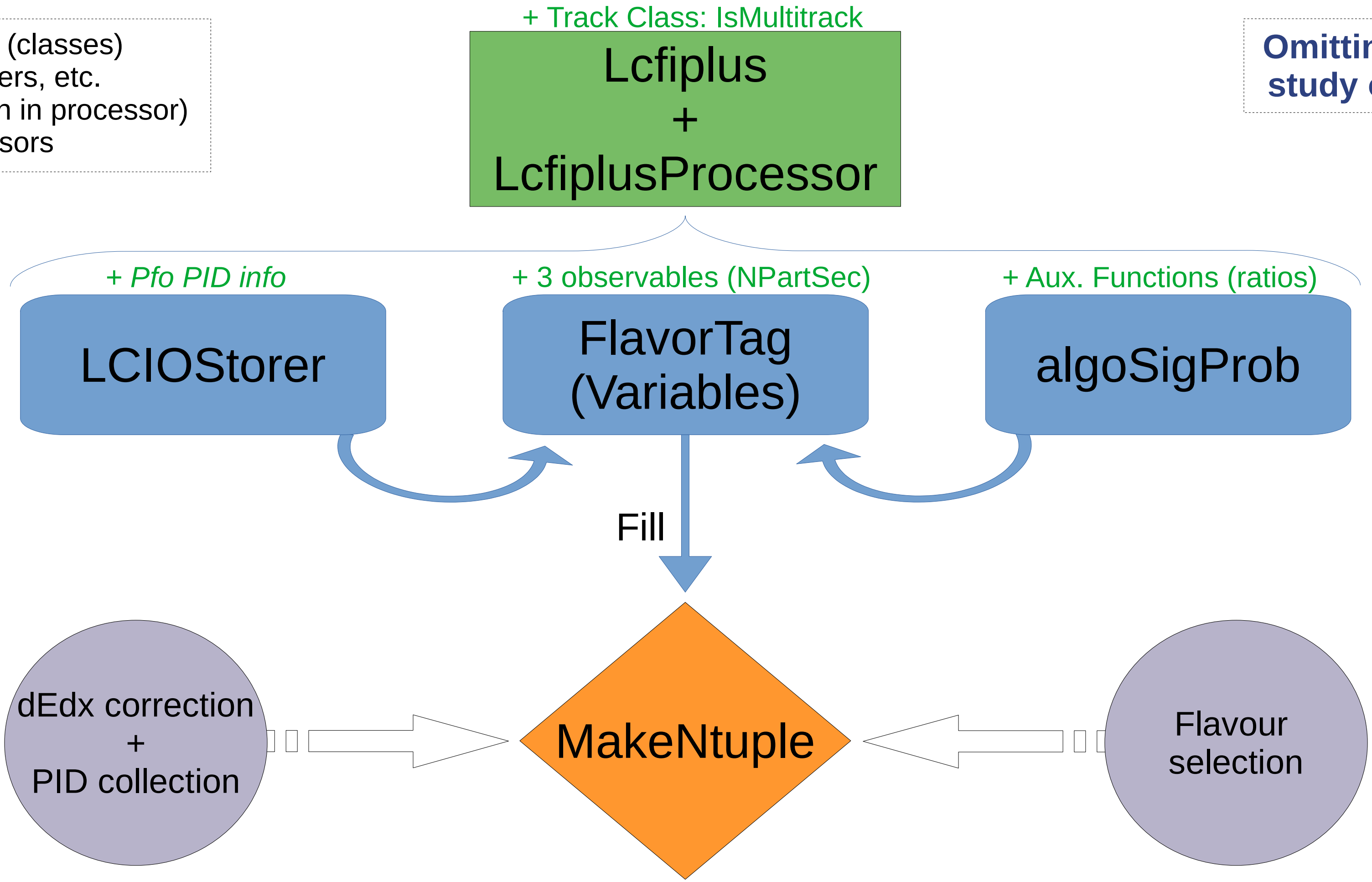
To introduce dEdx in the training process we need to:

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

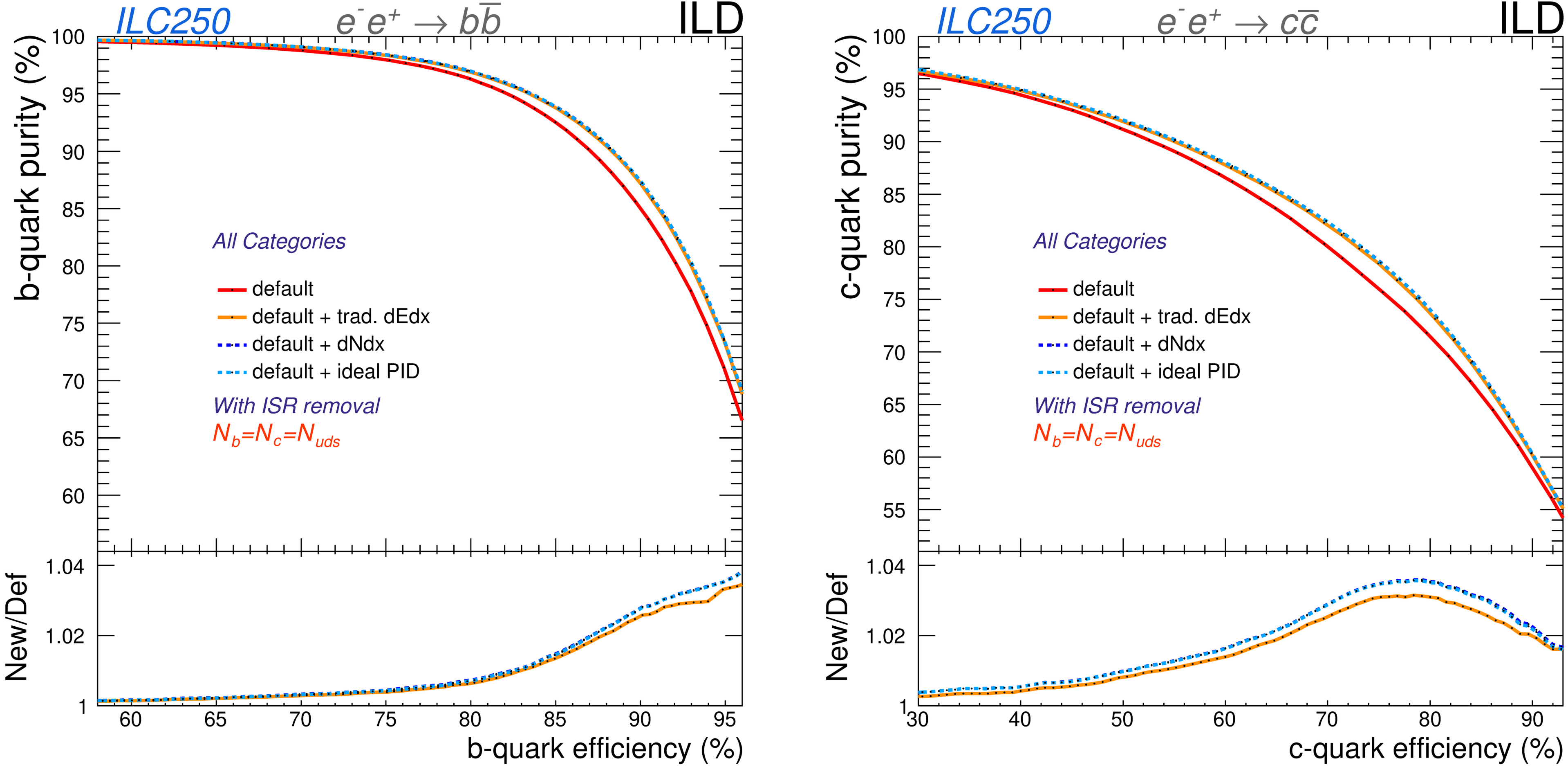
Fill

dEdx correction
+
PID collection

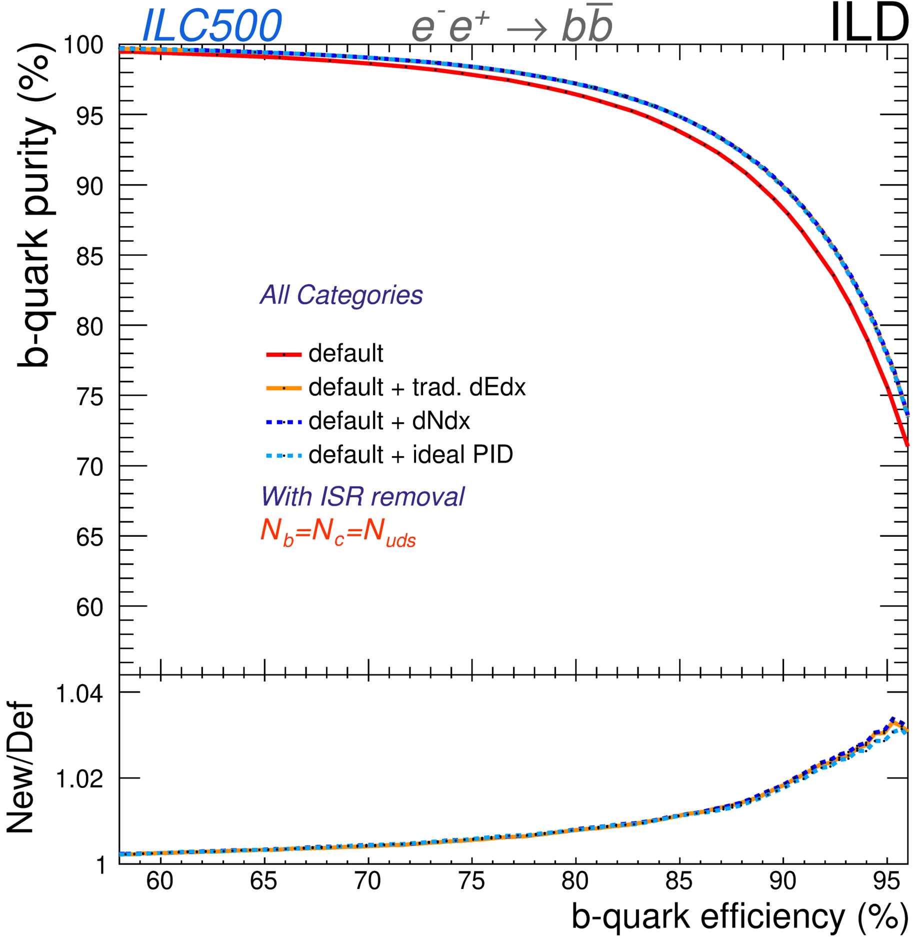
MakeNtuple

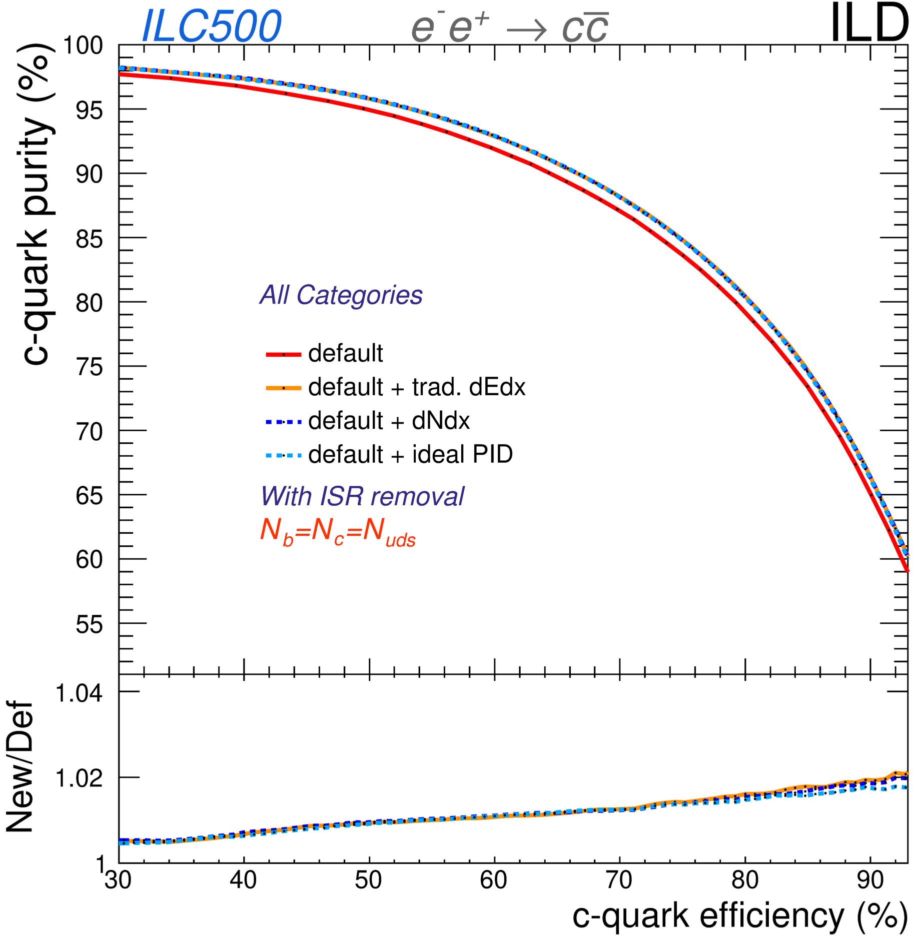
Flavour
selection

Effects of dNdx in Flavour Tagging (250 GeV)



Effects of dNdx in Flavour Tagging (500 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).

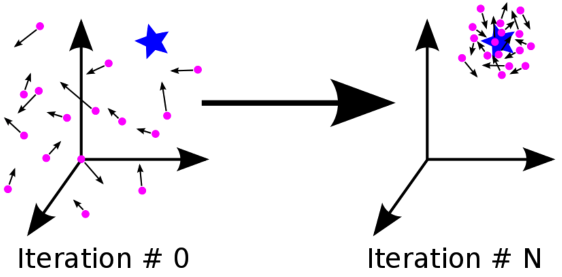


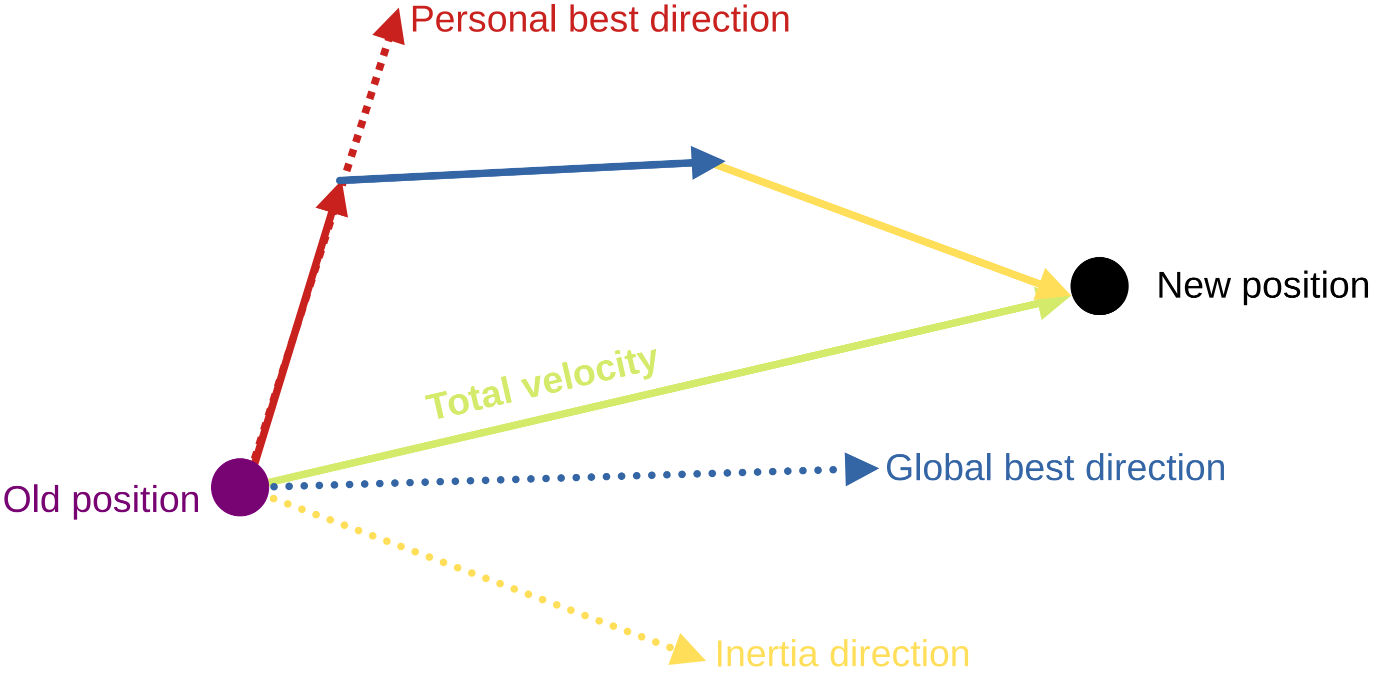
Image taken from a website

For each iteration

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).