Higgs and Light Quark Studies at the ILC

Higgs Hunting 2023
13/09/2023

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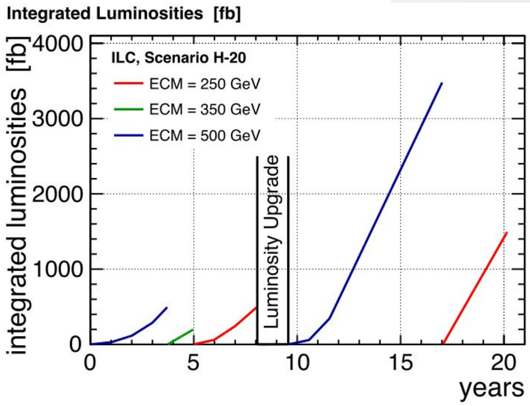
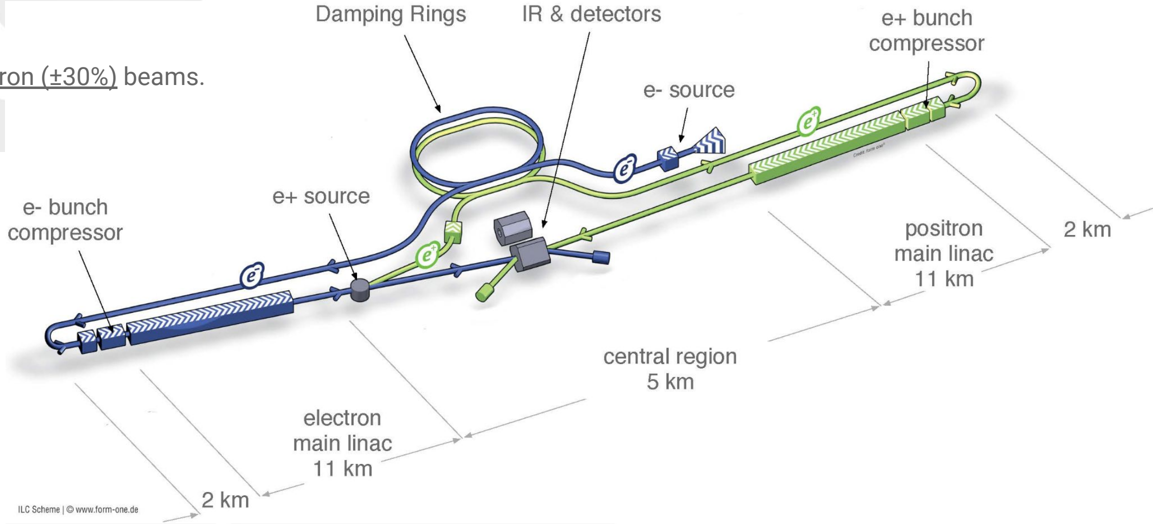
On behalf of IDT-WG3

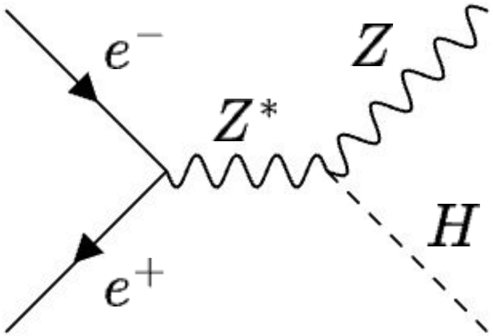
- **e$^+$e$^-$ linear collider**
- Well defined initial state, best suited for precision measurements aimed for **BSM searches**.
- **Model independent** profiling of Higgs boson.
- Operates at **√s = 0.1 - 1 TeV**
- **Enables the polarization** of electron (±80%) and positron (±30%) beams.

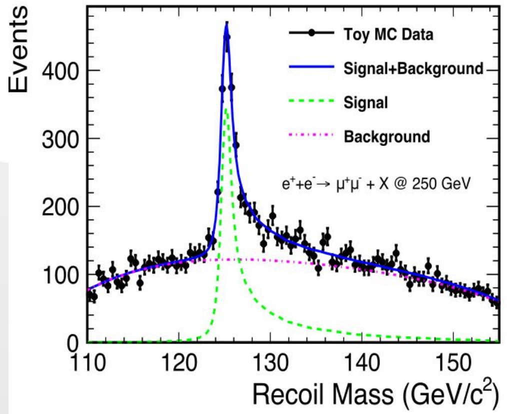




Physics at the International Linear Collider

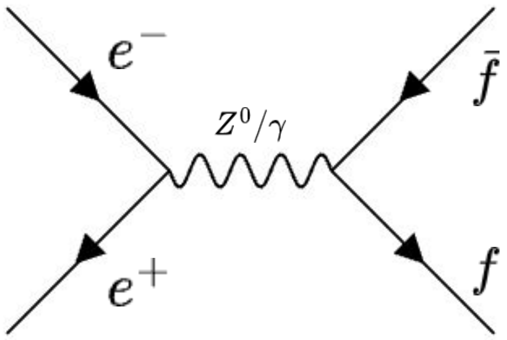
- One of the primary objectives at the ILC is Higgs production. (*Higgs Factory*)
- Important thresholds
  - ZH Higgs Strahlung ($\sqrt{s}$ = 250 GeV)
  - ZHH, tHH production ($\sqrt{s}$ = 500 GeV)
- Both **left- and right-handed** electrons and positrons beam polarization will be used to measure the cross section.
- Higgs Couplings at or well better that **1% level** in global EFT fits





Physics Beyond Standard Model

- **Z-pole** experiments at **LEP/SLC**
  → Unable to access Z/γ interferences
- Measurements of coupling between Z and fermion pair can be used as an observable to exploit BSM physics.
  - E.g. Gauge-Higgs Unification (1811.07877)
- Large angular acceptance, quark tagging and charge measurements facilitate the precise measurement of the coupling (compared to LEP/SLC)



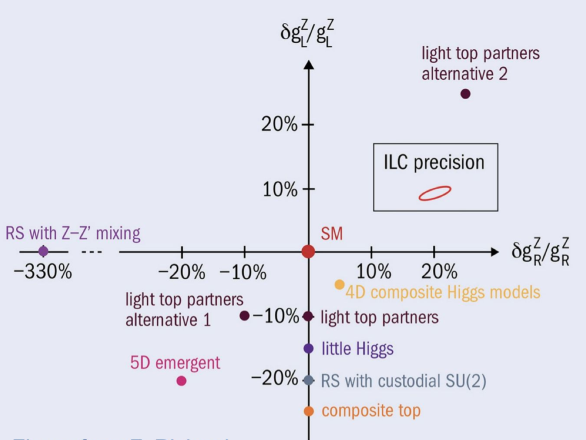
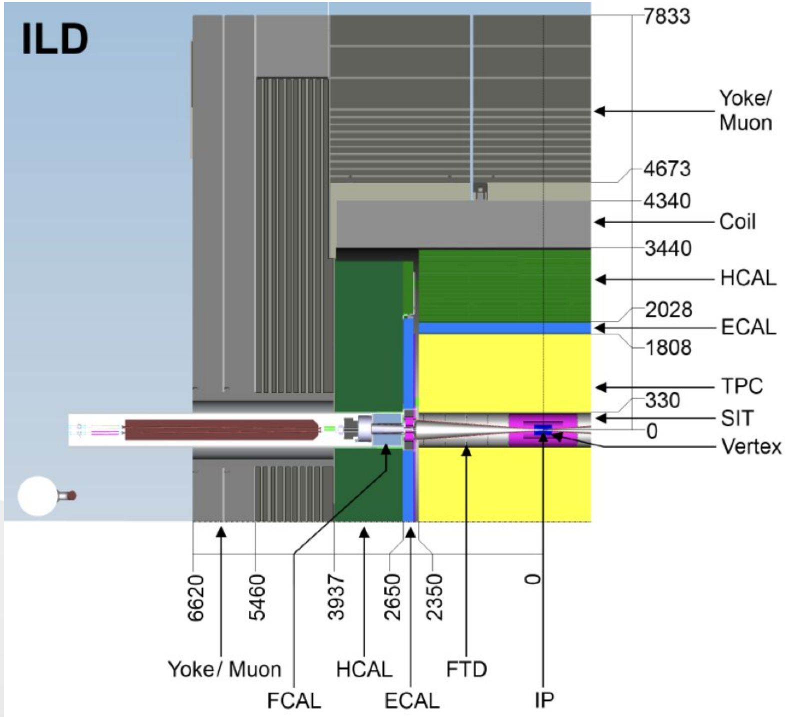


Figure from F. Richard

International Large Detector (ILD)

- Multi-purpose 4π detector designed for the ILC.
- Composed of multiple sub-detectors:
    - **Vertex Detector (VTX)**
        - b, c-tagging
    - **Time Projection Chamber (TPC)**
        - dE/dx measurements
    - Electromagnetic Calorimeter (ECAL)
    - Hadronic Calorimeter (HCAL)
    - Muon Yoke
- Optimized for the application of **Particle Flow Algorithm (PFA)**



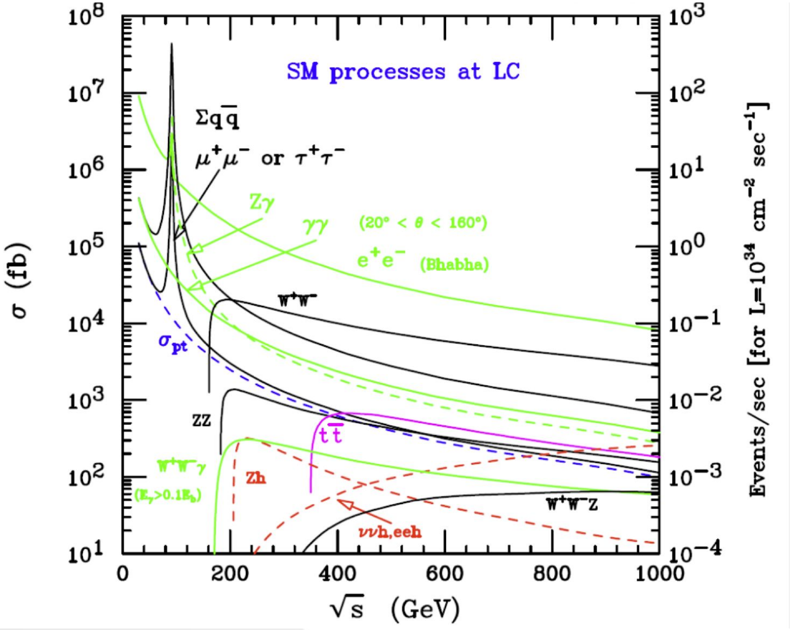
Fermion Pair Production

- **Di-fermion production**
  - $e^+e^- \rightarrow qq$
  - CME 250 GeV.
  - Int. Lumi. 4300 fb^{-1}
- **Differential Cross Section**
  - Couplings can be extracted from helicity amplitudes included within the Differential Cross section

$$\frac{d\sigma}{d\cos\theta} = S(1+\cos^2\theta) + A\cos\theta$$

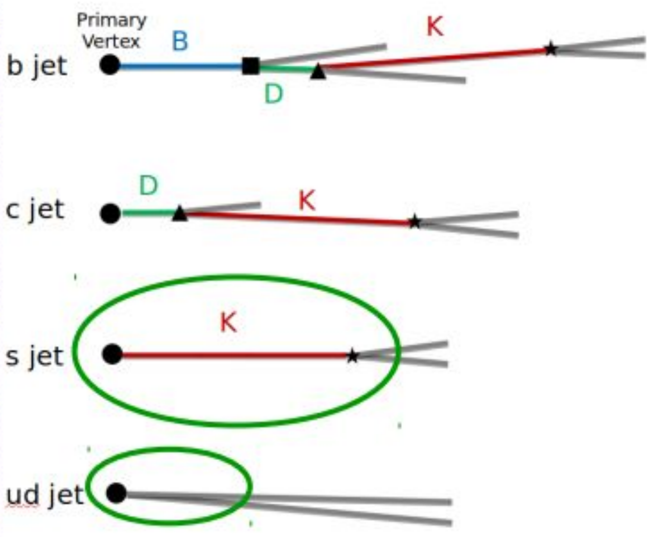
  - Extracted via forward-backward asymmetry. (AFB)

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



QQbar Production

- **Particle Identification** plays a key role in precise cross section measurement.
- Mis-identification of particles will result in mis-identification of charge, which will be the source of **migration** and **mis-measurements**.
- Each process produces jets with unique characteristics:
    - **bb**: b-jets with high b-tag, based on various jet and vertex parameters. Mostly from SV.
    - **cc**: c-jets with high c-tag.
    - **ss**: Jets with kaons which carry predominant energy and momentum.
    - **uu,dd**: Jet with mixture of pions and kaons.



Taken from Slide 5 of Tomohiko Tanabe's 2020/11/24 presentation.

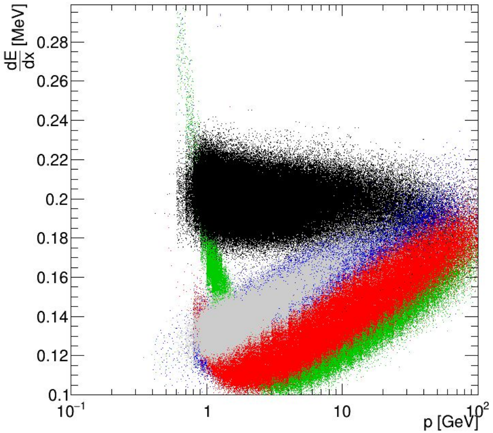
M.Basso 2021

dE/dx Particle Identification

- TPC provides information on average dE/dx values for each track.
- Bethe-Bloch formula tells each particle type has unique dE/dx vs p function.

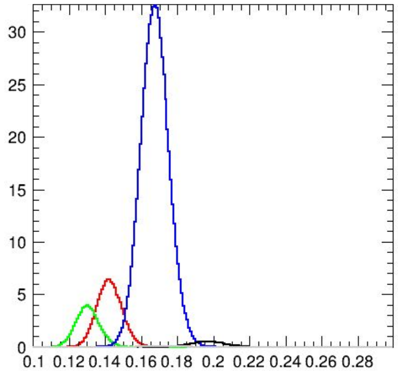
Leading PFO

- uu & dd hadronize into pions or kaons.
- Those hadrons will possess high momentum among jet constituents
- The PFO with the highest momentum in a jet is called the Leading PFO (LPFO)



dE/dx vs. p
Each color represent different types of particles.

Red:	Kaon
Blue:	Pion
Green:	Proton
Gray:	Muon
Black:	Electron



p = 10.0 - 11.5 GeV

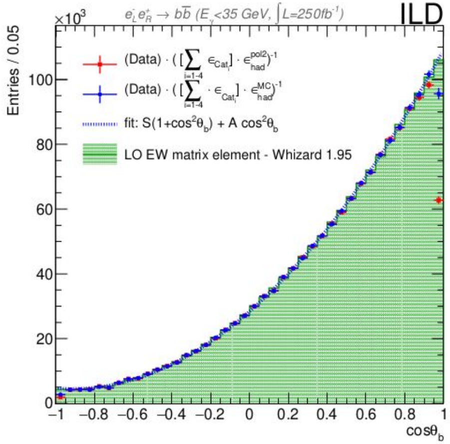
dE/dx projection of above plot for momentum between 10 - 11.5 GeV.

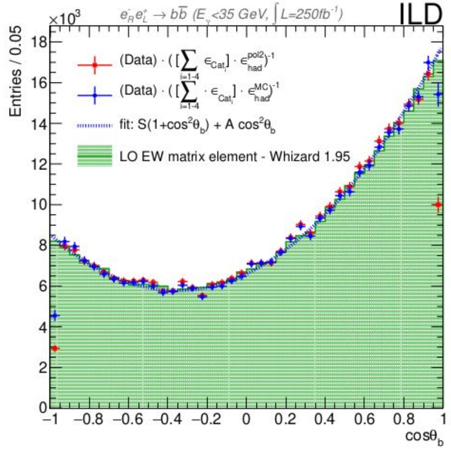
Heavy Quark Polar Angles

bb result (2306.11413)

- The plot shows the polar angle distributions for different beam polarization
  - Top: (e-,e+) = (-0.8, +0.3)
  - Bottom: (e-,e+) = (+0.8, -0.3)
- Data is shown for the cases before and after the acceptance correction, due to the detector coverage.
- Parton level curve (green) has excellent agreement with the reconstructed distribution (blue)
- Fit is restricted to the |cosθ| < 0.8 region

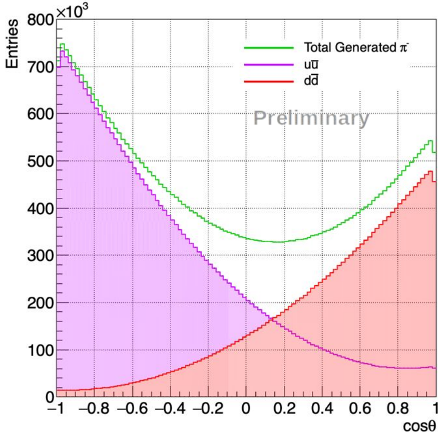
Recent tt (1505.06020) and cc (2306.11413) analysis also showed results with great agreement with the parton level.

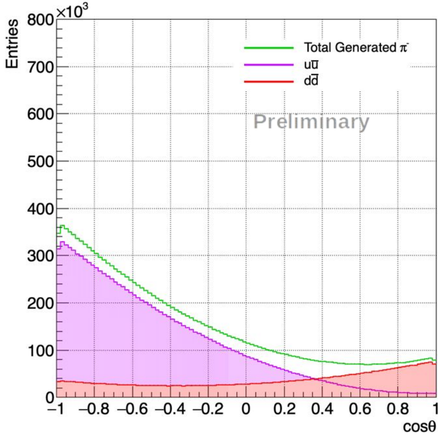




uu & dd distribution

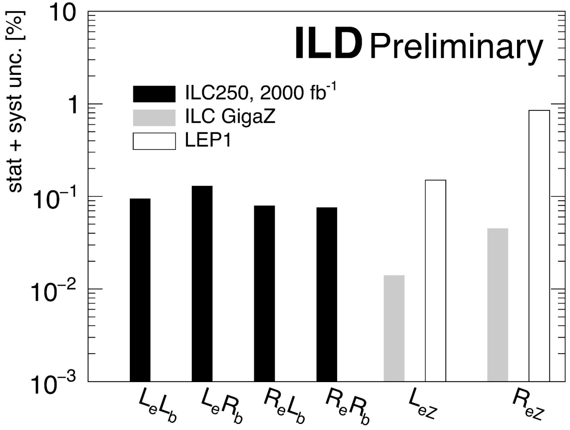
- The plot shows the polar angle distributions at the parton level for different beam polarization
  - Top: (e-,e+) = (-1.0, +1.0)
  - Bottom: (e-,e+) = (+1.0, -1.0)
- The uu and dd creates interference between the two processes which makes it difficult to separate from one another.
- The recent result has shown that the reconstruction of uu and dd process can be achieved with high precision
  - The result is currently being scrutinized by the ILD group for the quality check.





EW coupling and form factor precision

- Uncertainties for the couplings at $e^+e^- \rightarrow bb$ are presented.
- All couplings are an order of magnitude better than at LEP.
- Only **polarized beam** and **well defined initial states** can realize the precision measurements of the couplings.
  - Full disengagement of the helicity structure



$$\mathrm{LeLb} = QeQb + \frac{LeZLbZ}{s^2wc^2w}BWZ + \sum_{Z'} \frac{LeZ'LbZ'}{s^2wc^2w}BWZ'$$

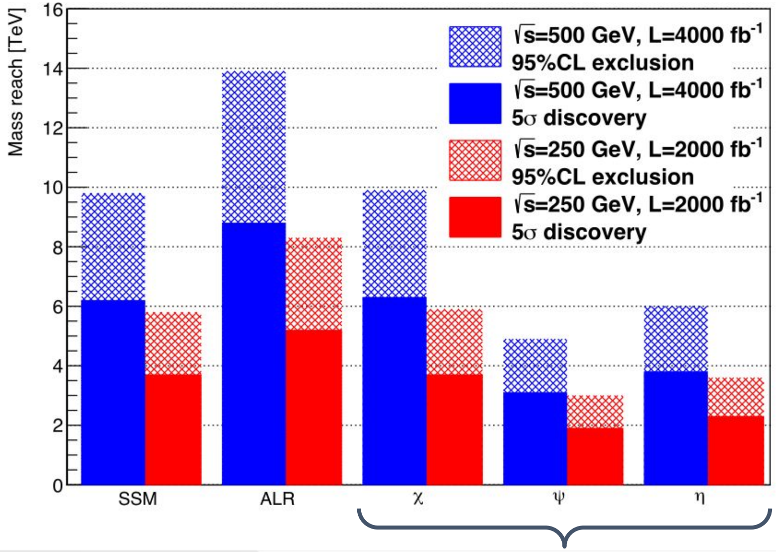
ILC250 SM GigaZ New resonances

Z' discovery reach

- SUSY expects supersymmetry preserving parameter μ naively in the order of Planck scale, while phenomenology requires it to be weak scale.
- U'(1) breaking allows MSSM parameter range to be extended
- Appearance of $M_{Z'}$ is expected in TeV scale if supersymmetry scale is there.
- $e^+e^- \rightarrow f\bar{f}$ can be used since the s-channel resonance could affect the cross sections.

Addition of quarks provides improvements to the limit.

e/μ/τ combined



χ/ψ/η appearing in GUT with coupling to the SM Z.

Summary

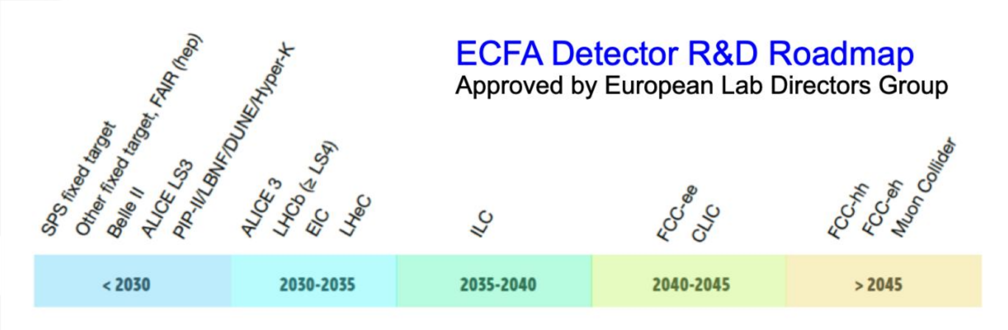
- $e^+e^- \to q\bar{q}$ analysis aimed to measure the **EW couplings between Z boson and fermion pairs**
  - Useful to probe SM/BSM, re-evaluation of LEP/SLC results etc.
  - BSM theories can lead this observable to **Higgs coupling measurement** (e.g. GHU model)
    Such indirect search requires precision in the original EW coupling as well.

- The high precision measurement is necessary for our analysis
  - ILC: Beam polarization, clean physical signatures,
  - ILD: Vertex detector, TPC
- Particle Identification is the KEY
  - Flavor tag & dE/dx measurements provides efficient and pure identification
- Precision measurements achieve for the coupling measurements surpasses the analysis at the LHC.
  - Systematic & Statistical uncertainty of **0.1% level**.
- Quark pair production can probe the Z' mass, which can lead to indirect searches for the Higgs coupling.

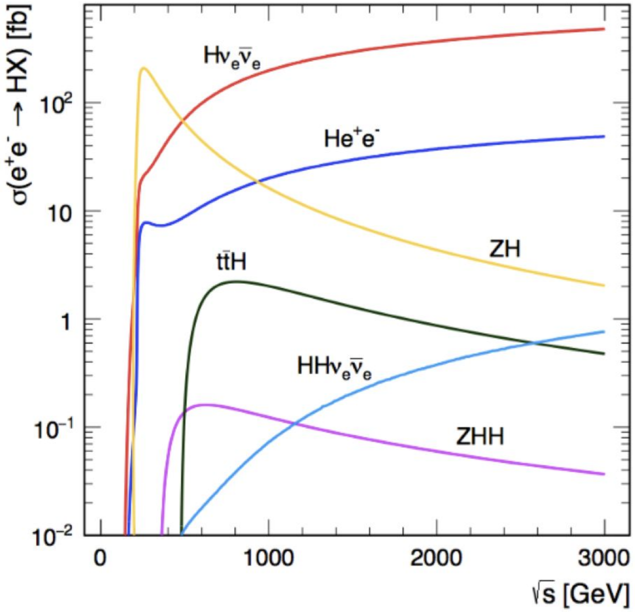
Backup

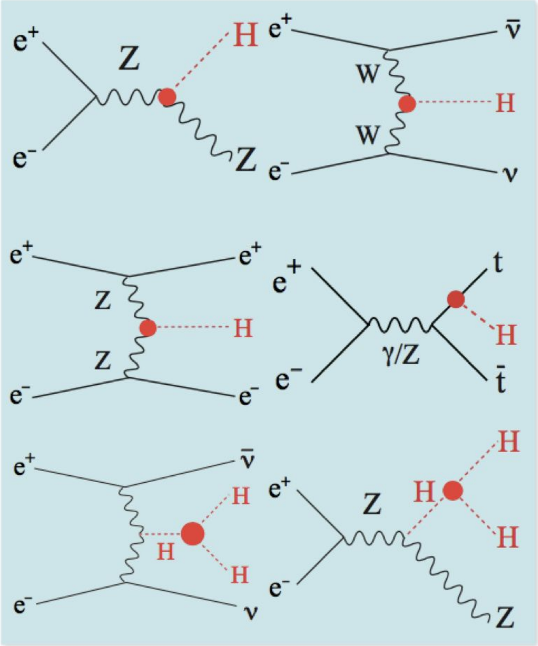
Snowmass EF-Vision (L. Reina)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1} /IP	Start Date Const.	Start Date Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2	2028	2038
		350 GeV	$\pm80/\pm30$	0.2		
		500 GeV	$\pm80/\pm30$	4		
		1 TeV	$\pm80/\pm20$	8		
CLIC	ee	380 GeV	$\pm80/0$	1	2041	2048
CEPC	ee	M_Z		50	2026	2035
		$2M_W$		3		
		240 GeV		10		
		360 GeV		0.5		
FCC-ee	ee	M_Z		75	2033	2048
		$2M_W$		5		
		240 GeV		2.5		
		$2\ M_{top}$		0.8		
μ-collider	$\mu\mu$	125 GeV		0.02		



- International roadmaps consider construction of a linear collider towards the end of this decade
- We may seek to combine the best of all (linear) worlds into a linear facility
  - Avoids entangling of a electron-positron collider and a hadron machine
- It would be the parallel running of a TeV hadron machine and a electron positron collider at the TeV scale that “maximises scientific output “





two important thresholds:
$\sqrt{s}$ ~ 250 GeV for ZH, ~500 GeV for ZHH and ttH

- In the Gauge-Higgs Unification (GHU) model, the Higgs boson is considered as part of the extra-dimensional component of gauge potentials, represented by the Aharonov-Bohm phase θ_H.
- The GHU model also features a Z' boson with a large coupling to the right-handed components of fermions.
- When θ_H is known, it determines the couplings of the Z' boson to fermions and the Higgs boson.

$$\frac{g_{HWW}^{GHU}}{g_{HWW}^{SM}}, \frac{g_{HZZ}^{GHU}}{g_{HZZ}^{SM}}, \frac{y_{f\bar{f}}^{GHU}}{y_{f\bar{f}}^{SM}} \simeq \cos\theta_H$$

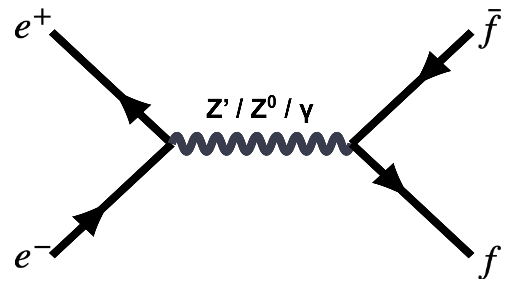
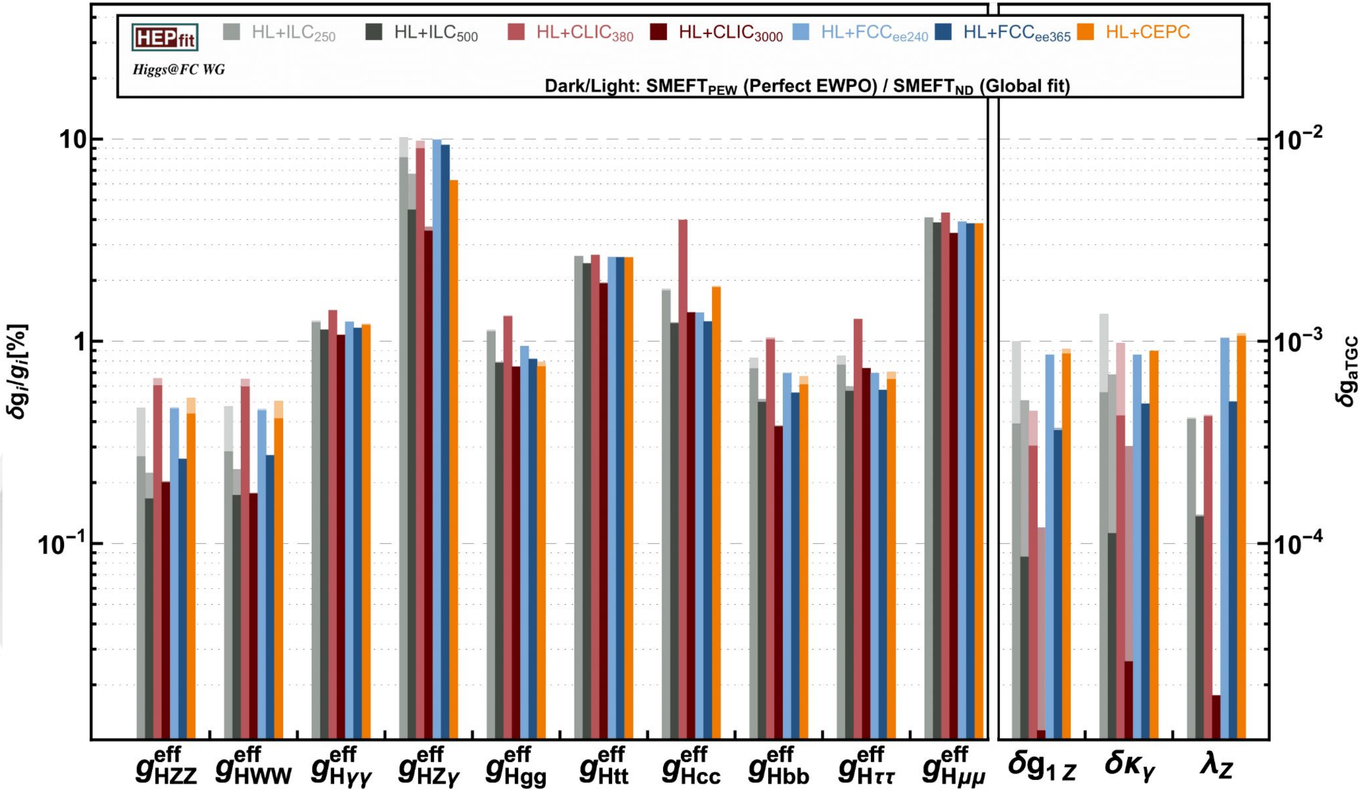


Table 2: Couplings of neutral vector bosons (Z' bosons) to fermions in unit of $g_w = e/\sin\theta_W$ for $\theta_H = 0.115$. Corresponding Z-boson coupling in the SM are $(g_{Z\nu}^L, g_{Z\nu}^R) = (0.57027, 0)$, $(g_{Ze}^L, g_{Ze}^R) = (-0.30651, 0.26376)$, $(g_{Zu}^L, g_{Zu}^R) = (0.39443, -0.17584)$ and $(g_{Zd}^L, g_{Zd}^R) = (-0.48235, 0.08792)$.

f	g_{Zf}^L	g_{Zf}^R	$g_{Z^{(1)}f}^L$	$g_{Z^{(1)}f}^R$	$g_{Z_R^{(1)}f}^L$	$g_{Z_R^{(1)}f}^R$	$g_{\gamma^{(1)}f}^L$	$g_{\gamma^{(1)}f}^R$
ν_e	0.57041	0	−0.1968	0	0	0	0	0
ν_μ	0.57041	0	−0.1968	0	0	0	0	0
ν_τ	0.57041	0	−0.1967	0	0	0	0	0
e	−0.30659	0.26392	0.1058	1.0924	0	−1.501	0.1667	−1.983
μ	−0.30659	0.26391	0.1058	1.0261	0	−1.420	0.1667	−1.863
τ	−0.30658	0.26391	0.1057	0.9732	0	−1.354	0.1666	−1.767
u	0.39453	−0.17594	−0.1361	−0.7152	0	0.9846	−0.1111	1.2983
c	0.39453	−0.17594	−0.1361	−0.6631	0	0.9205	−0.1111	1.2036
t	0.39339	−0.17712	0.5068	−0.4764	1.0314	0.6899	0.4158	0.8666
d	−0.48247	0.087972	0.1665	0.3576	0	−0.4923	0.05557	−0.6491
s	−0.48247	0.087970	0.1664	0.3315	0	−0.4602	0.05556	−0.6018
b	−0.48254	0.087964	−0.6303	0.2387	1.0292	−0.3446	−0.2082	−0.4331

EFT Framework

- Analysis in EFT Framework
- No clear winner among lepton colliders
- Polarisation at Linear Colliders compensates for higher integrated luminosity at Circular Machines



C-Quark Pair Production

- High efficient flavour tagging for c-quarks expected at future colliders
- **Charge measurement**
  - **Primary method**: identification of Kaons produced D-meson decays → K-method (requires PID)
  - **Secondary method**: reconstruction of charged mesons → VTX-method
- PID is mandatory to reach competitive accuracies

B-Quark Pair Production

- High efficient flavour tagging for b-quarks expected at future colliders
- **Charge measurement**
  - **Primary method**: Reconstruction of charged mesons → VTX-method
  - **Secondary method**: Identification of Kaons produced B-hadron decays → K-method (requires PID)

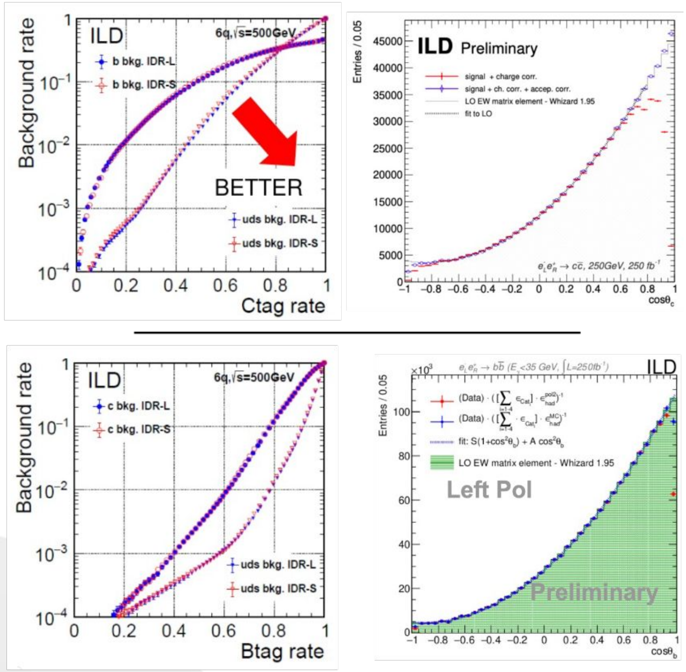
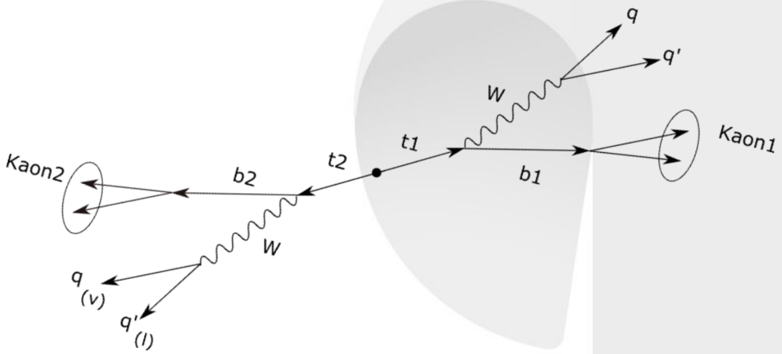


Figure 9: c and b background rate vs c and b tag rate (left) and reconstructed b and c polar angle for $e_L^- e_R^+$ polarization (right) [7]

T-Quark Pair Production

- Massive quark like top is focused with $\sqrt{s} = 500$ GeV for pair production
- Top quark charges are identified by using vertex charge, kaon charge and isolated lepton charge (in case of semi-leptonic and full-leptonic)
- One charge originated from one top is compared to the other charge coming from another top to see the consistency in two charges.



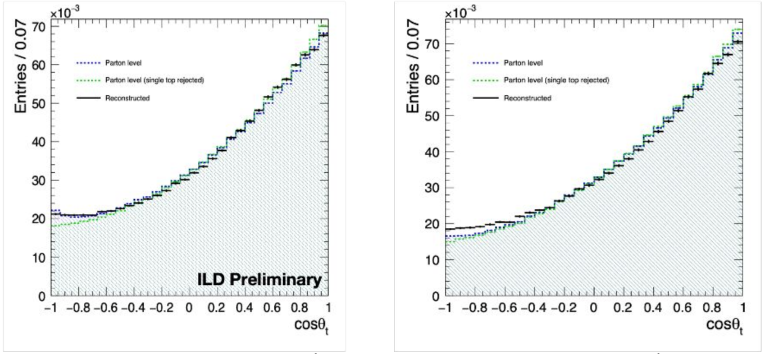


Figure 9: Polar angle distribution of $e^+e^- \to t\bar{t}$ semi-leptonic channel for $e_L^- e_R^+$ (left) and $e_R^- e_L^+$ (right) polarization.

	Final States	# of jets	B.R.
Full Leptonic	$t\bar{t} \to (b\ell\bar{\nu})(\bar{b}\bar{\ell}\nu)$	2 jets + 2 ℓ	10.5%
Semi Leptonic	$t\bar{t} \to (b\ell\bar{\nu})(\bar{b}q\bar{q}')$	4 jets + 1 ℓ	43.8%
Full Hadronic	$t\bar{t} \to (bq\bar{q}')(\bar{b}q\bar{q}')$	6 jets	45.7%