New physics at ILC250/500 with ILD

From b & c quark production with dEdx PID

SW&ANA group meeting

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26/04/23

This presentation

- Current status on 250 & 500 GeV studies on $e^- e^+ \rightarrow q\bar{q}$ production.
  - Focus on (heavy) b & c quarks.

- Experimental techniques:
  - Precision measurements.
  - Flavour tagging (+ dEdx).
  - Full signal+background simulations ILCSoft (ft. LCFI+).

  See A. Irles talk in ECFA (Precision measurements, Flavour tagging)

- 16 different experimental observables to maximize the discrimination power:
  - 2 observables: A_{FB} & R_q.
  - 2 polarisation configurations: $e^-_L e^+_R$ & $e^-_R e^+_L$.
  - 2 energies: 250 & 500 GeV.
  - 2 quarks: b & c.

Observables

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

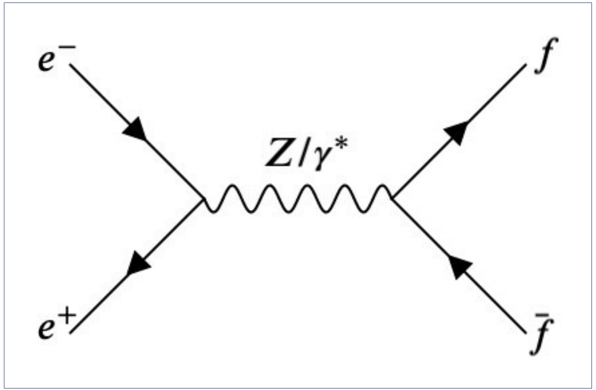
$$\frac{d\sigma^{f\bar{f}}}{d\cos\theta}(P_{e^-}, P_{e^+}, \cos\theta) = (1 - P_{e^-}P_{e^+})\frac{1}{4}\left\{(1 - P_{eff})\frac{d\sigma^{f\bar{f}}_{LR}}{d\cos\theta}(\cos\theta) + (1 + P_{eff})\frac{d\sigma^{f\bar{f}}_{RL}}{d\cos\theta}(\cos\theta)\right\}$$

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

  - 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):
  - We could only inspect them using polarisation.

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

Observables

- Ratios (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.

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

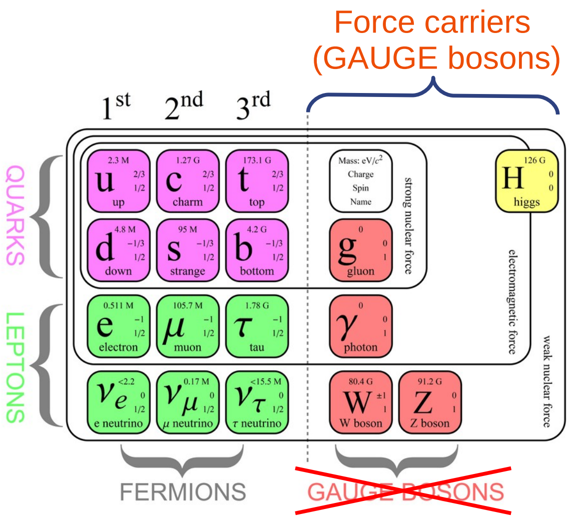
Normalized & **differential** observables are highly preferred:
Control (removal) of systematic uncertainties

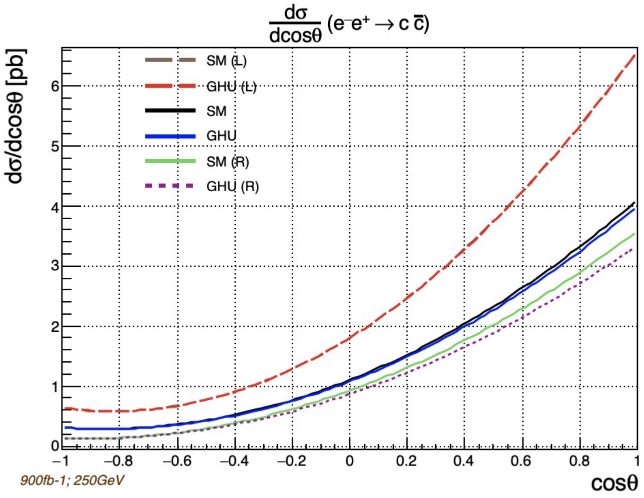
$$A_{FB}^{Exp} = \frac{N_F - N_B}{N_{Total}}$$

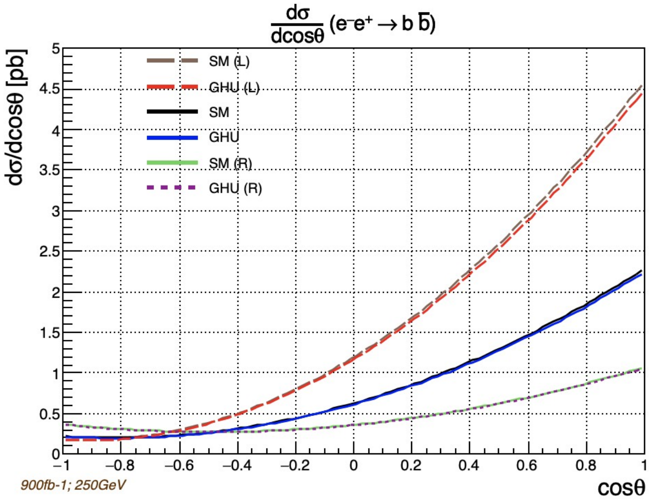
$$R_q^{Exp} = \frac{N_q}{N_{hadron}}$$

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).







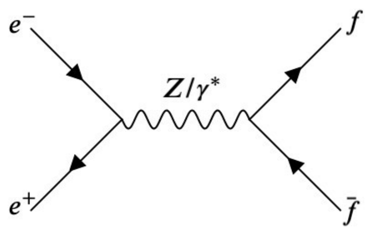
- The breaking pattern is way more complex than in the SM and features the Hosotani's mechanism.
    - Most of the fields are localized in the bulk and we feel the IR-projections.
        - Effects in EW couplings & KK-resonances of Z/γ!
        - Deviations from SM start being noticeable at 250 GeV!
    - We distinguish **A-Models** (GHU) and **B-Models** (GHU+GUT).

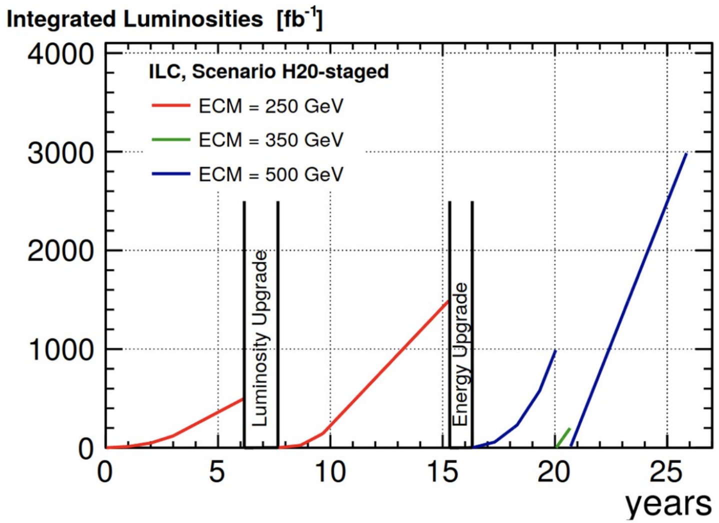
Projection of couplings and EW mixing angle:

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

ILC physics program

- The ILC is more than a Higgs factory:
  - It provides access to **all SM fermions**.
- It also features polarized beams:
  - $P(e^-) \sim 80\%$
  - $P(e^+) \sim 30\%$
- We can aim for specific processes by adjusting:
  - **Center-of-mass energy**
  - **Beam polarization**
- BSM Models sensitive to polarization can be tested using these all these features.
- ILC run plan:
  - 4 different energies: Z-Pole, **250**, **500**, 1000 GeV.
  - 4 different polarisation configurations:
    - $\text{sgn}(P(e^-),P(e^+))$ = **(+,-)**, **(-,+)**, (+,+), (-,-)



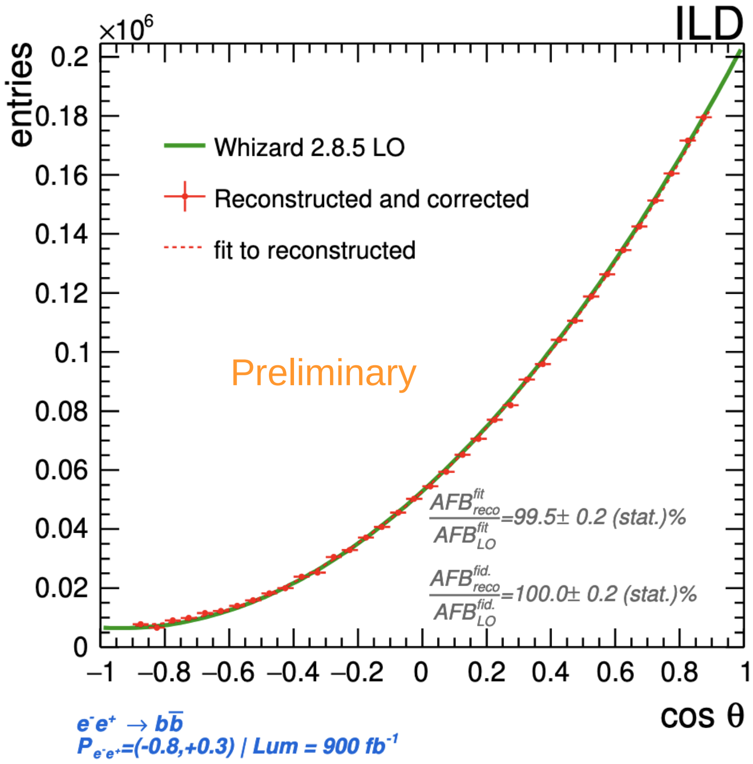


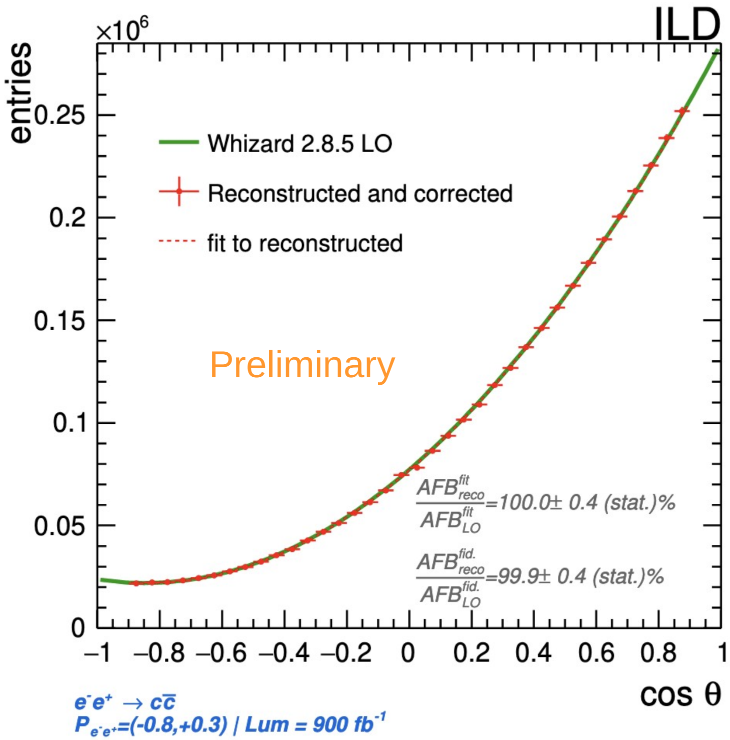
Luminosity upgrade: 5 Hz to 10 Hz.
Energy upgrade: Extend the linac

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

Status of current studies

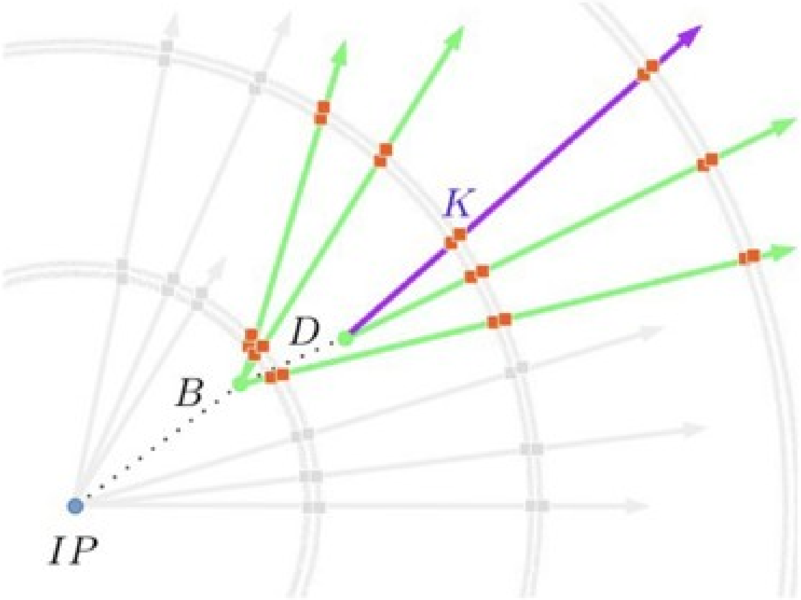
Preliminary Results for b & c quark 250 GeV
Presented in ECFA , LCWS19 (and others)
IJCLab/Tohuku/IFIC collaboration: F. Richard, R. Poeschl, T. Okugawa, H. Yamamoto, A. Irles, J. Márquez
Draft for ILD Note to appear soon





Preselection of $q\bar{q}$ signals

- Experimental procedure:
  - Preselection.
    - To remove backgrounds.
      - Specially **radiative return**.
        - Up to x10 more data than the signal!
  - Flavour tagging.
    - Using standard ILD Tool: LCFI+
  - Charge measurement.
    - Using full vertex charge reconstruction and kaon PID



Current prospects for R_q and A_{FB} (250 GeV)

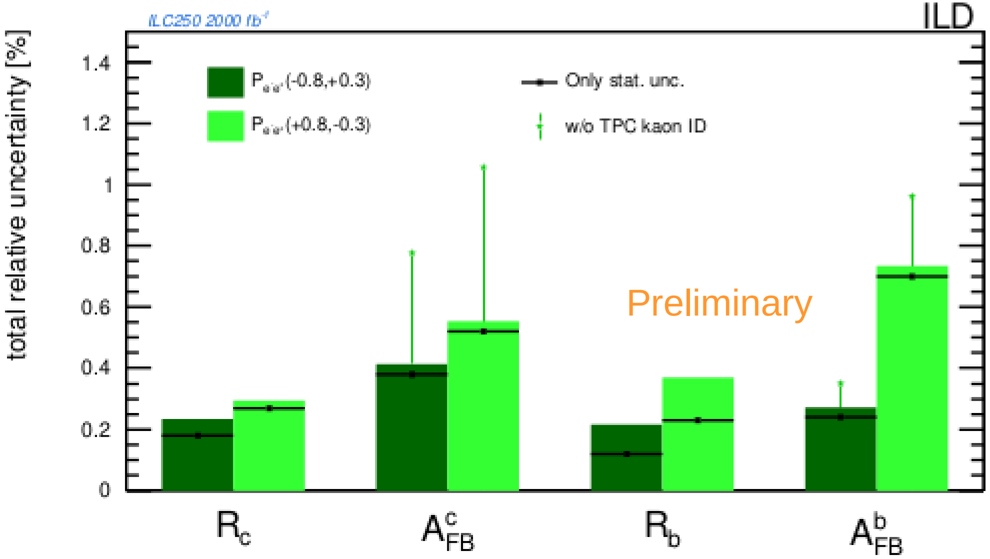


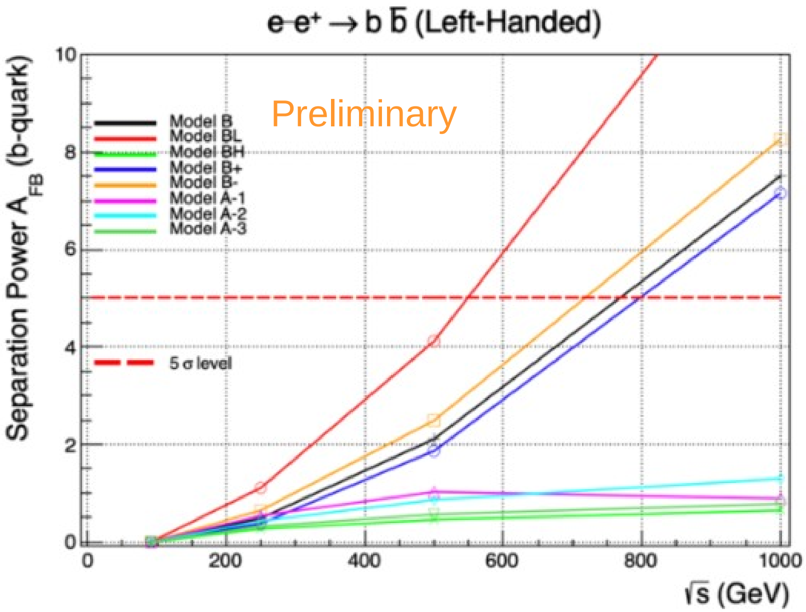
Figure 20: Expected achievable precision for the measurement of electroweak observables R_q and $A_{FB}^{q\bar{q}}$ at ILC250 with the ILD. We include the scenario in which no charged hadron identification capabilities is provided by the TPC, hence having only the Vtx-method for the charge measurement used for A_{FB}.

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

Phenomenology of Hosotani's Models

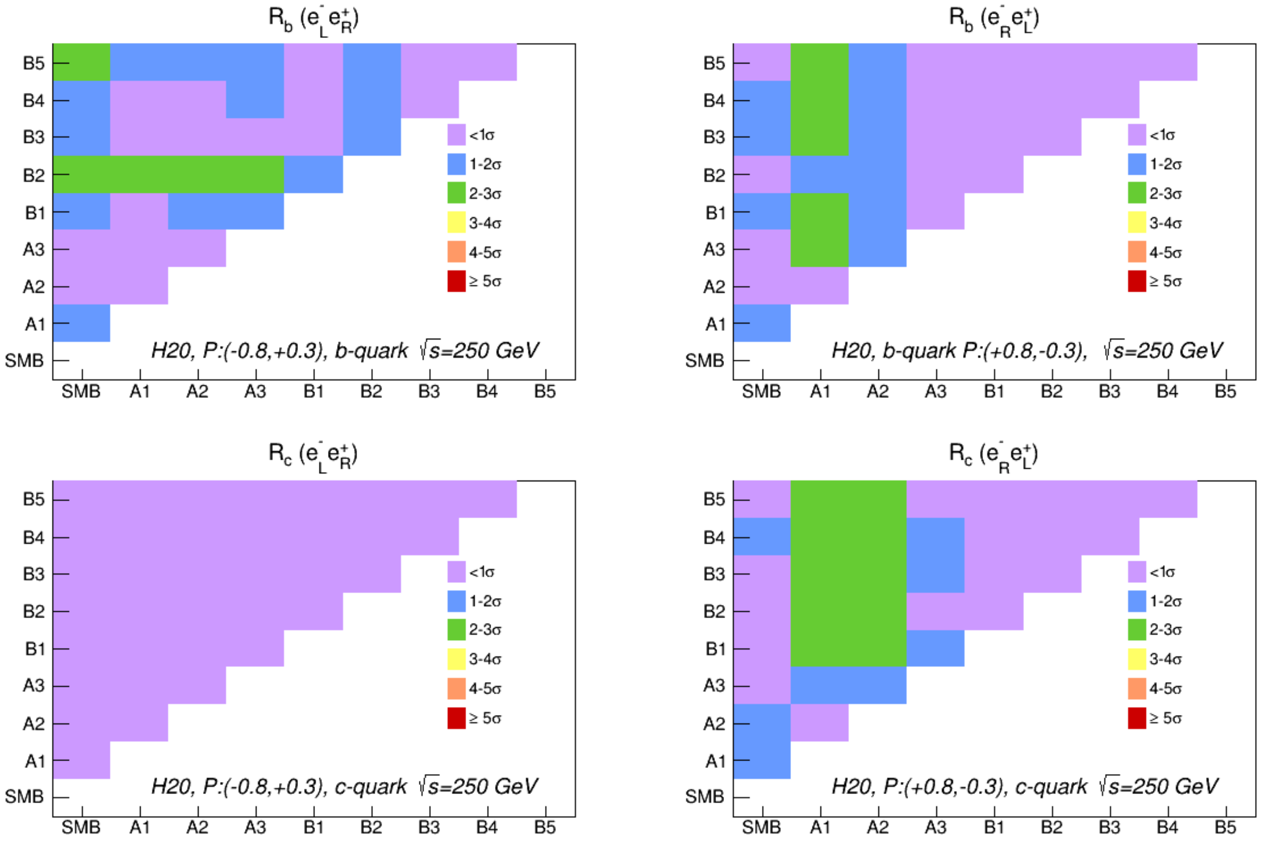
- 2 kinds of models: A & B Models:
  - A & B Models distribute differently the fields along the 5-dimensions (see back-up for more).
    - We consider 3 A-Models & 5 B-Models.
  - B Models are also related to GUT.
- Extra dimension produce KK-resonances:
  - ~10 TeV: No direct production.
  - Contributions from $Z^{(1)}$ and $\gamma^{(1)}$ as virtual particles.
- Projection of the fields affects EW mixing angles and couplings:
  - All bosons are affected (SM and BSM).
  - All fermion channels are affected!
- Higher energy leads to higher deviations.

Example of separation dependence with energy



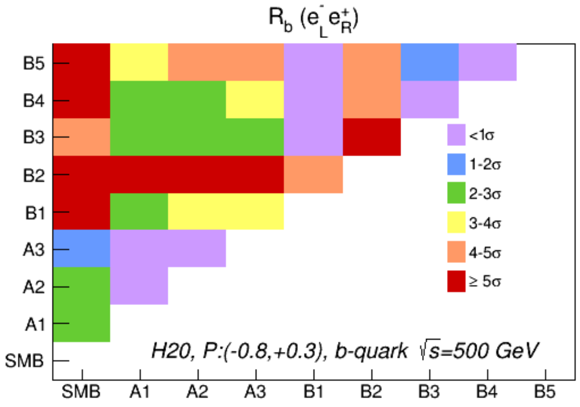
Next slides: Discrimination between models for A_{FB} & R_q given the current expected precisions for 250 GeV. For 500 GeV we are using x2 stat. and same syst. uncertainties than the 250 GeV case (real values not still available).

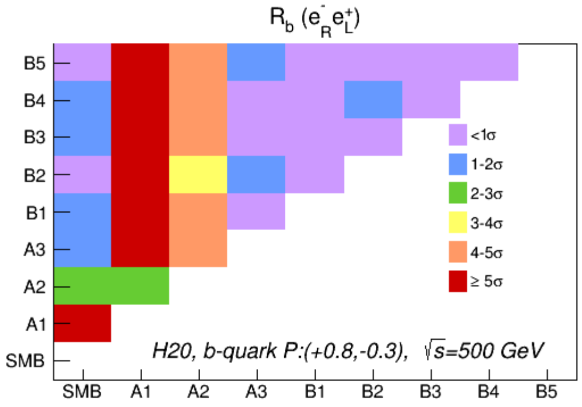
R_q at 250 GeV

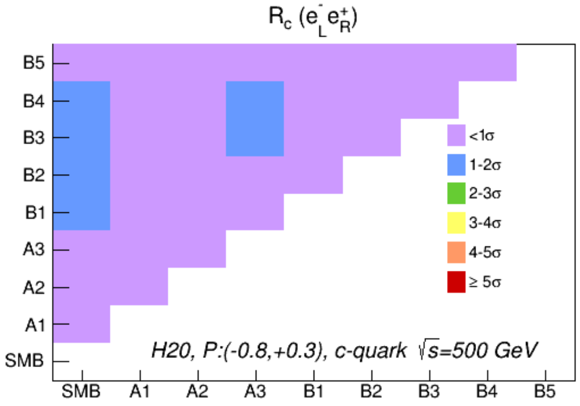


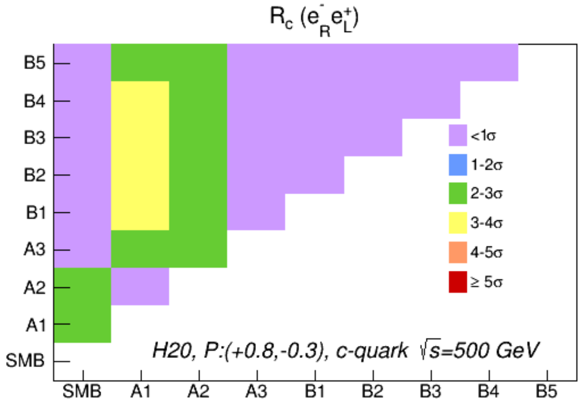
We need a proper estimation of correlations before combining R_q measurements

R_q at 500 GeV



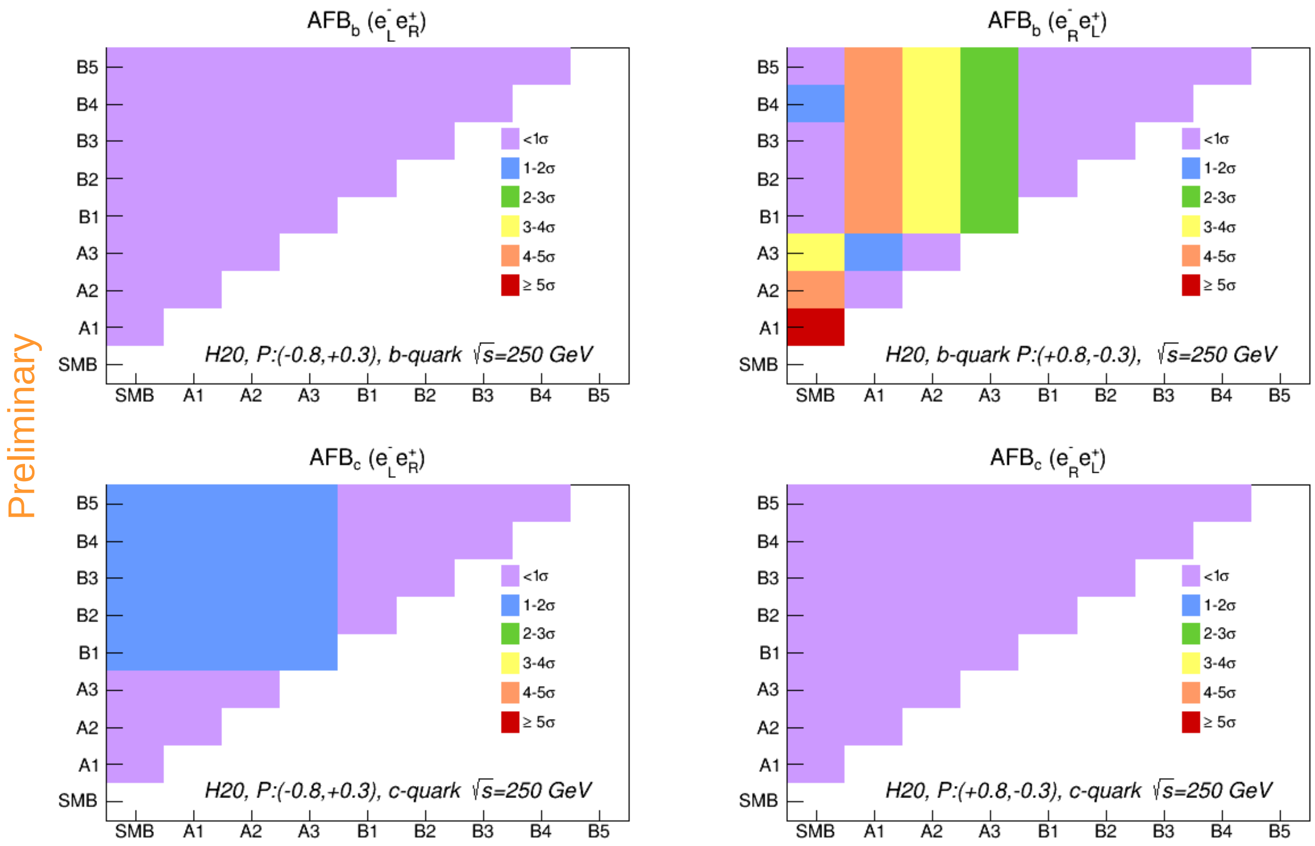




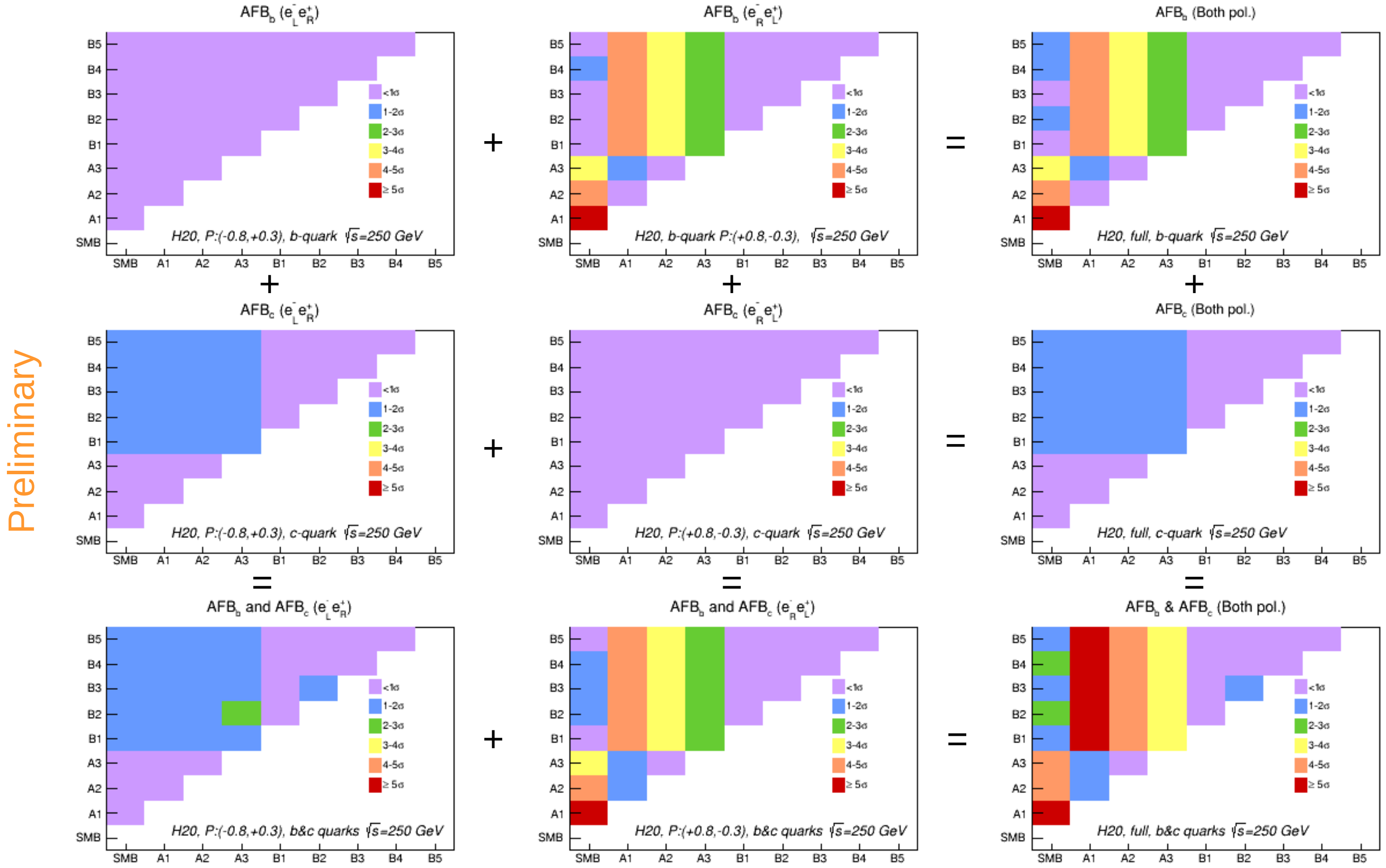


This is only an estimation, full calculation at 500 GeV TBD

A_{FB} at 250 GeV

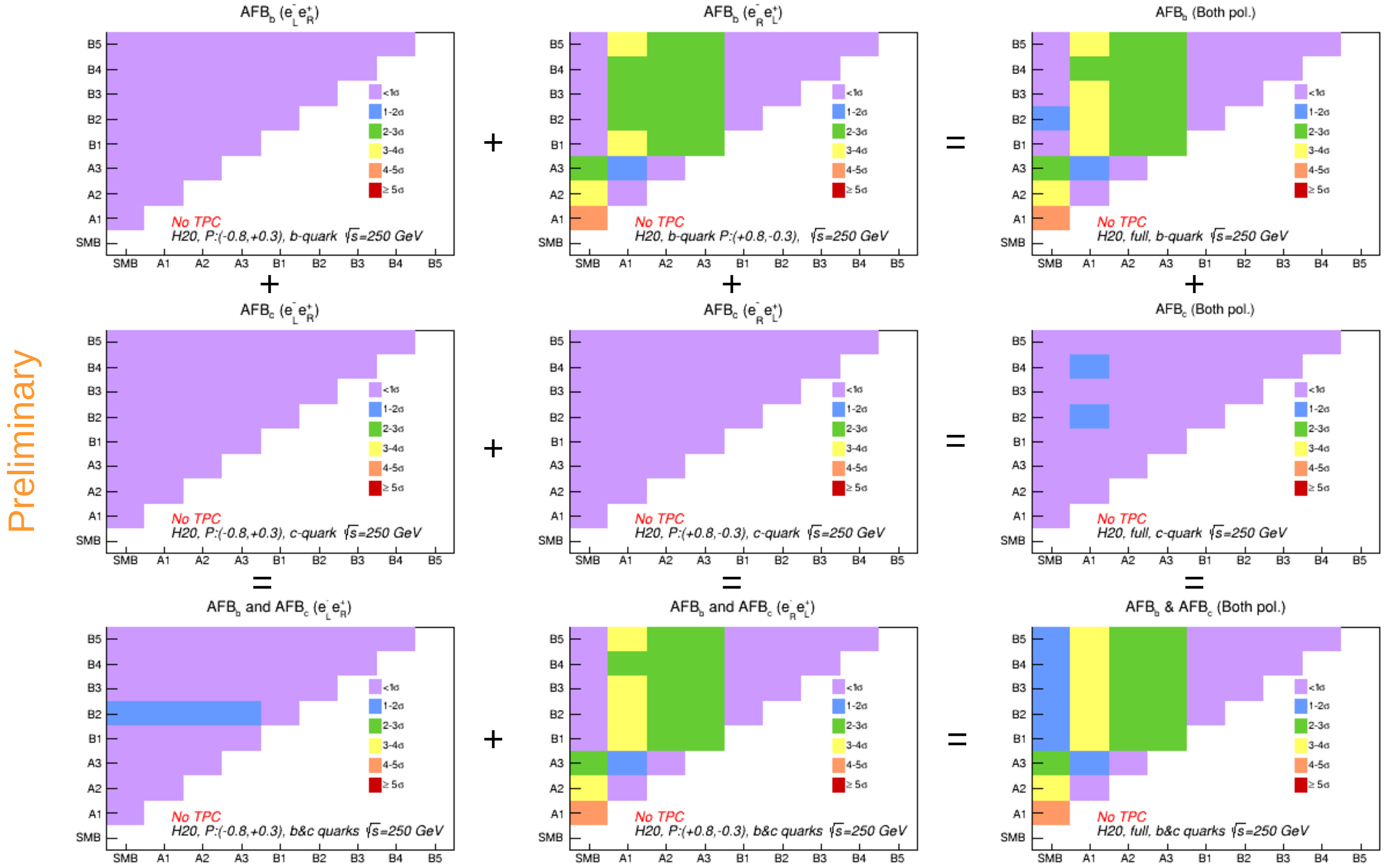


A_{FB} at 250 GeV



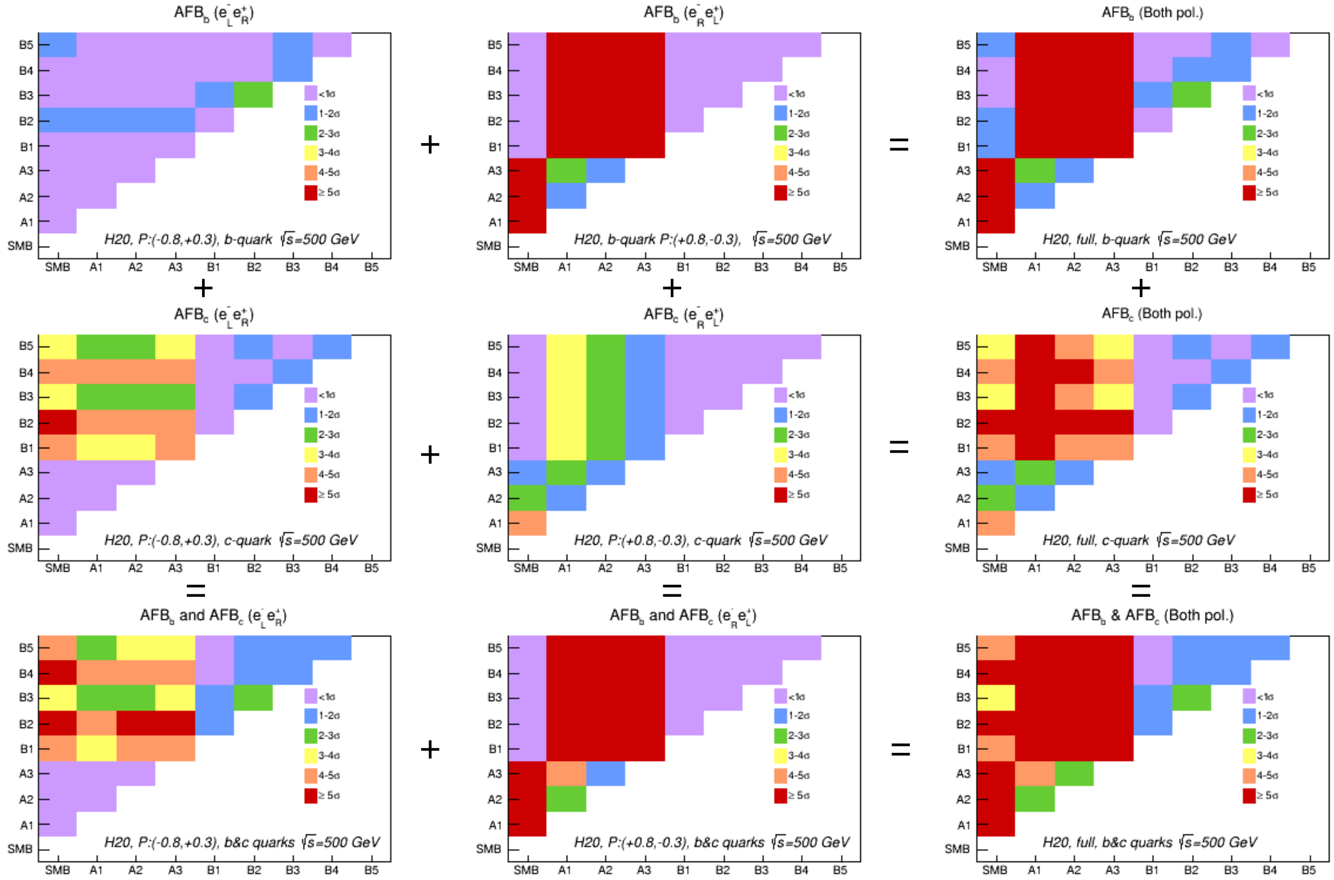
We can combine the measurements as a *diagonal* multivariate gaussian (small correlations)

AFB at 250 GeV (no TPC)



A_{FB} at 500 GeV

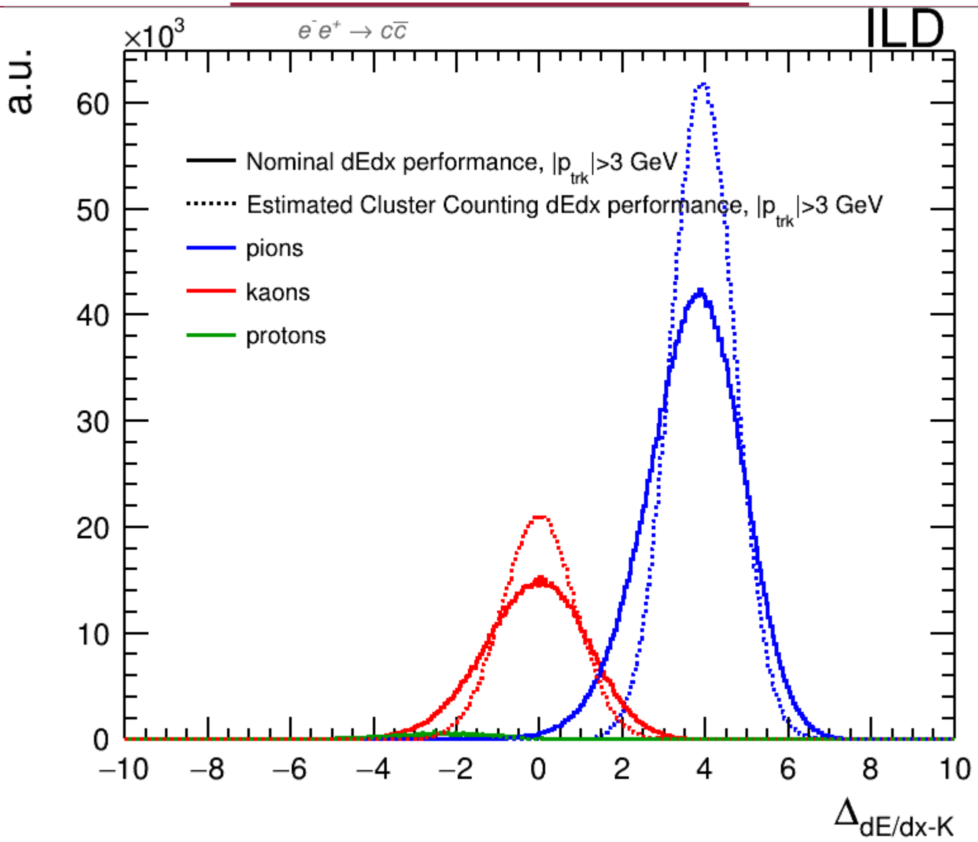
Preliminary



Remember: This is using an estimation for the uncertaintites, full calculation at 500 GeV TBD. Preliminary numbers appear slightly larger than the 250 GeV but of the same order

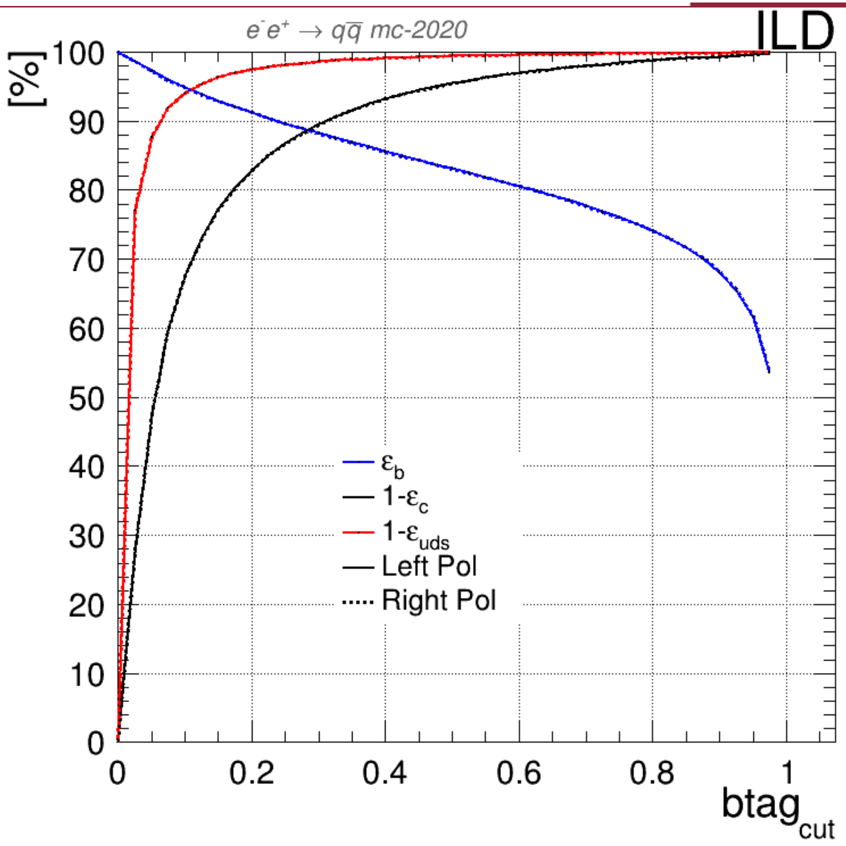
Improvements in dEdx

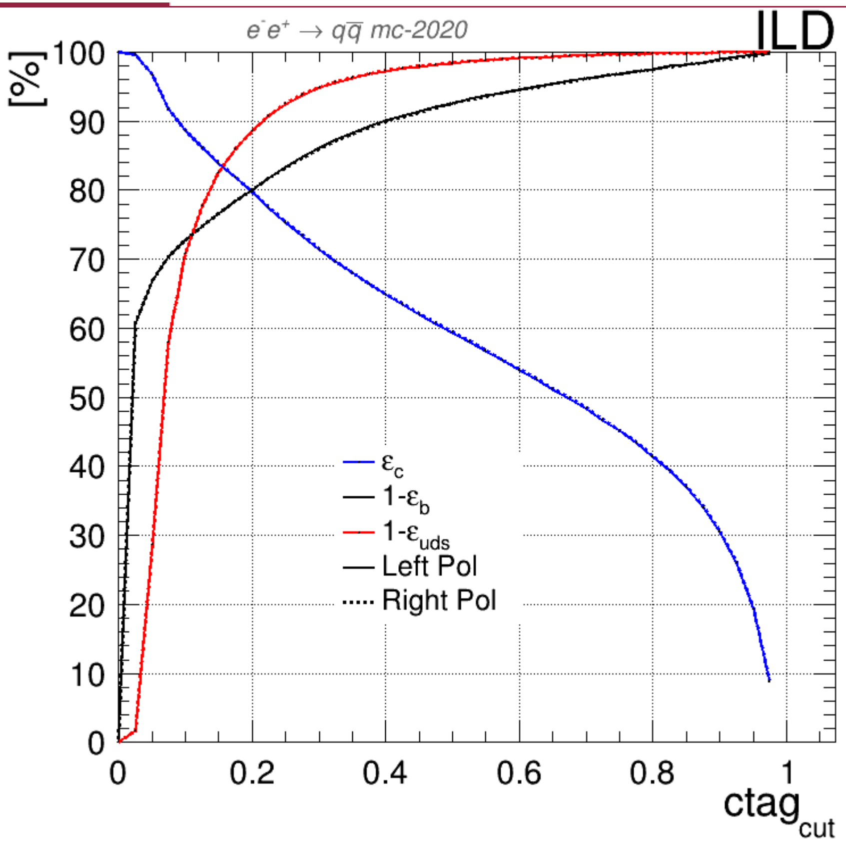
Prospects for improving dEdx



The gaussians represented by each type of particle would be thinner, allowing better classification when we use them to build our variables

Flavour tagging (250GeV)





Nominal values of Flavour tagging at 250 GeV, without adding dEdx information.
We will focus in the **useful** range (**high purity**) in further comparisons.

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.)

↓

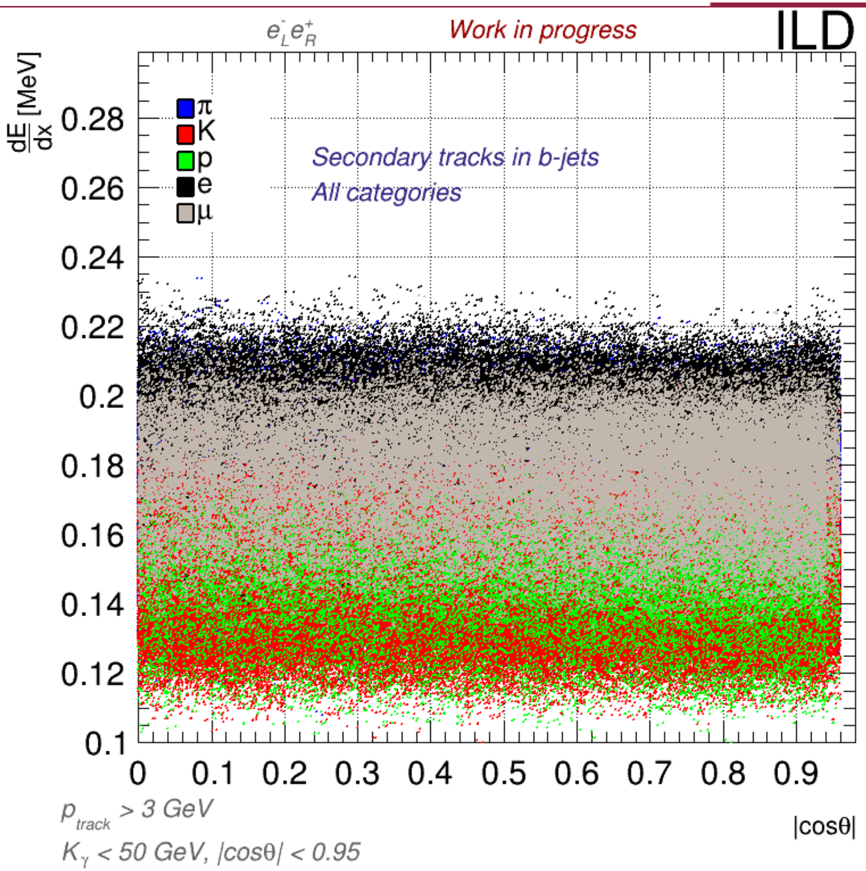
TrainMVA.cc ← Run the TMVA with the BDTs for each category. Creates the weight files for b/c-tag.

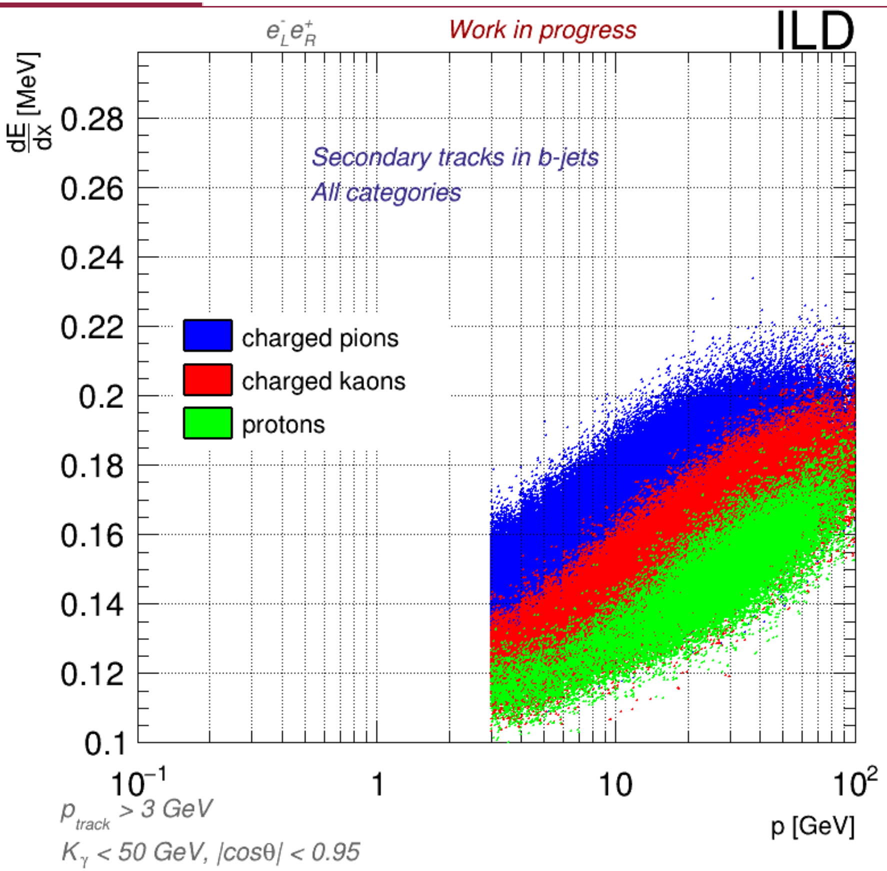
To introduce dEdx in the training process we need to:

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)

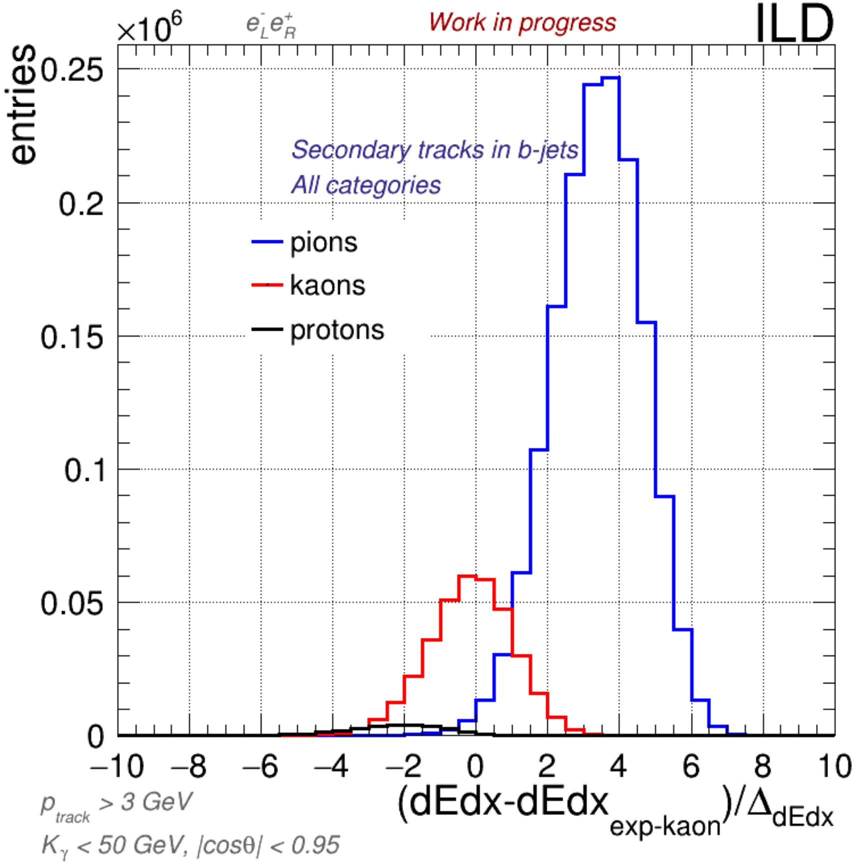
dEdx – Preselection of pfos

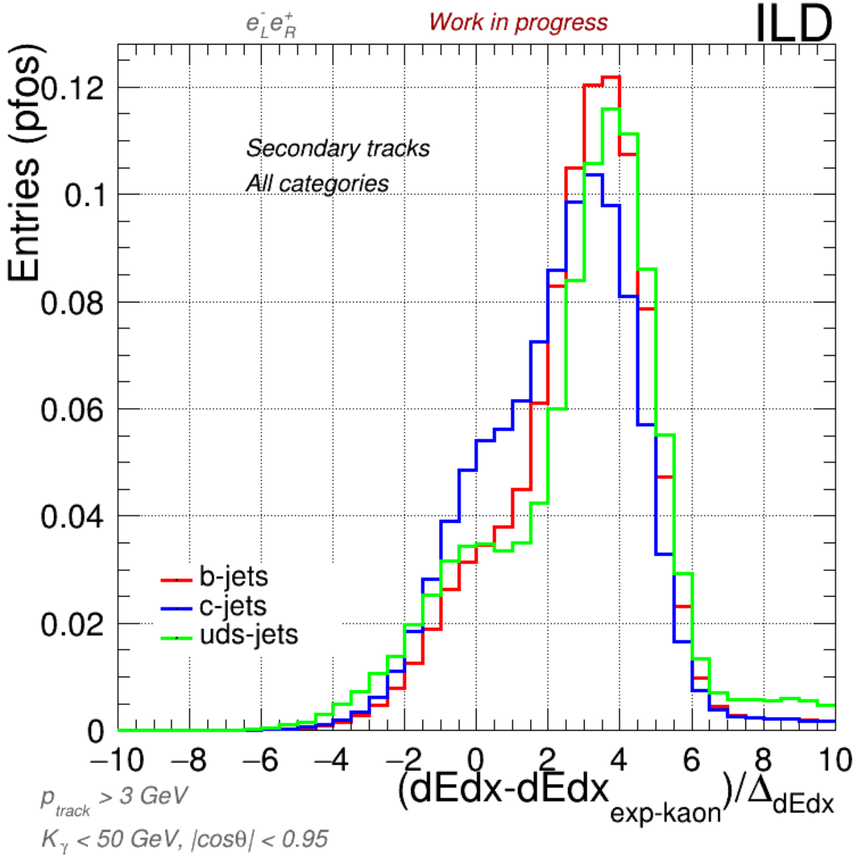




Adjusting this points to the Bethe-Bloch formula: Estimate PID

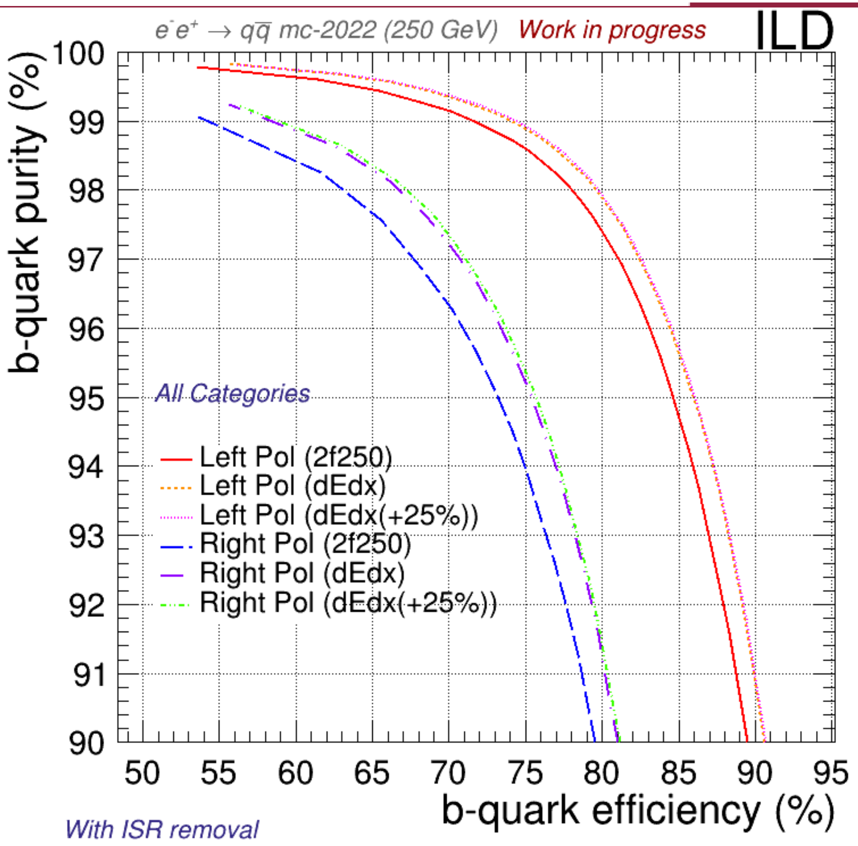
dEdx – KDS for different quark flavours

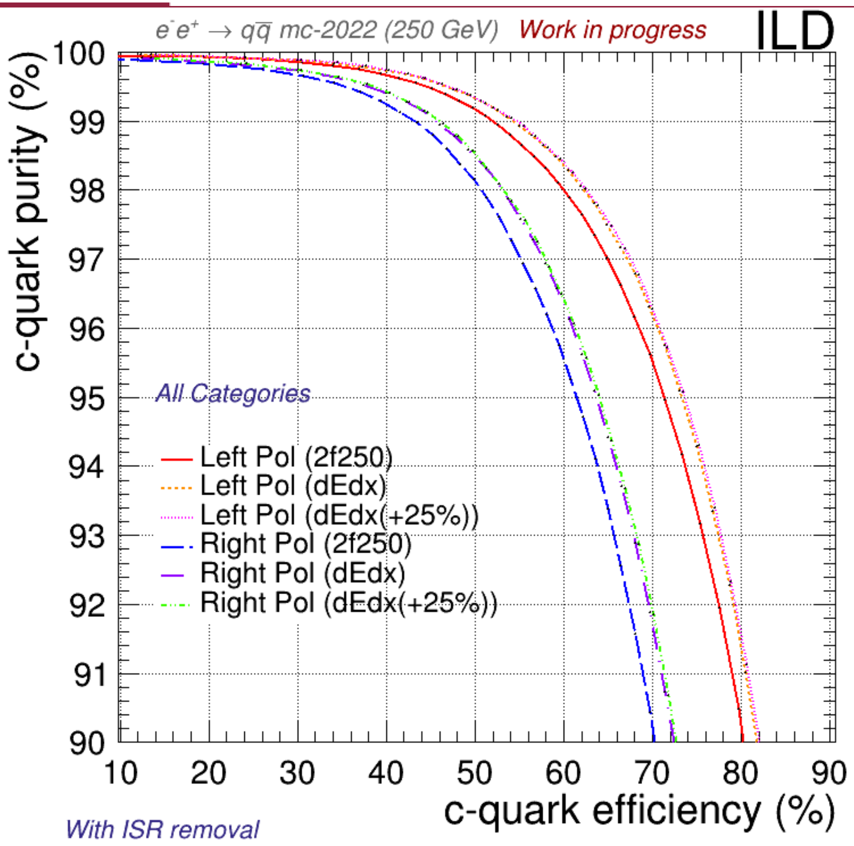




We repeat this also with Pions and Protons.
We build 3 variables NKaonSec, NPionSec & NProtonSec and add them to the FT!

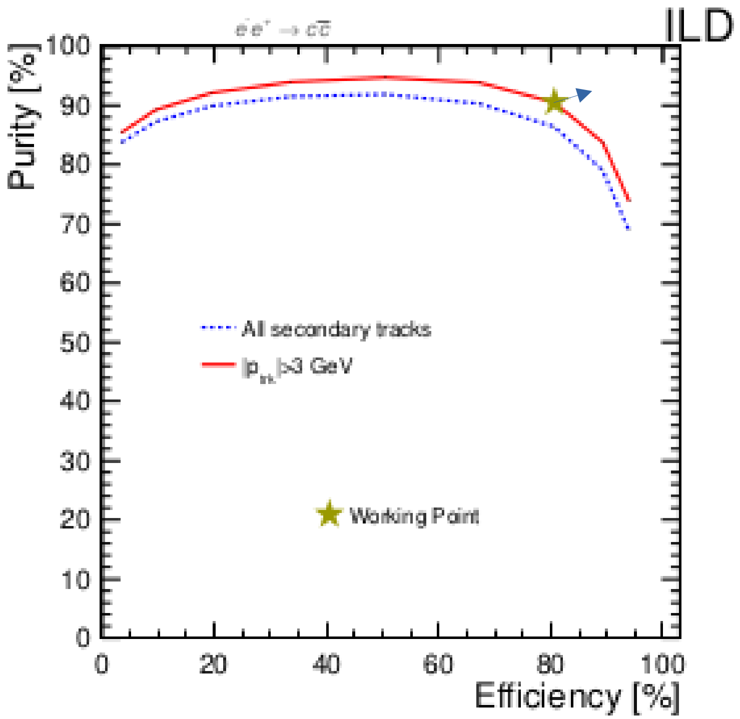
Efficiency vs Purity (250 GeV) - Tag(+dEdx)

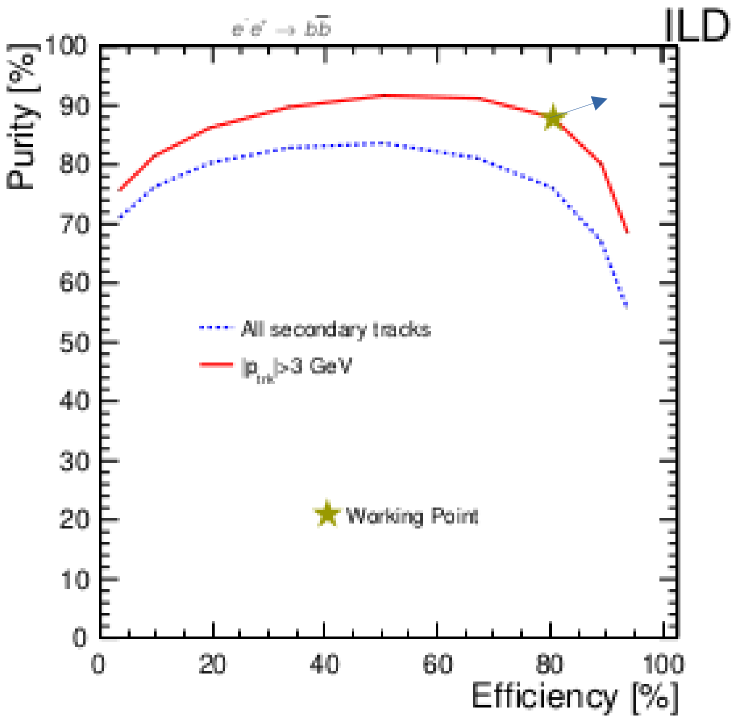




	Ef. (%) impact (90-99% purity range)			
	b-quark		c-quark	
	$e^-_L e^+_R$	$e^-_R e^+_L$	$e^-_L e^+_R$	$e^-_R e^+_L$
dEdx	1.2	1.7	1.7	2.0
dEdx(+25%)	1.3	1.9	1.9	2.5

Other expected improvements in dEdx





We expect a big impact when measuring the charge of the jets using Kaon ID via dEdx. TBD!

Conclusions & prospects

- Beam polarisation, Beam energy upgradibility and PID capabilities make ILC+ILD and excellent tool for measuring EW observables with great precision and test BSM Physics!

- We still have work to do (A. Irles & J. Márquez):
  - Finalize the training of 500 GeV samples (with dEdx & improved dEdx)
  - Implement new FT weights and improved PID into the analysis chain.
    - Get full precision results for all cases.
  - Study the model discrimination power for all different cases!

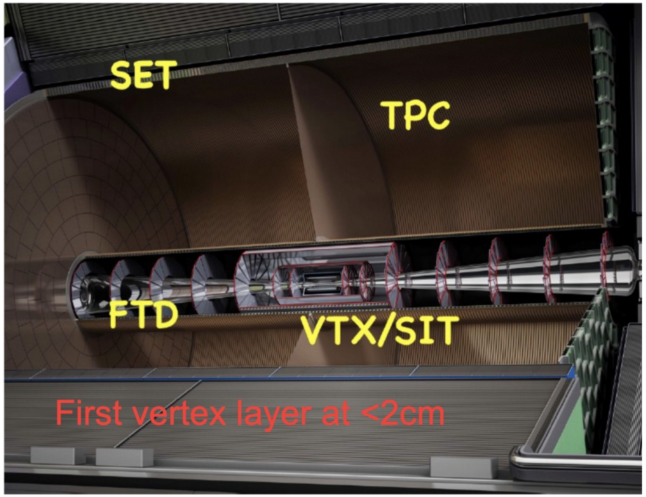
Thanks for your attention

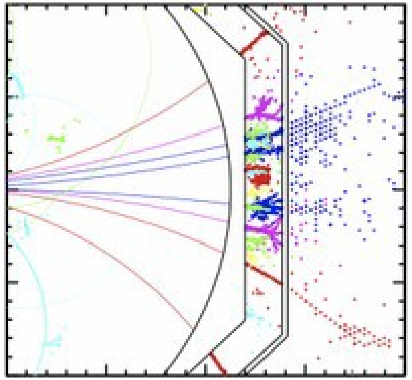
Back-up

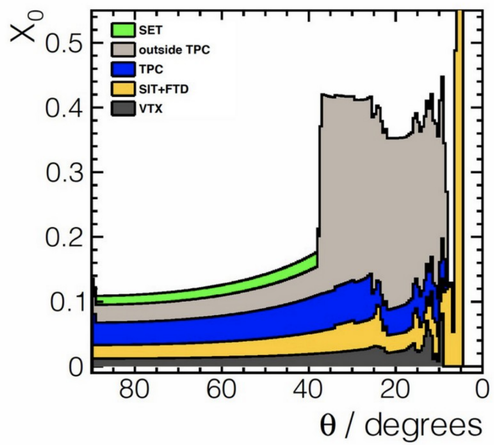
ILD overview

- 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





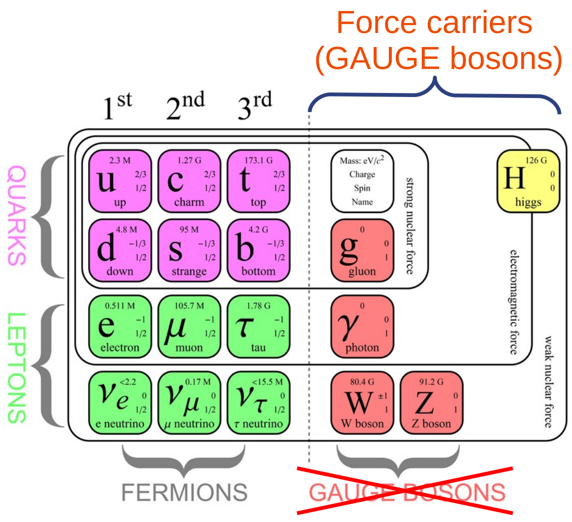


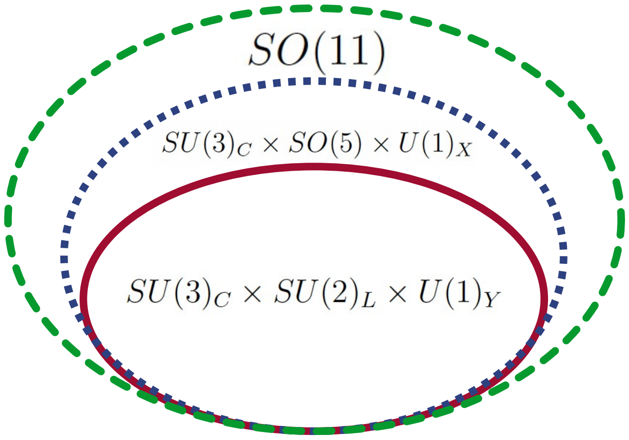
ILD: Interim Design Report.
ArXiv:1003.01116

Hosotani Models

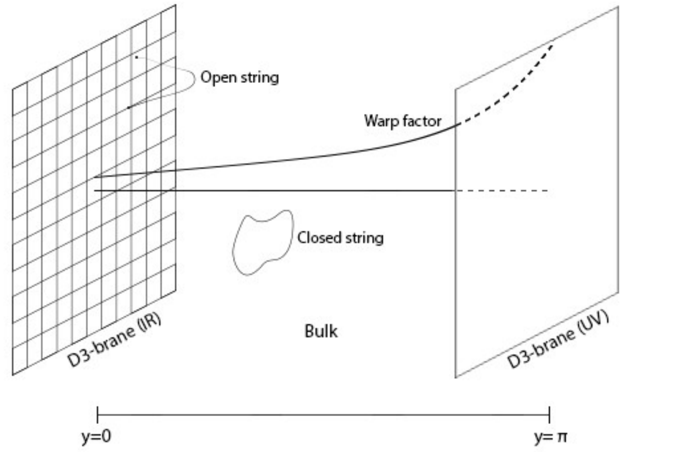
Gauge-Higgs Unification (GHU) Models

- 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:

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

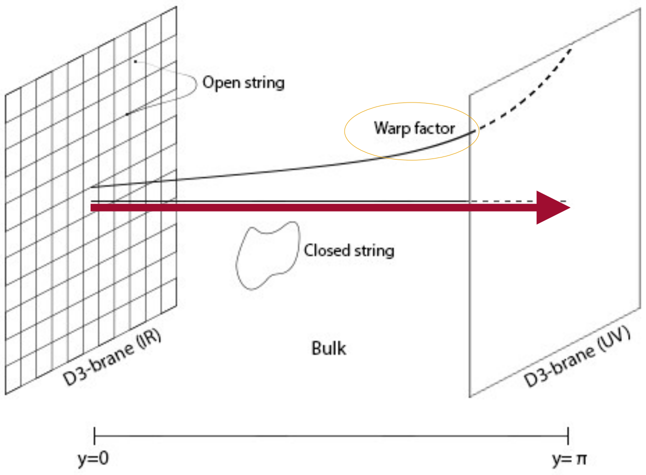
Extra-dimension (+1D)

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:

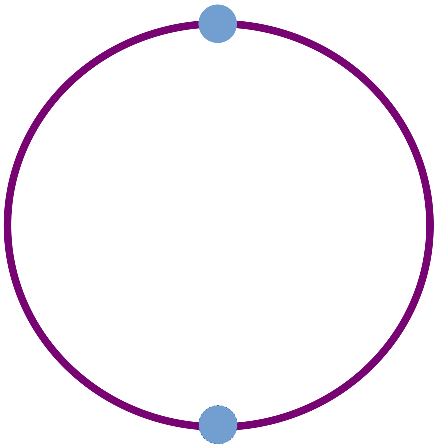


warping

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

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

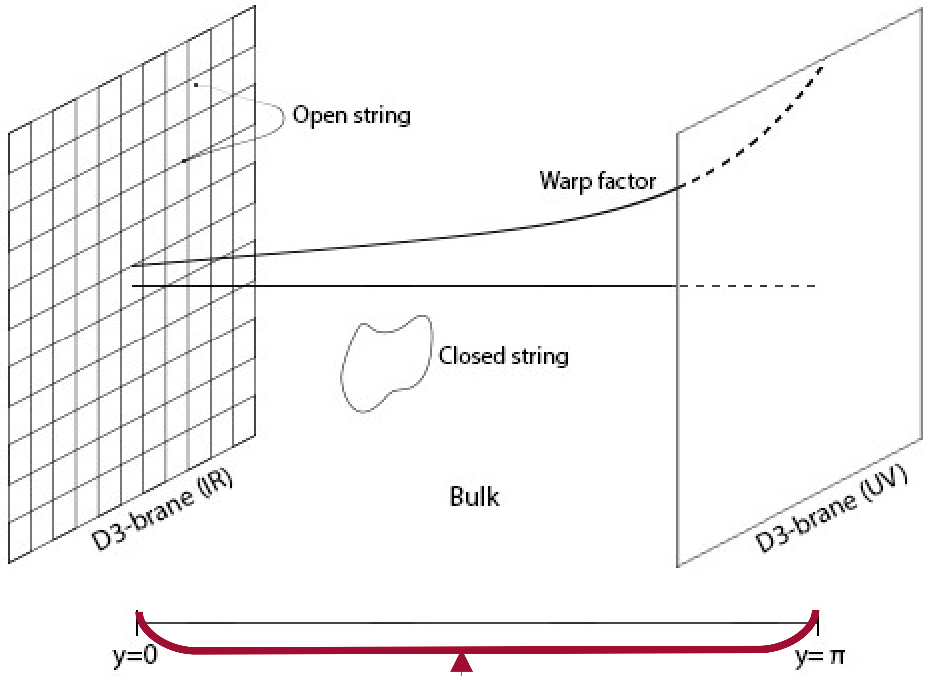


this other side

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

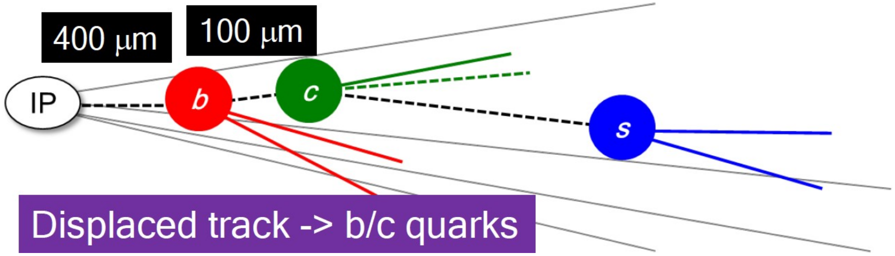
Projection of couplings and EW mixing angle:

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

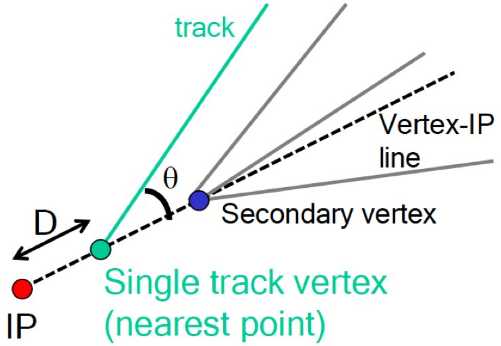
LCFI+

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.

arXiv:1506.08371

TMVA in LCFI+

- Most of the variables used in the TMVA are derived from d0, z0, the number of vertexes, the number of pseudo-vertexes and other kinematical variables (e.g. p_T).
  - e.g. b-quark probability in d0 values for all tracks.
- Classification in categories:
  - The training is performed 4 times (A, B, C, D), *in a single run* , with different selection of vertexing and single track pseudo-vertexing.

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

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

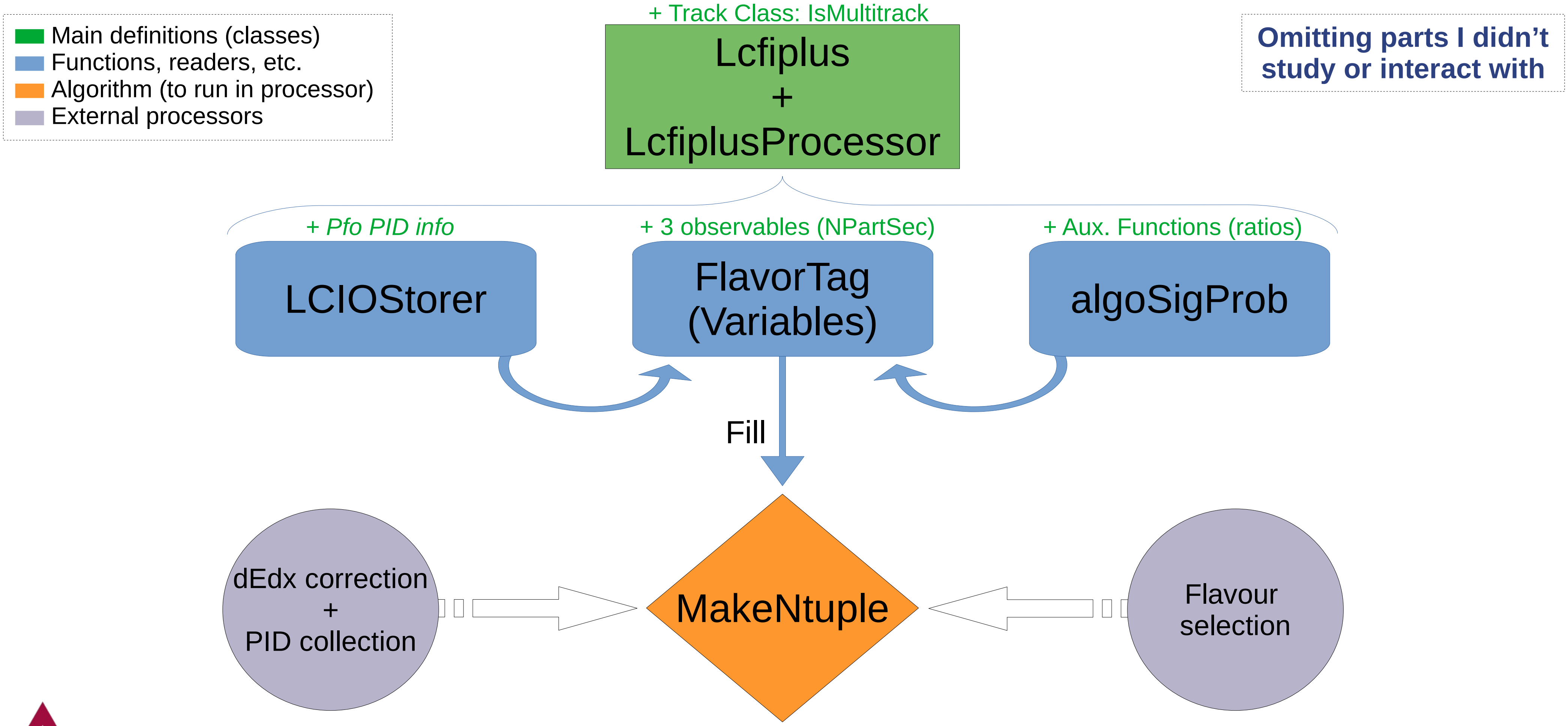
Events (%)			
Cat.	b jets	c jets	uds jets
A	13.9	46.2	98.2
B	30.5	51.0	1.59
C	23.9	2.29	0.11
D	31.7	0.55	0.14

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

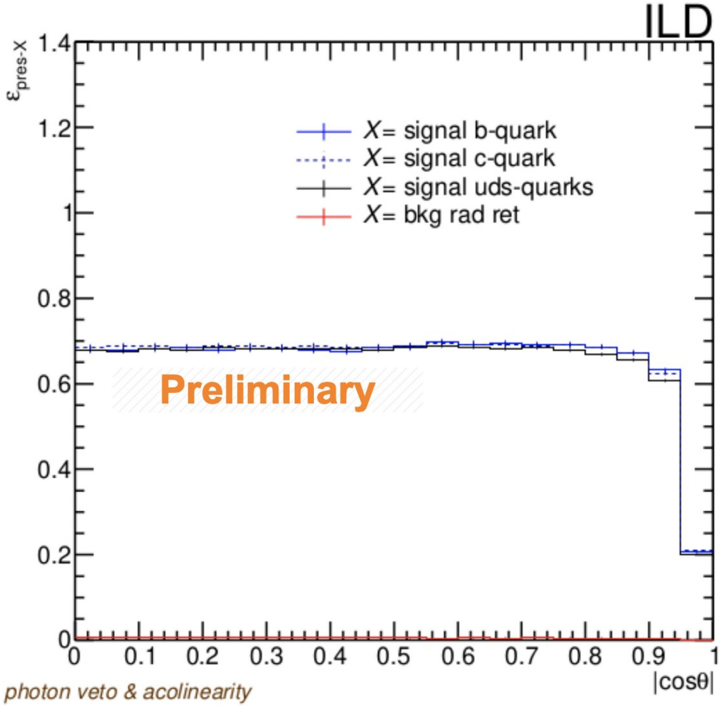
LCFI+ MakeNtuple Workflow (+dEdx)



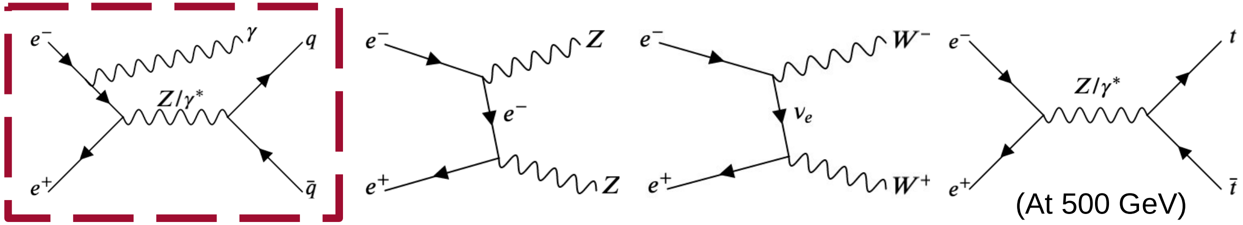
Experimental methods

Preselection of $q\bar{q}$ signals

- We 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!

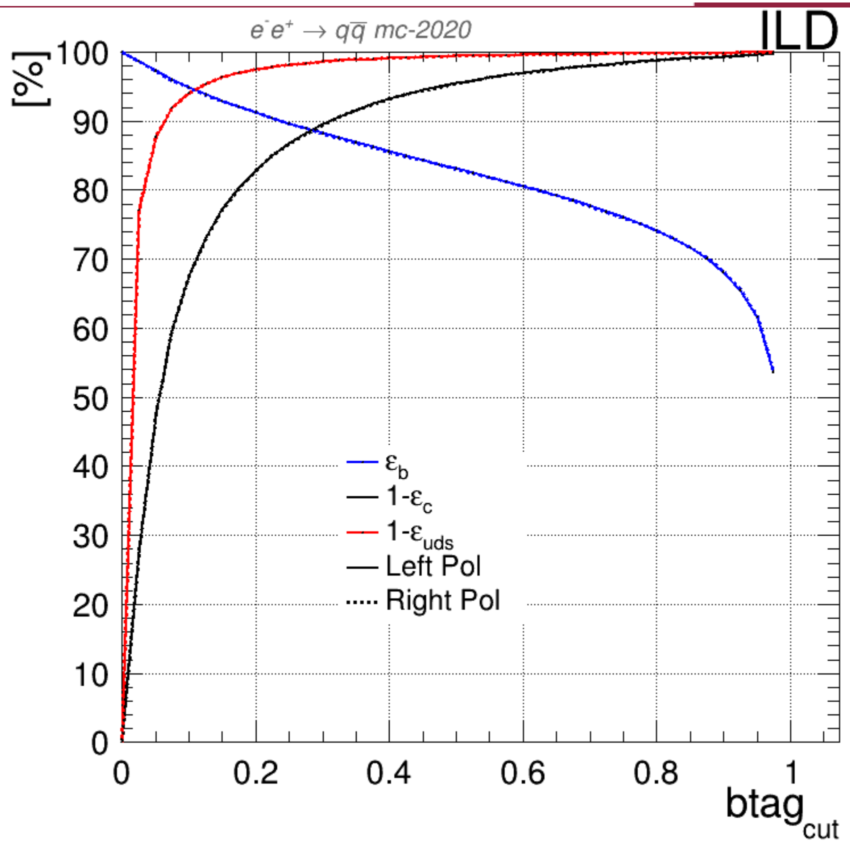


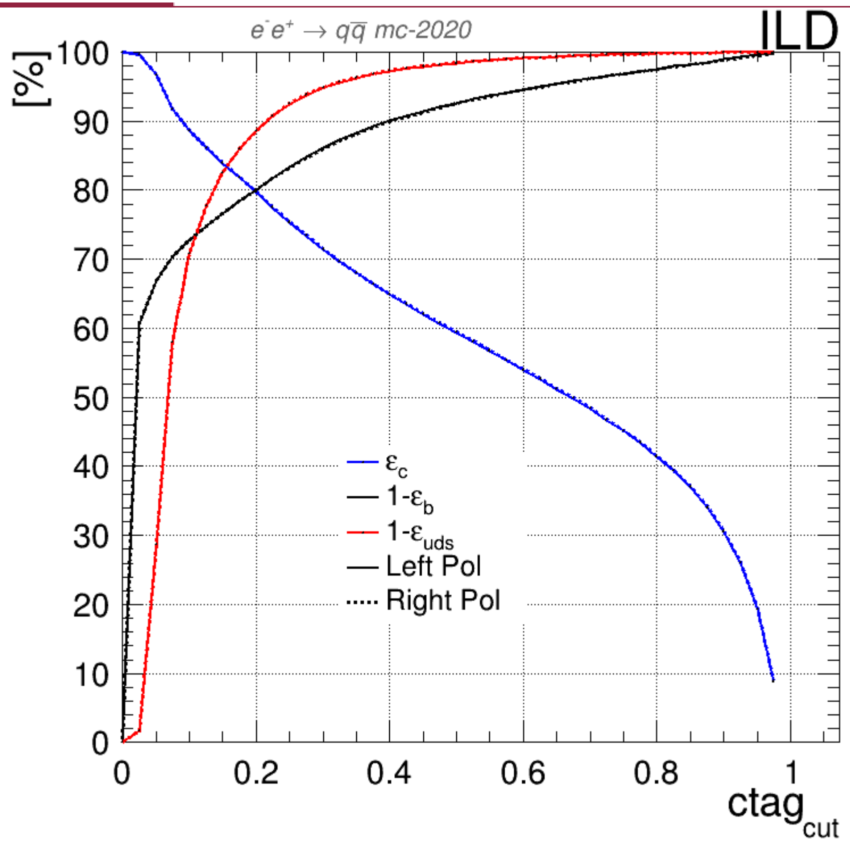
photon veto & acolinearity & K_{reco} & m_{j1j1} & y_{23} cuts



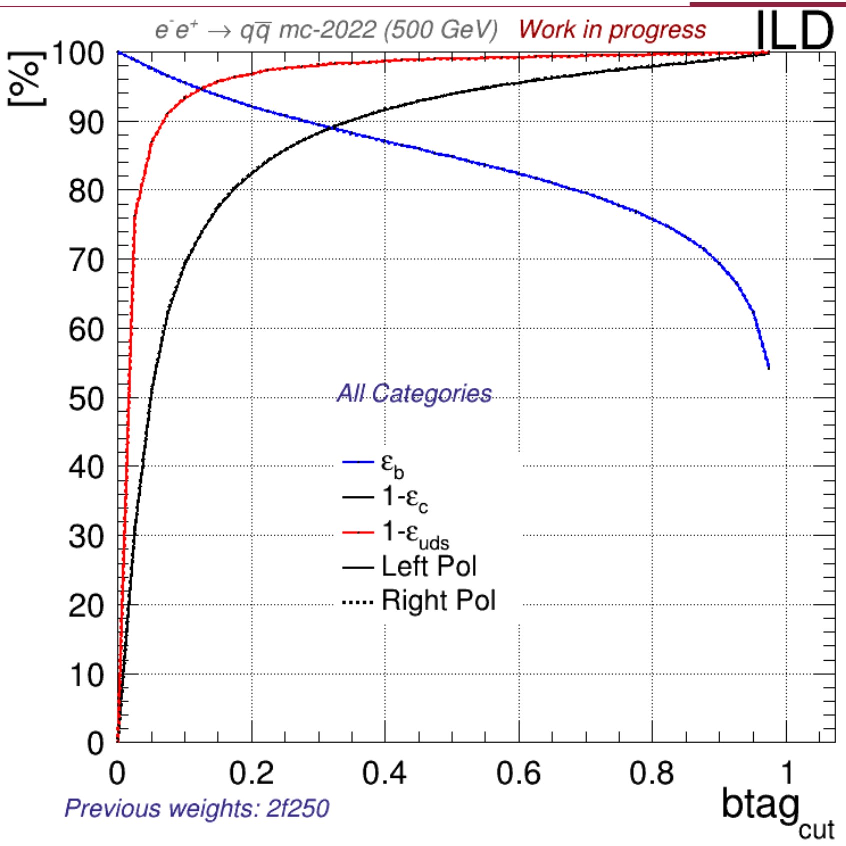
(At 500 GeV)

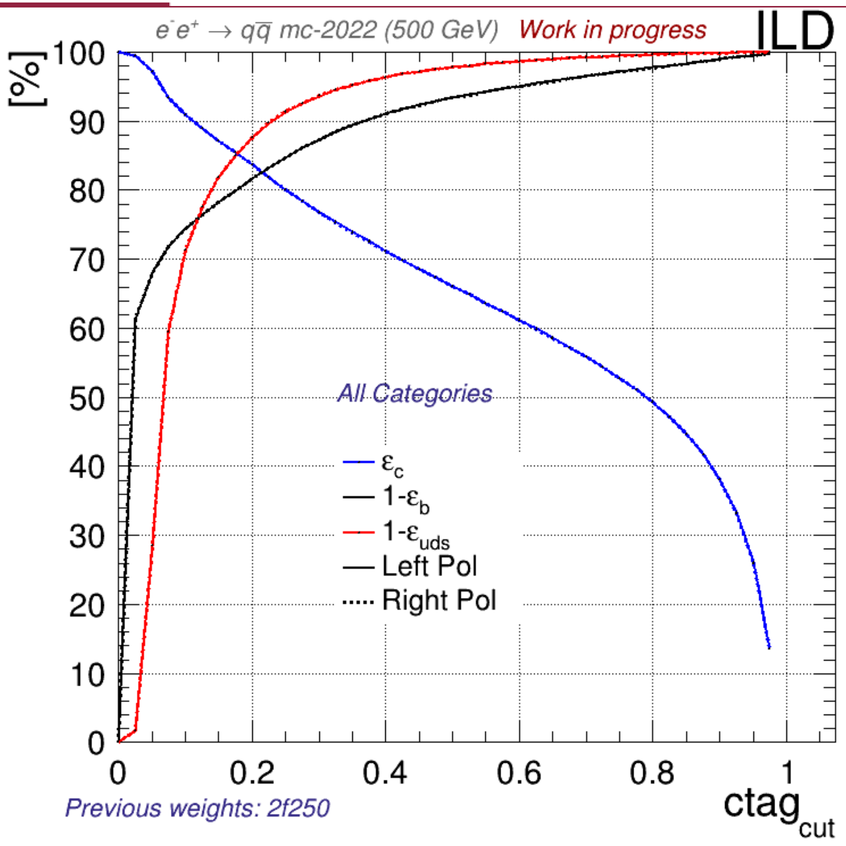
Flavour tagging (250GeV)





Flavour tagging (500GeV)



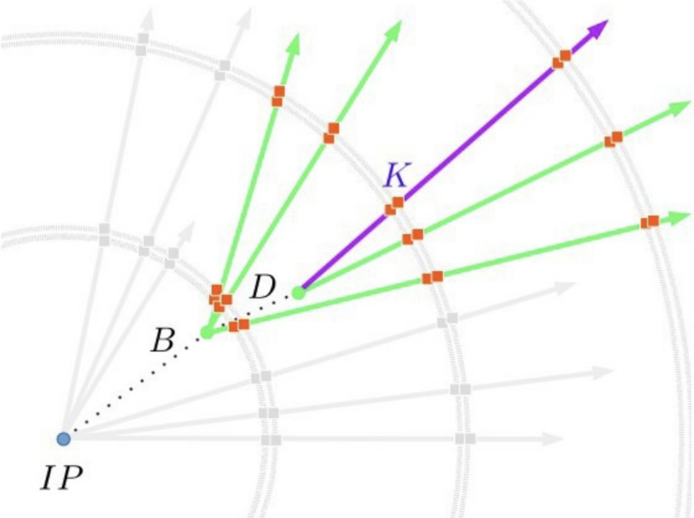


Jet charge

- 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



Irles A.,

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

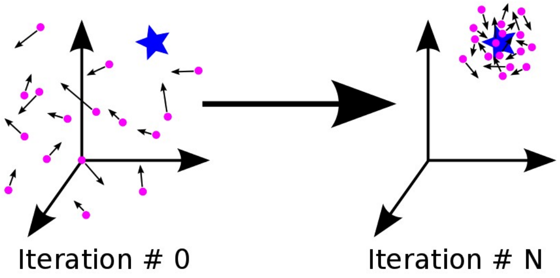
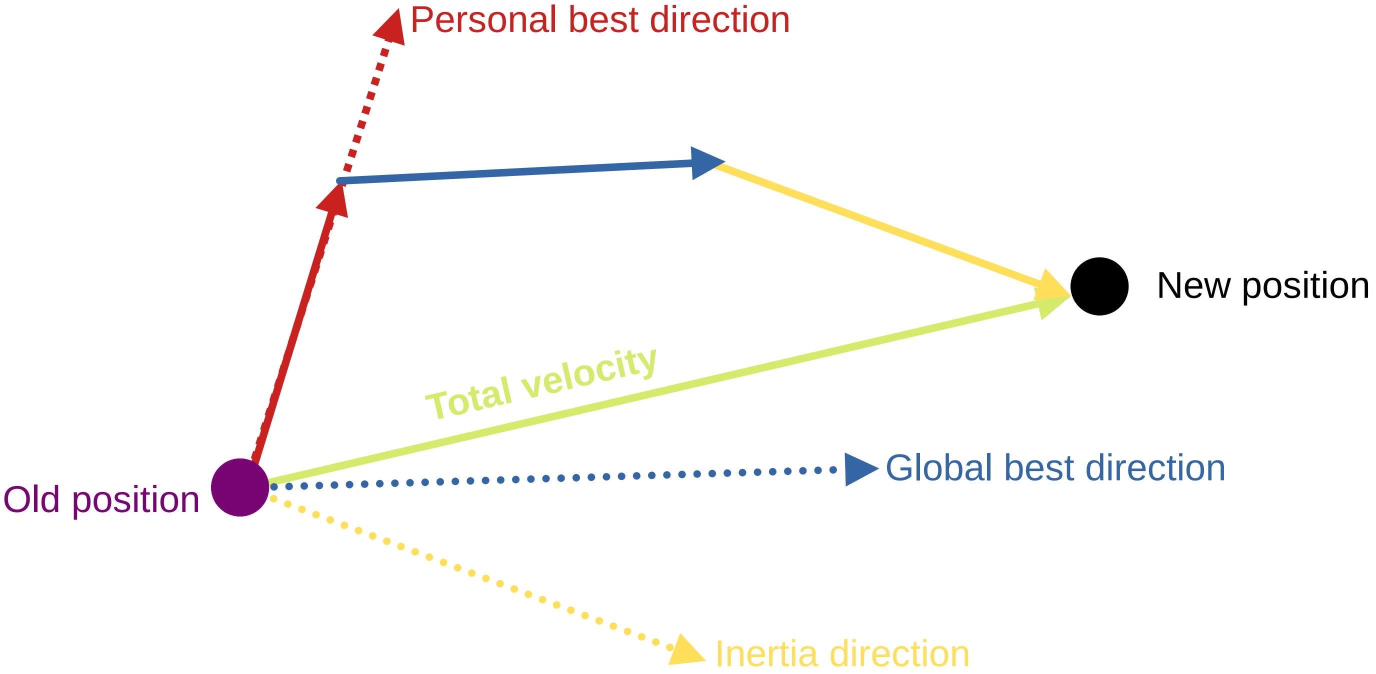


Image taken from a website

PSO - Overview

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

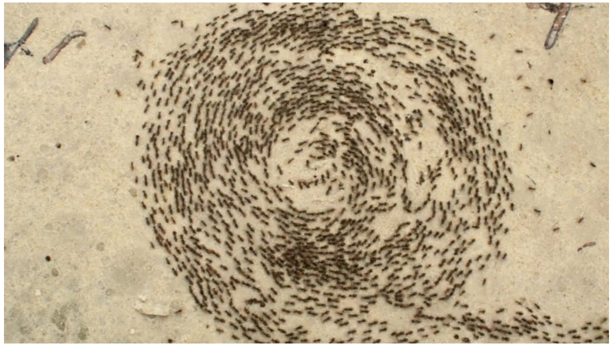
Velocity: $\overrightarrow{V_i^{t+1}} = w\overrightarrow{V_i^t} + c_1 r_1 \left(\overrightarrow{P_i^t} - \overrightarrow{X_i^t}\right) + c_2 r_2 \left(\overrightarrow{G^t} - \overrightarrow{X_i^t}\right)$



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!

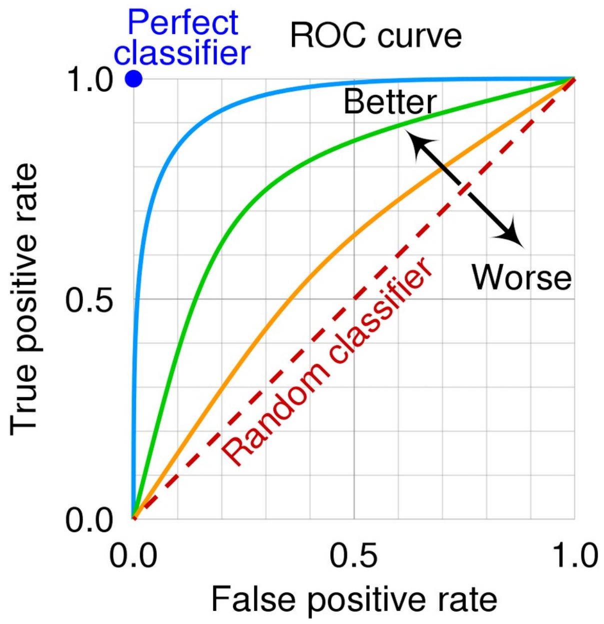
PSO – Function Of Merit (FOM)

- 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:

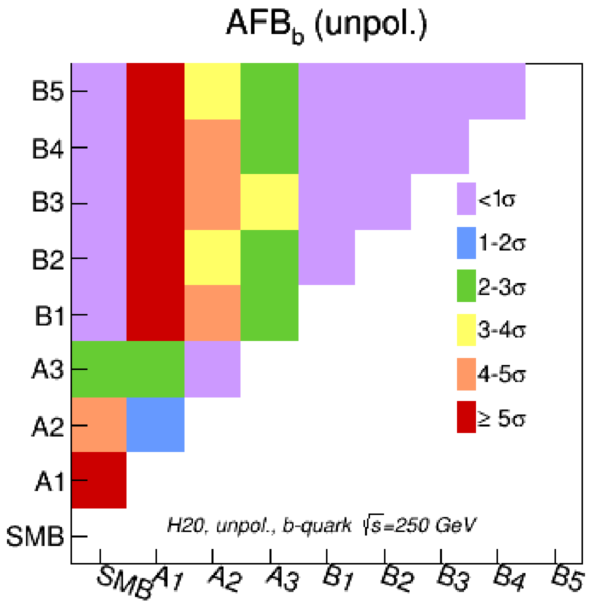
  FOM = (AUC[b_{quark}] + AUC[c_{quark}] + AUC[uds_{quarks}]) / 3,

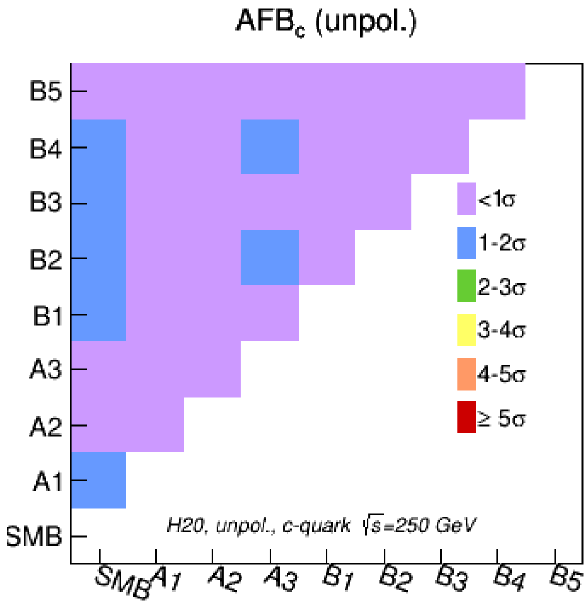
  where AUC = "Area Under Curve" (ROC Integral).

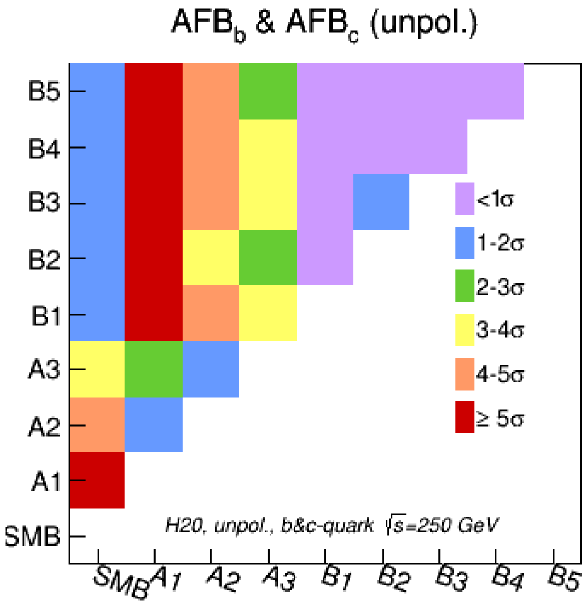


FCC-ee comparison (250 GeV)

A_{FB} at 250 GeV (FCC-ee comparison)

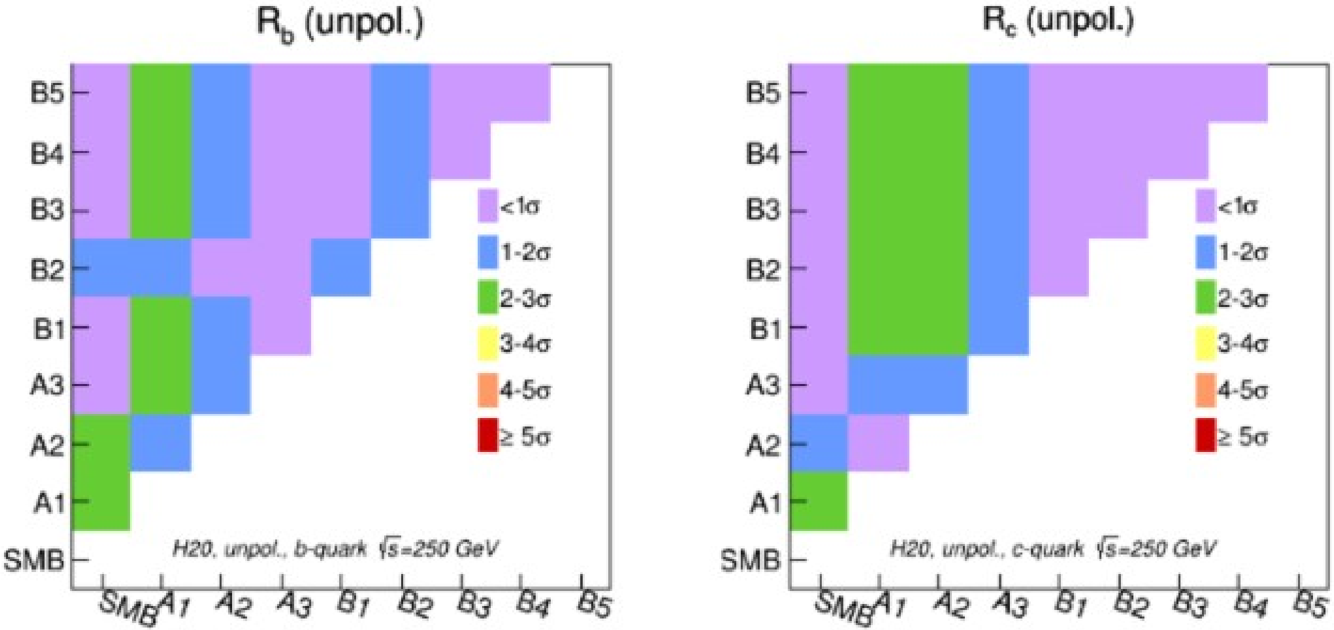






Luminosity scaled to the FCC-ee prospects.
Taking the same systematic errors that our Left-Handed case

R_q at 250 GeV (FCC-ee comparison)



Luminosity scaled to the FCC-ee prospects.
Taking the same systematic errors that our Left-Handed case