BSM physics at the International Linear Collider

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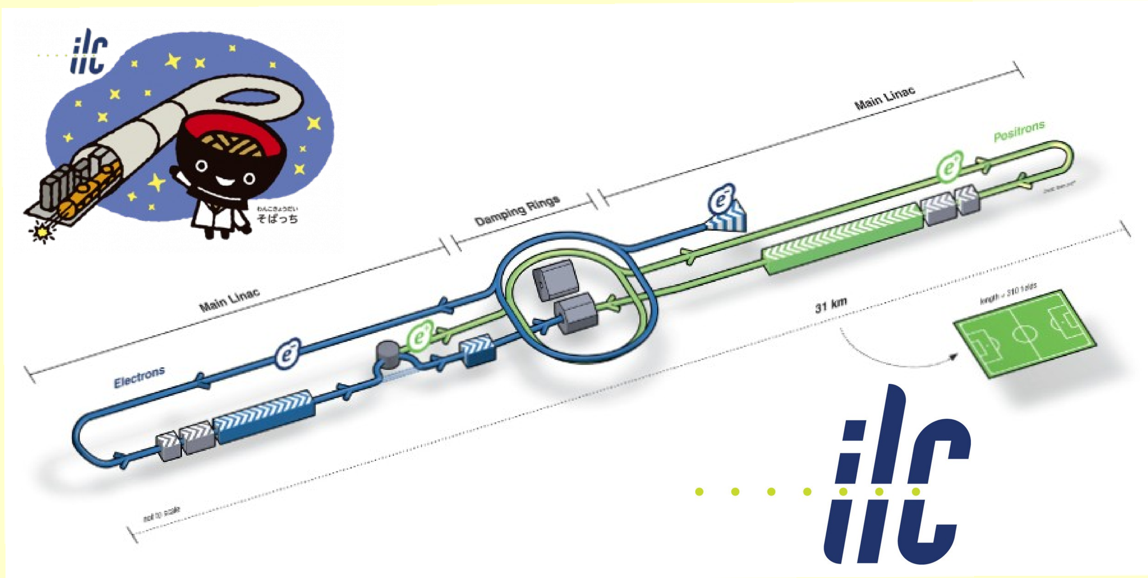
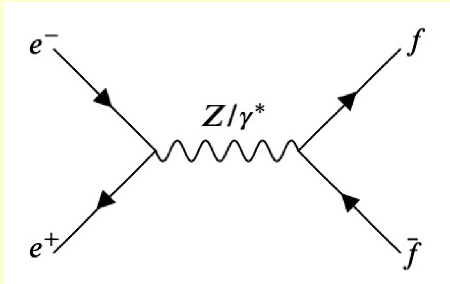
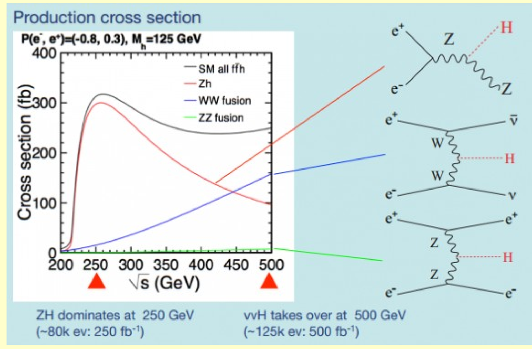
The International Linear Collider (ILC) & International Large Detector (ILD)



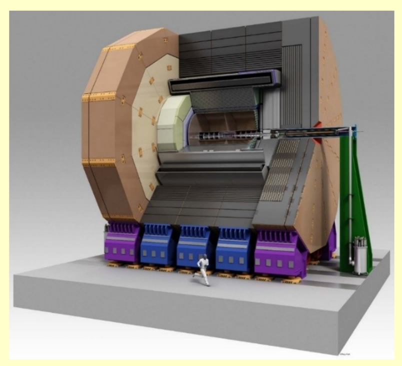
Higgs and ff̄ factory: e^-e^+ collisions at **91.2 GeV (Z-Pole), 250 GeV, 500 GeV and 1 TeV.** Both beams (e^+, e^-) are polarized (80% e^-, 30% e^+). Beam polarization enables the inspection of the chiral structure of nature (left/right helicities).



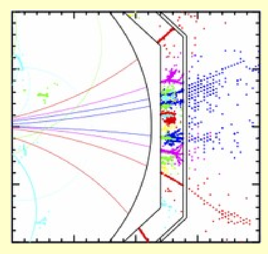
Access to **ALL fermions**



ILD: Optimized for **Particle Flow Concept,** i.e., single particle reconstruction.



It features excellent tracking, vertexing and IP constraining capabilities with minimal material budget.



Finely-grained, compact and hermetic calorimetry systems

Gauge-Higgs Unification Model (GHU)

In GHU the Higgs boson is the zeroth mode of the fifth dimensional component of a gauge potential in the bulk of a Randall-Sundrum warped space. In such case, the gauge group, in 5 dimensions, is $SU(3)_C \times SO(5) \times U(1)_X$. Once the orbifold boundary conditions and vacuum expectation value (VEV) are set, the masses of fermions are produced through the Hosotani mechanism and the resulting phenomenology is very close to the SM.

Gauge symmetry breaking pattern:

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

Different models, same set-up:

- A-Models (A1,A2,A3) [1]:
  - Quark-leptons multiplets in the vector part of SO(5).
  - **Stronger couplings** to the Z' bosons for **right-handed fermions**.
- B-Models (B,BL,BR,B+,B-) [2]:
  - Quark-leptons multiplets in the vector part of SO(5).
  - **Stronger couplings** to the Z' bosons for **left-handed fermions**.
  - Can be embedded in SO(11) Grand Unification Theory (GUT).
- Differences between models are given by different warping factors, mixing angles, Aharonov-Bohm 5D phase, KK-masses and mixing angles.

[1] S. Funatsu, H. Hatanaka, Y. Hosotani and Y. Orikasa, arXiv:1705.05282
[2] S. Funatsu, H. Hatanaka, Y. Hosotani, Y. Orikasa and N. Yamatsu, arXiv:2006.02157v3

The $e^+e^- \rightarrow f\bar{f}$ process:

Differential Cross-Section:

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{4}\left[(1-P_{e^-})(1+P_{e^+})\frac{d\sigma_{LR}}{d\cos\theta} + (1+P_{e^-})(1-P_{e^+})\frac{d\sigma_{RL}}{d\cos\theta}\right]$$

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

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

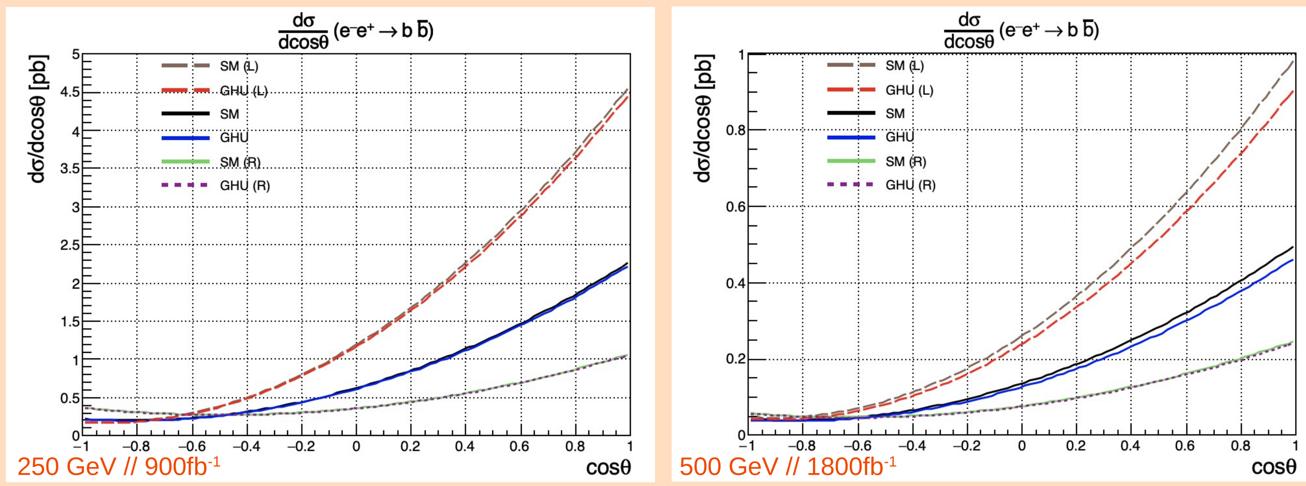
- GHU features an extra neutral boson Z_R and KK-resonances (Z' & γ') of the SM neutral bosons (Z & γ); in the TeV scale and above.
- There are helicity-dependent couplings (gL/gR) that appear in the $Q_{e_X e_Y}$ coefficients (helicity amplitudes).
- Beam polarisation (P_{e-},P_{e+}) allows inspection of the 4 different helicity amplitudes.
- A-Models generally have bigger deviations than B-Models.

Forward-Backward Asymmetry:

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

- It's a normalised quantity, which reduces bias from systematic errors.

Example of deviations from the standard model (Model B):



Signal preselection and quark-tagging

QCD analysis at ILC ($e^+e^- \rightarrow q\bar{q}$) :

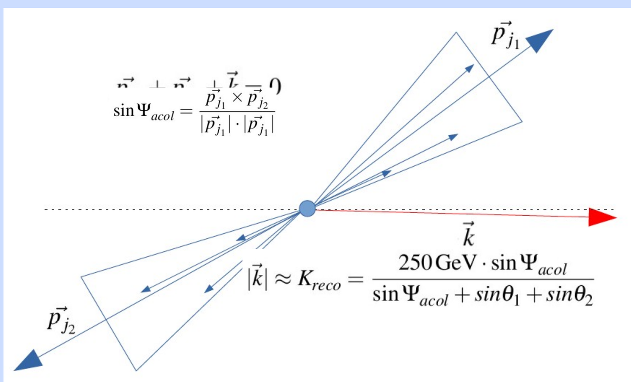
The data is first **simulated and reconstructed** with ILD modelling and then a **high level reconstruction** is performed, all using specific software (**ILCSoft**). In this case, we study **EW couplings** focusing on **b-quark full-simulated ILC data**:

Monte-Carlo events + Detector geometry + PFOs reconstruction **+** Jet reconstruction + Flavour tagging + Particle ID & vertexing → **Data analysis**

Signal preselection (for all quark flavours) :

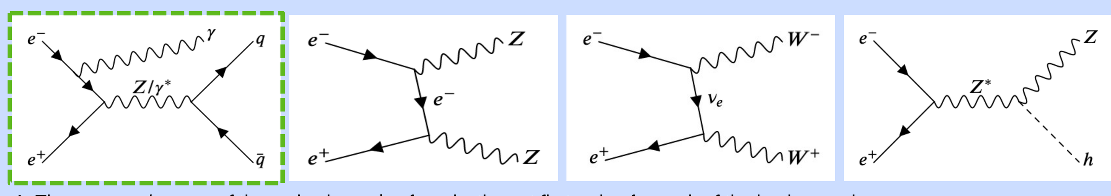
We need an homogeneous efficiency in the volume of the detector and minimal flavour dependance, to avoid modelling uncertainties. We reconstruct the events by using the **Valencia algorithm**:

- The algorithm packs together the PFOs into two jets.
  - Signal is expected in a back-to-back topology (but not the backgrounds!).
- Most of the background is **radiative return (γqq̄)**.
  - And most of the data is background! (x3 for $e^-_L e^+_R$ and x6 for $e^-_R e^+_L$).



Topology of an event with two jets and radiative return and definition of K_{reco}

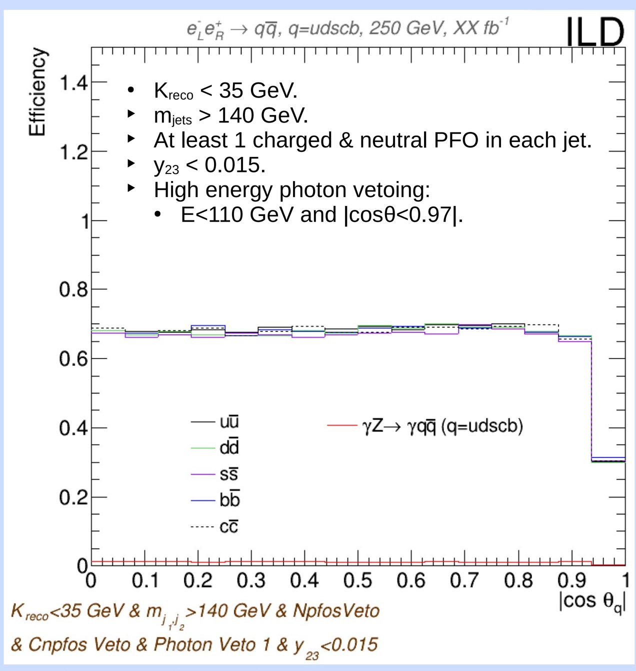
Event preselection remove signals₁ from:



1: These are *only some* of the main channels of production, at first order, for each of the background processes

Final selection of cuts applied to the data. In the right plot:

- K_{reco}: momentum associated to an expected photon collinear to the beam pipes.
- m_{jets}: sum of the masses of both jets.
- y_{23}: distance at which our algorithm would reconstruct the 2 jet system as a 3 jet system.
- **High energy photon vetoing**: We cluster together the PFOs identified as photons *inside the jets* and veto these events.



Preselection of all quark flavours and remaining radiative return

Optimisation of the jet reconstruction parameters:

The Valencia Algorithm features 3 parameters (R, β, γ) that we also optimised:

$$d_{ij} = 2\min(E_i^{2\beta}, E_j^{2\beta})(1-\cos\theta_{ij})/R^2$$

$$d_{iB} = E_i^{2\beta}\sin^{2\gamma}\theta_{iB}$$

R=1, γ=0, β=1

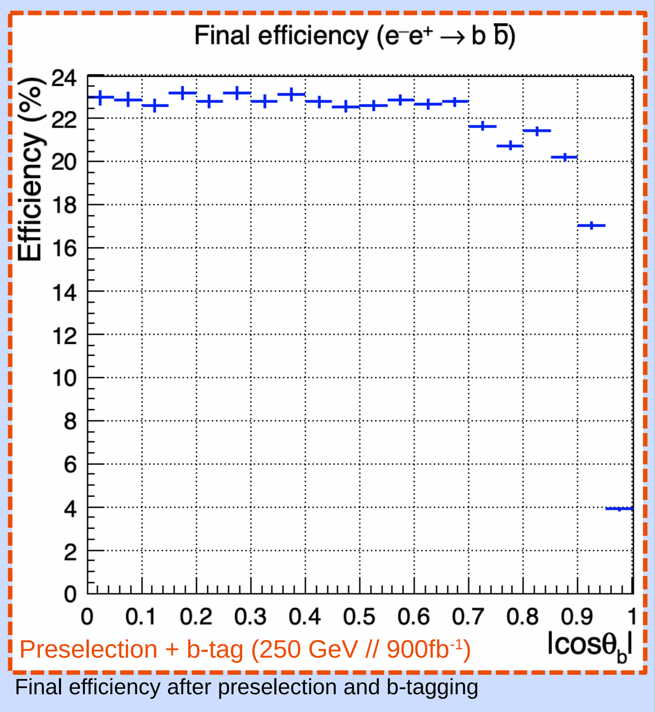
where d_{ij} is the inter-particle distance and d_{iB} the beam distance.

Quark tagging and jet charge measurements:

Dedicated tools for vertexing and flavour tagging: **LCFIPlus** (for lepton colliders). Around **80% efficiency and 99% purity for b quarks!**

LCFIPlus: High-purity secondary vertex finder + Jet-clustering algorithm + Multivariate jet flavour tagging

Charge measurement: Vtx charge and **Kaon Identification** + High efficiency (**Double tagging**) + High purity & control of migrations



Final efficiency after preselection and b-tagging

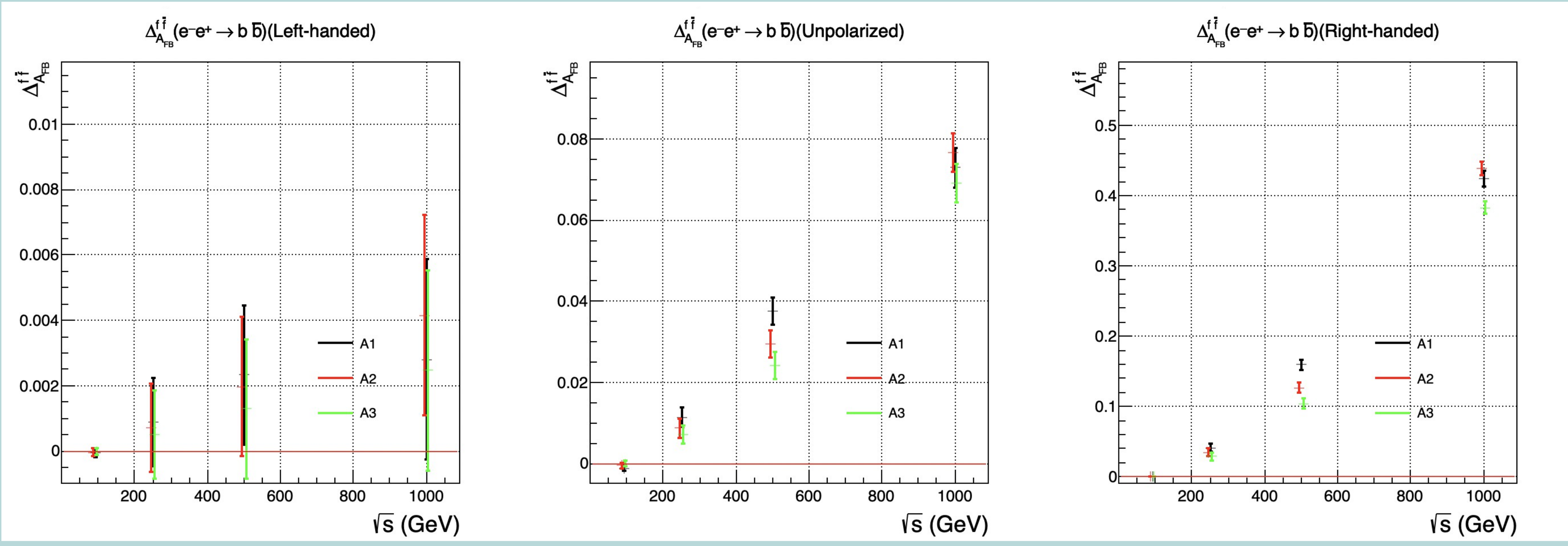
High purity selection of b-quarks events with a very homogeneous efficiency in most of the detector (~21-23%) but a loss of efficiency in the very forward & backward regions (~10%) is inevitable.

Experimental prospects for GHU

A-Models:

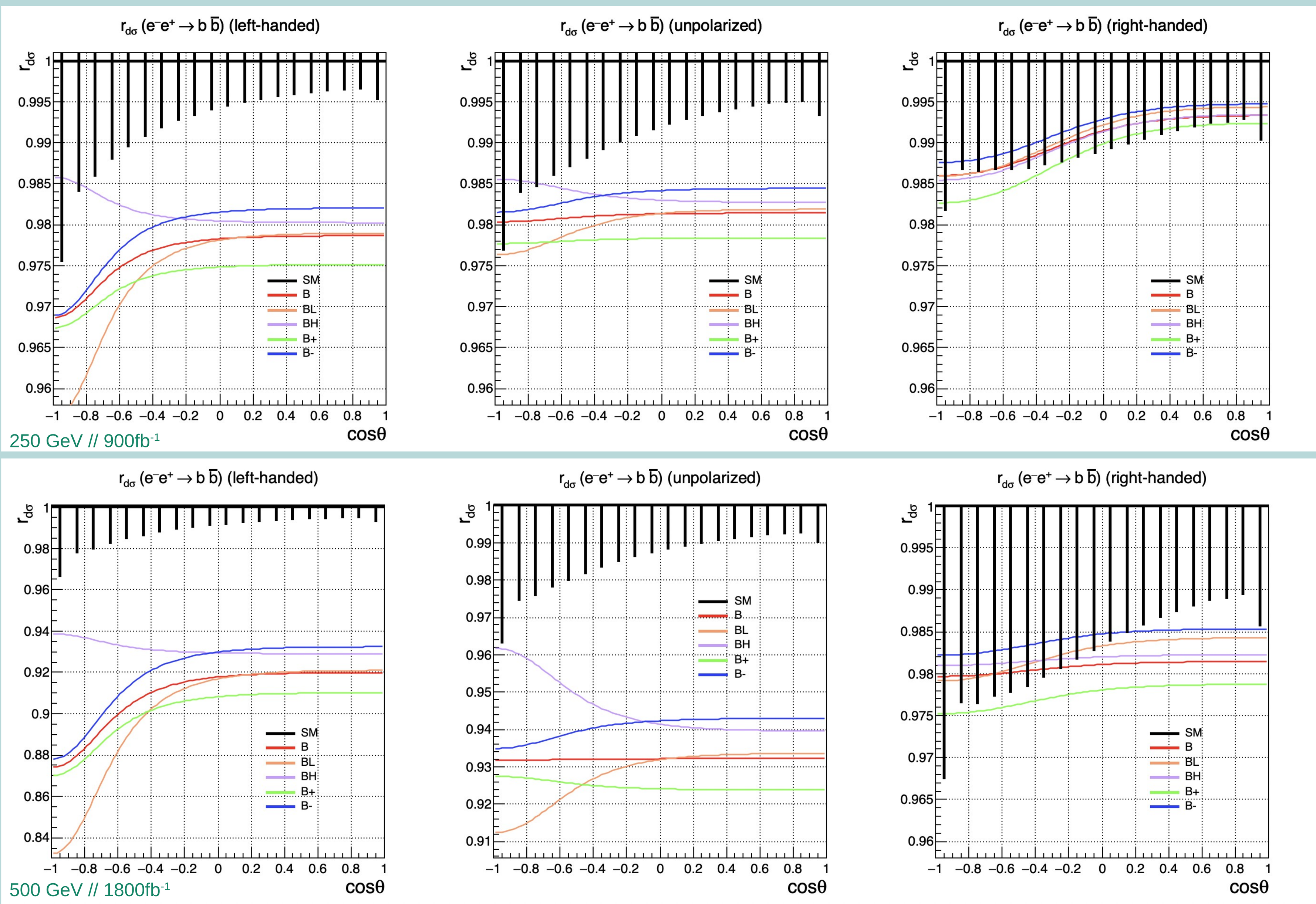
The A-Models are more sensitive to deviations for unpolarised and right-handed beams, i.e. (P_{e-},P_{e+})=(0.8,-0.3), by studying the deviation on A_{FB} (Δ_{AFB}) at energies around **250 GeV₁** and above:

$$\Delta^{f\bar{f}}_{A_{FB}} \equiv \frac{A^{f\bar{f}}_{FB,\rm GHU}}{A^{f\bar{f}}_{FB,\rm SM}} - 1$$



B-Models:

The B-Models show larger deviation w.r.t. SM for beams with left-handed polarisation (P_{e-},P_{e+})=(-0.8,0.3). The next two rows show the ratio between the **differential cross-section** of the B-Models and SM at **250 and 500 GeV₂** for the three different beam polarisation set-ups. The error bars are the statistical error for SM signals according to the b-quark signal selection:



1,2: Assuming the same efficiency for b-quark at different energies than the one obtained at 250 GeV

On-going work:

- Exploring other observables to study these models.
- Estimation of systematic errors.
- New precision efficiencies will be obtained by a similar data analysis once new simulated data became available:
  - **B-quark at 500 GeV.**
  - **C-quark at 250 GeV and 500 GeV.**

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