

Quark Production in High Energy Electron Positron Collisions From Strange to Top

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on behalf of the ILD collaboration

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Discoveries anticipated at e^+e^- colliders

- **Z'** resonance coupling to fermion pair.
- Many **BSM theories** (e.g. *Composite Top*, *Randall-Sundrum model*...) predict different models for each couplings.
- **ILC** can play a central role for the indirect searches of the new particle beyond the Standard Model predictions to distinguish them from the various other theories.

How is it done?

- Electroweak coupling between fermion pair and Z^0/γ boson

Key observables: $e^+e^- \rightarrow f\bar{f}$ cross section ($\sigma^{f\bar{f}}$)
Forward-backward Asymmetry (A_{FB})

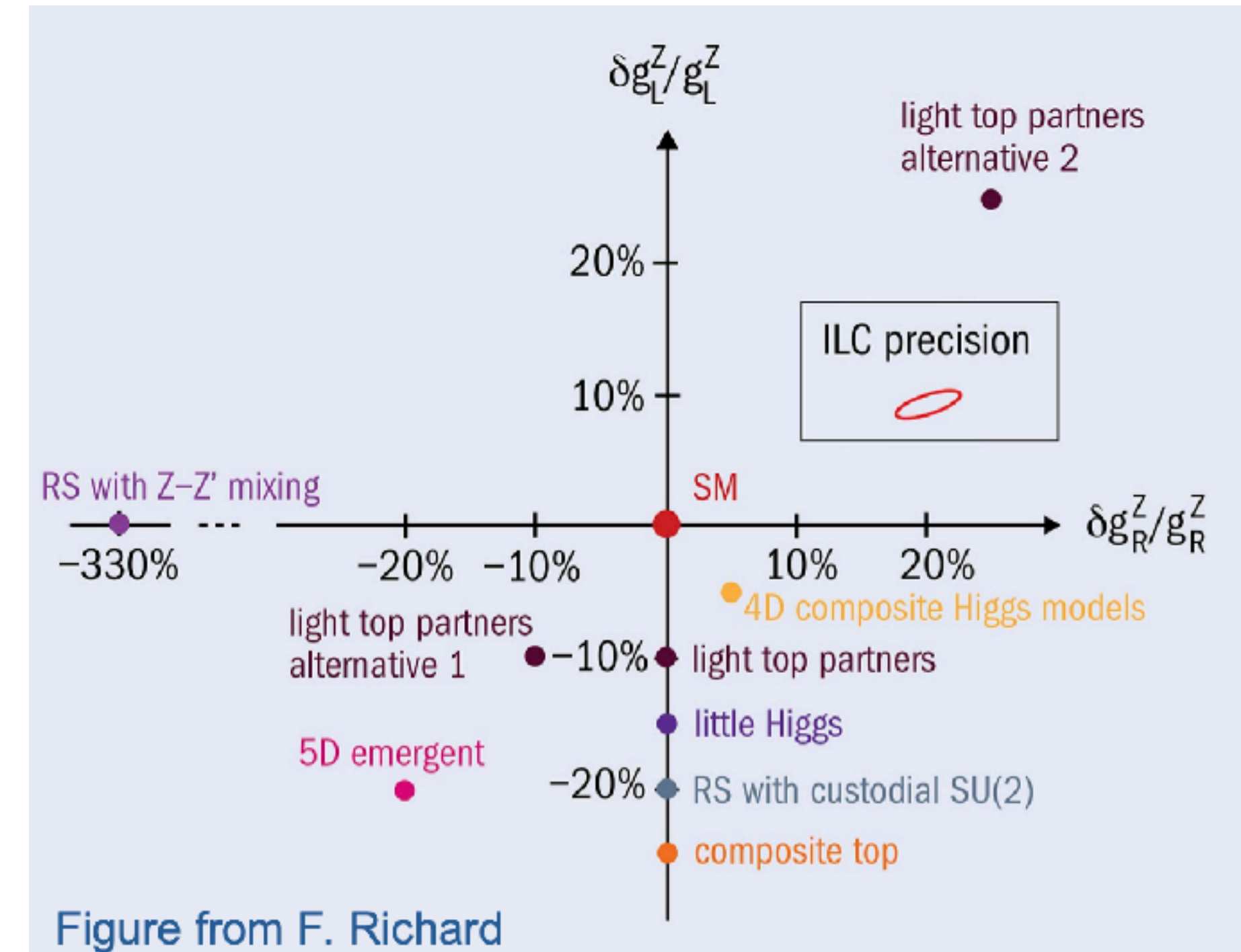


Figure 1: Predicted deviations of Z couplings to left and right handed top-quark [1]

Electroweak Couplings and Physical Observables

- Differential cross section

$$\frac{d\sigma_{ij}}{d\cos\theta}(\cos\theta) = \Sigma_{ij}(1 + \cos\theta)^2 + \Sigma_{ji}(1 - \cos\theta)^2$$

where helicity amplitude $\Sigma_{ij} \propto (g_R, g_L)$

$$A_{FB} = \frac{\overbrace{\sigma_F(\cos\theta_t > 0)}^{\text{forward}} - \overbrace{\sigma_B(\cos\theta_t < 0)}^{\text{backward}}}{\sigma_F(\cos\theta_t > 0) + \sigma_B(\cos\theta_t < 0)}$$

- Polarization** and **Particle ID** are the KEY!

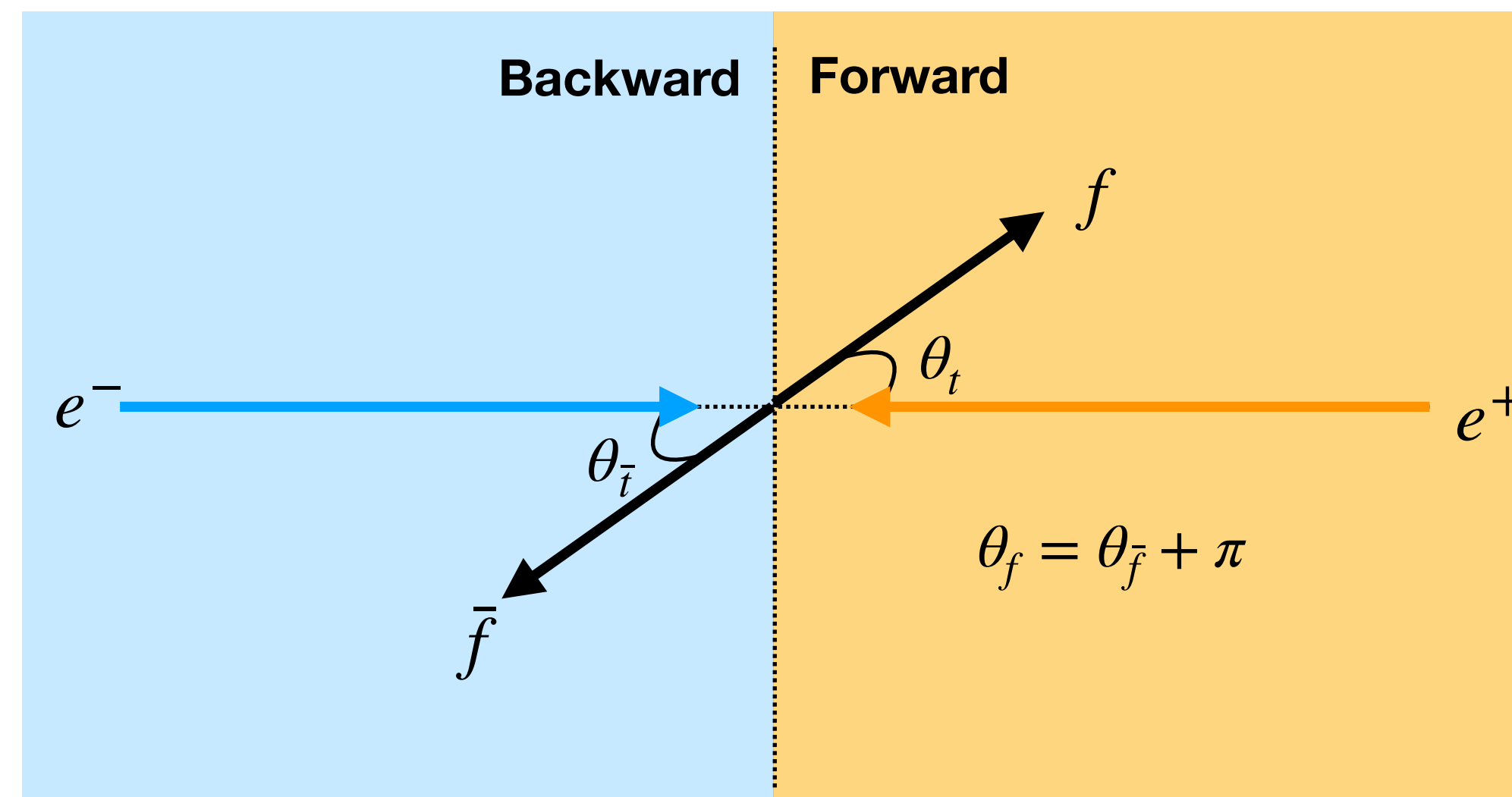
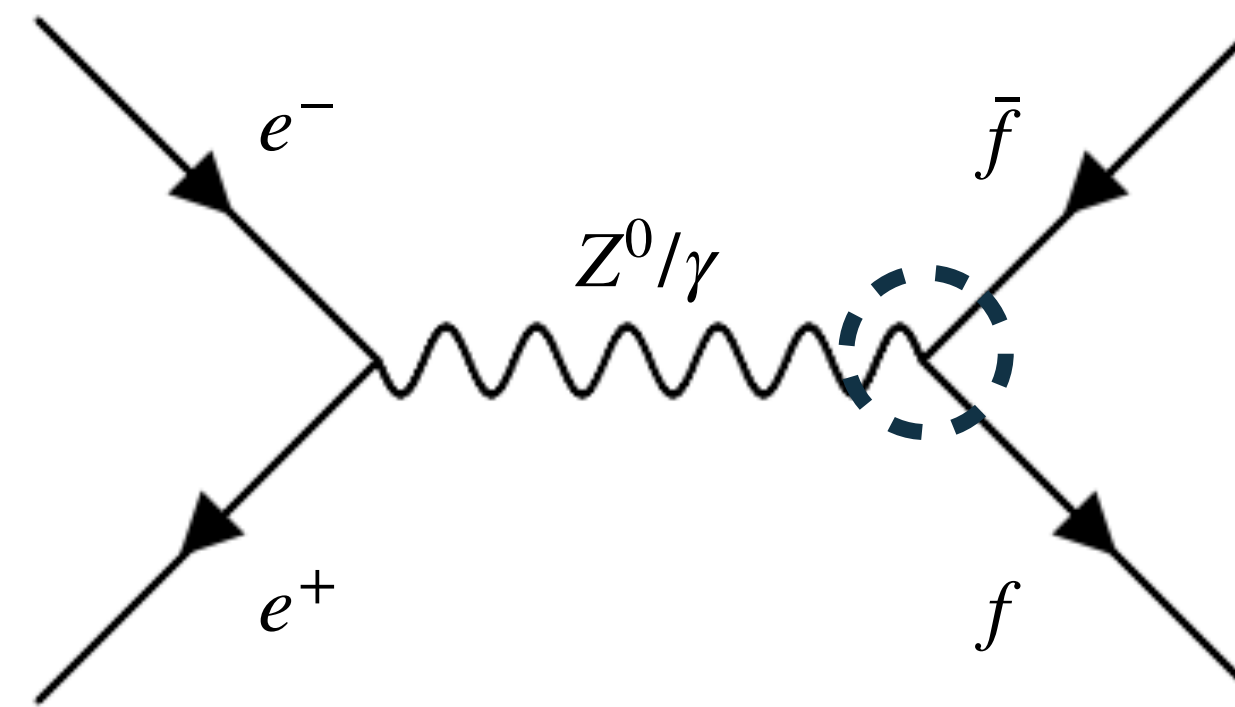


Figure 2: Feynman diagram of $e^+e^- \rightarrow f\bar{f}$ (top) and its kinematic representation in lab frame (bottom)

International Linear Collider (ILC)

- e^+e^- linear collider
- Background free, best suited for precision measurements aimed for **BSM searches**
- Operate at $\sqrt{s} = 250 \sim 500$ GeV
- **Enables the polarization** of Electron ($\pm 80\%$) and positron ($\mp 30\%$) beams.

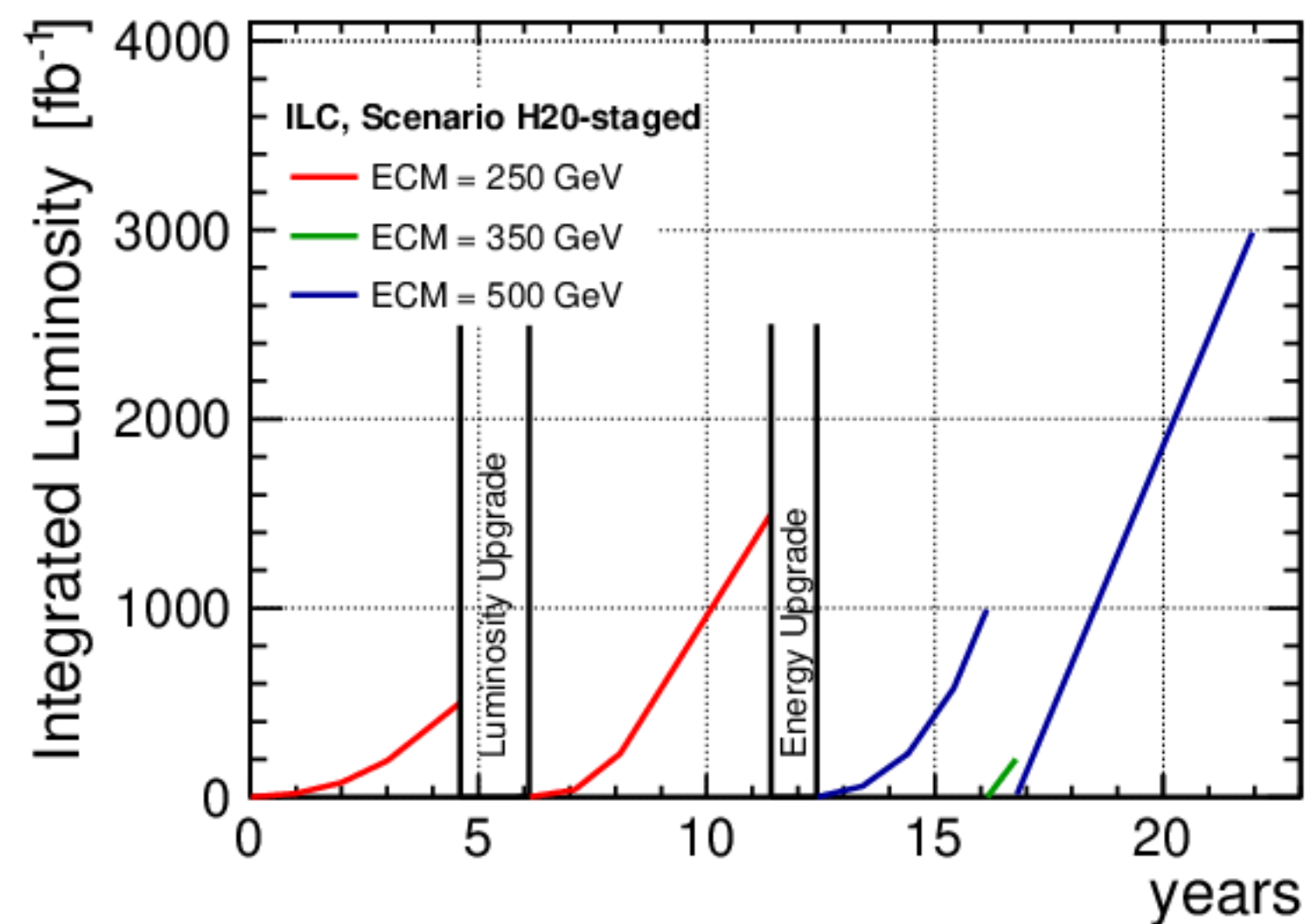


Figure 3: An example scenario of 22 year running program for staged ILC [2]

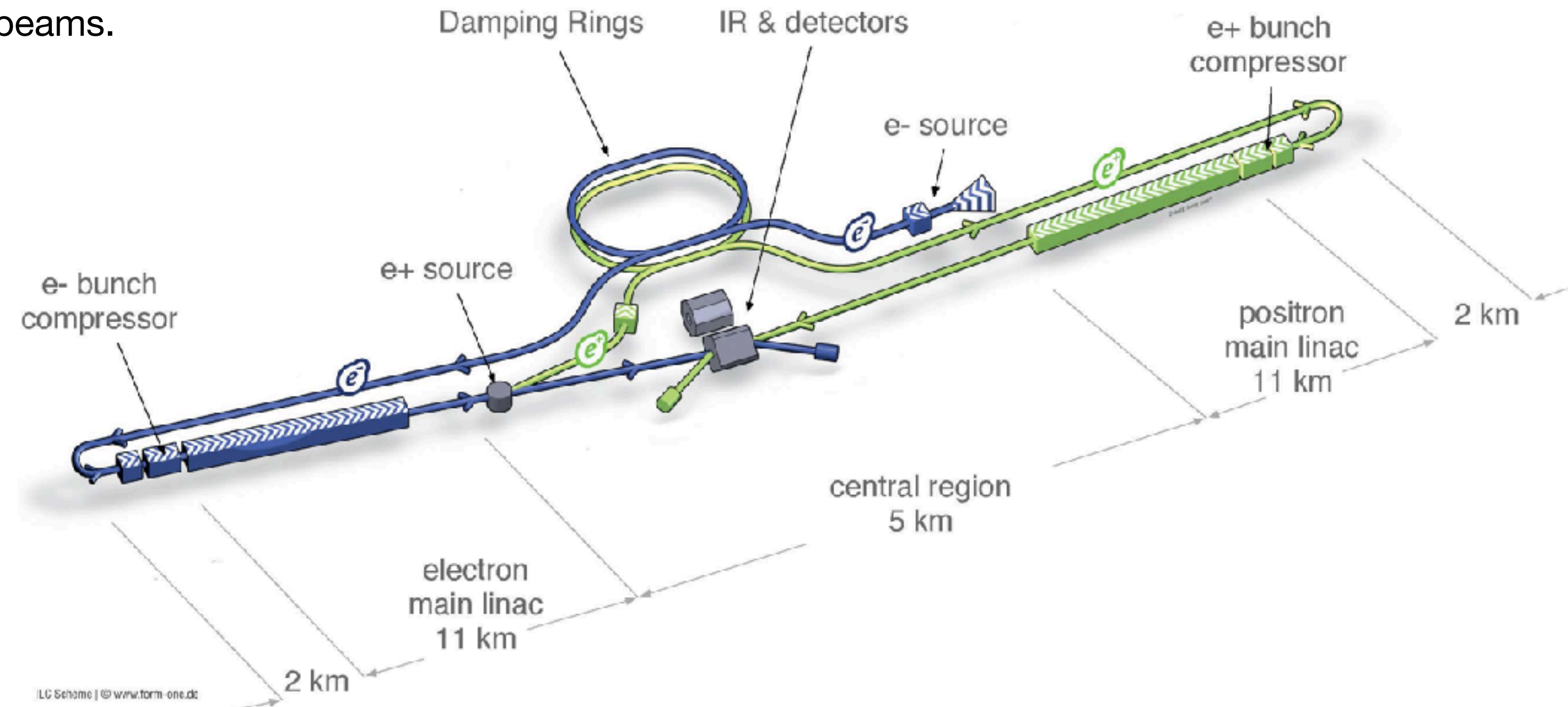


Figure 4: Schematic view of ILC after extension to $\sqrt{s} = 500$ GeV [3]

Fermion Pair Production

- Previous study suggested that electroweak coupling to the heavy fermion pairs ($t\bar{t}$, $b\bar{b}$, $c\bar{c}$) at $\sqrt{s} = 250, 500$ GeV running scenario can be measured to precision about **0.5%** for **top quark** and even more precise for other pairs.
- Extend these work to **lighter quarks** ($u\bar{u}$, $d\bar{d}$, $s\bar{s}$) at $\sqrt{s} = 250$ GeV scenario, to consolidate the results from the heavy quarks. The analysis requires the highest precision in $\pi/K/p$ separation.
- The attempt was also made in SLD experiment at the Z-pole.
(ref: arXiv:hep-ex/0006019)

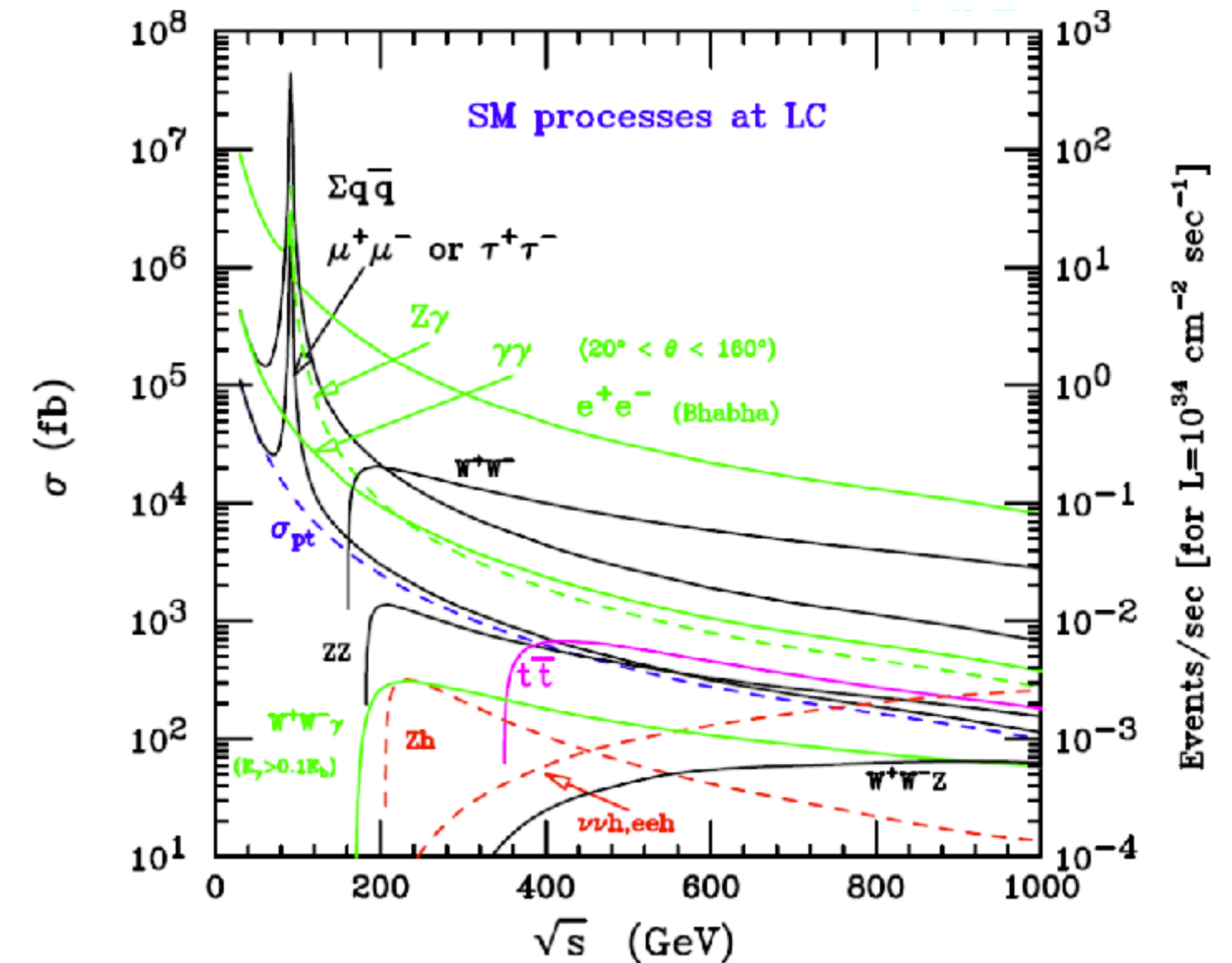


Figure 4: Production cross sections of several representative processes at Linear Colliders. [4]

Vertex Charge Measurement

- Charge identification of process such as $t\bar{t}$, $b\bar{b}$, $c\bar{c}$ can be based on the **vertex charge measurement**
- Vertex charge measurement is to sum the charge of constituents from a jet.
 - For $b\bar{b}$, $c\bar{c}$ process, this comes on top of c and b tagging of the jets
 - For $t\bar{t}$ process, one should also collect the charges from W, since top will decay via $t \rightarrow bW^+ \rightarrow bq\bar{q}$ or $b\ell\bar{\nu}_\ell$.

Kaon Charge Measurements

- An alternate way to measure the charge is to identify **charged kaons**.
- Kaons are contained inside both s, c, b jets and can be used as a charge identifier.
 - For $s\bar{s}$ process, s-quark predominantly decay into kaon thus it is an essential identifier for this process.
 - For $t\bar{t}$, $b\bar{b}$, $c\bar{c}$ process, since c and b jets contain kaons, can also be used as an alternate way to check its charge.

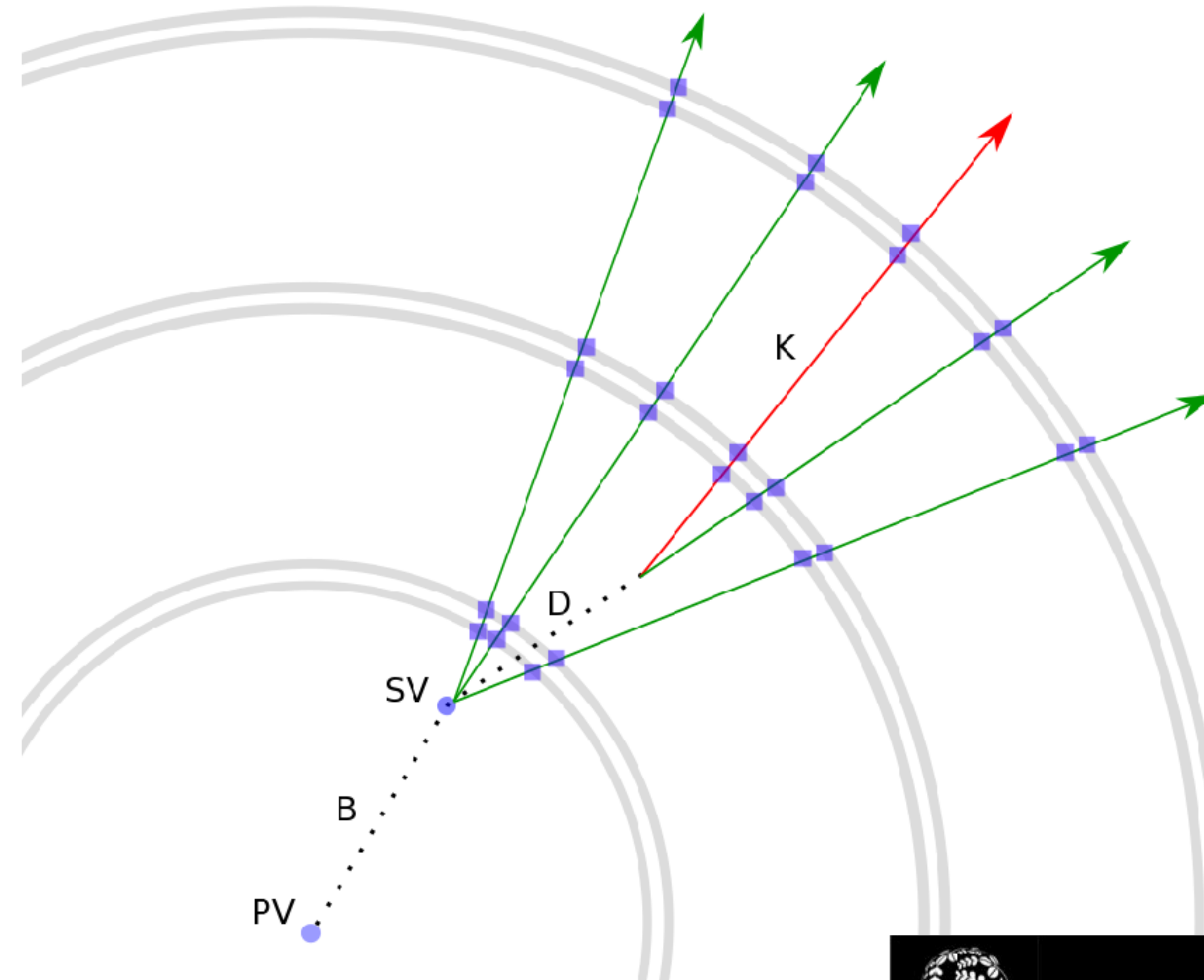


Figure 5: Cross sectional view of the detector during the fragmentation [5]

International Large Detector

Tracker

- Time Projection Chamber
 - GEM, Micromegas, pixel
 - Silicon pixel/strips

ECAL

- SiW ECAL
 - Silicon active layer
- ScECAL
 - Scintillator strips
- Absorber
 - Tungsten

HCAL

- Scintillator tile
- Gas RPC

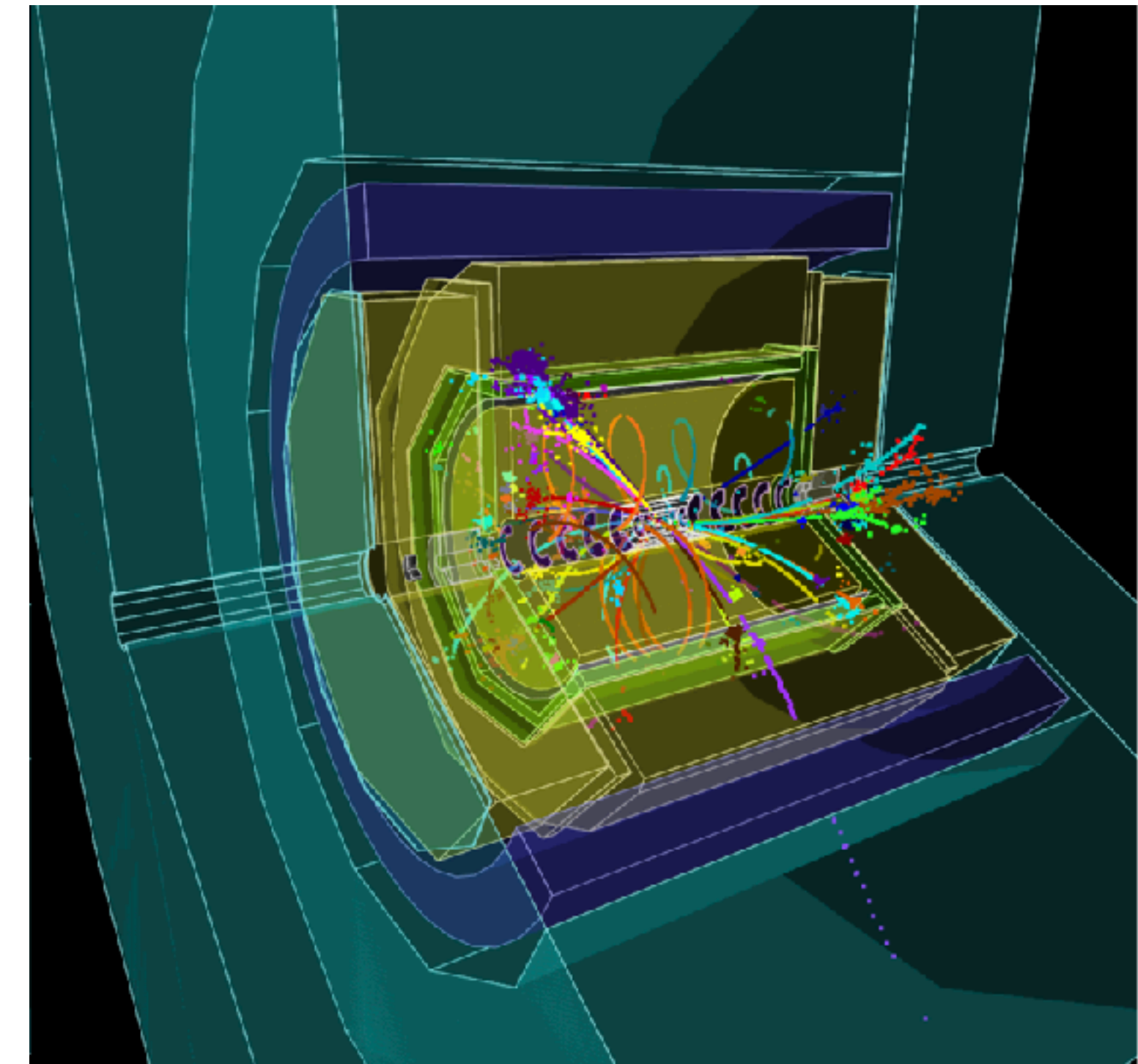
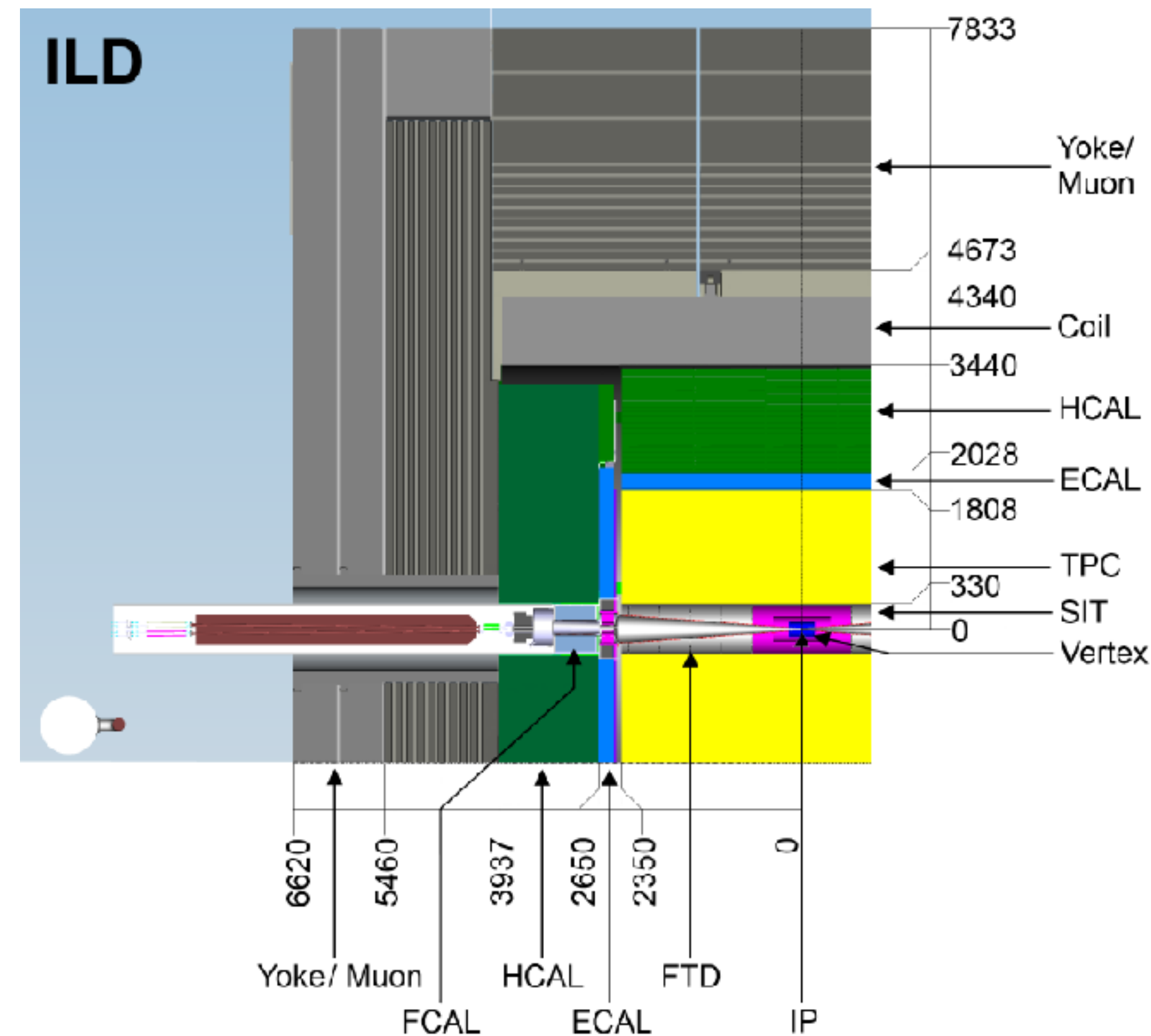


Figure 6: Quadrant view of the ILD detector (left) and a 3D event display of $e^+e^- \rightarrow t\bar{t}$ event (right) [6]

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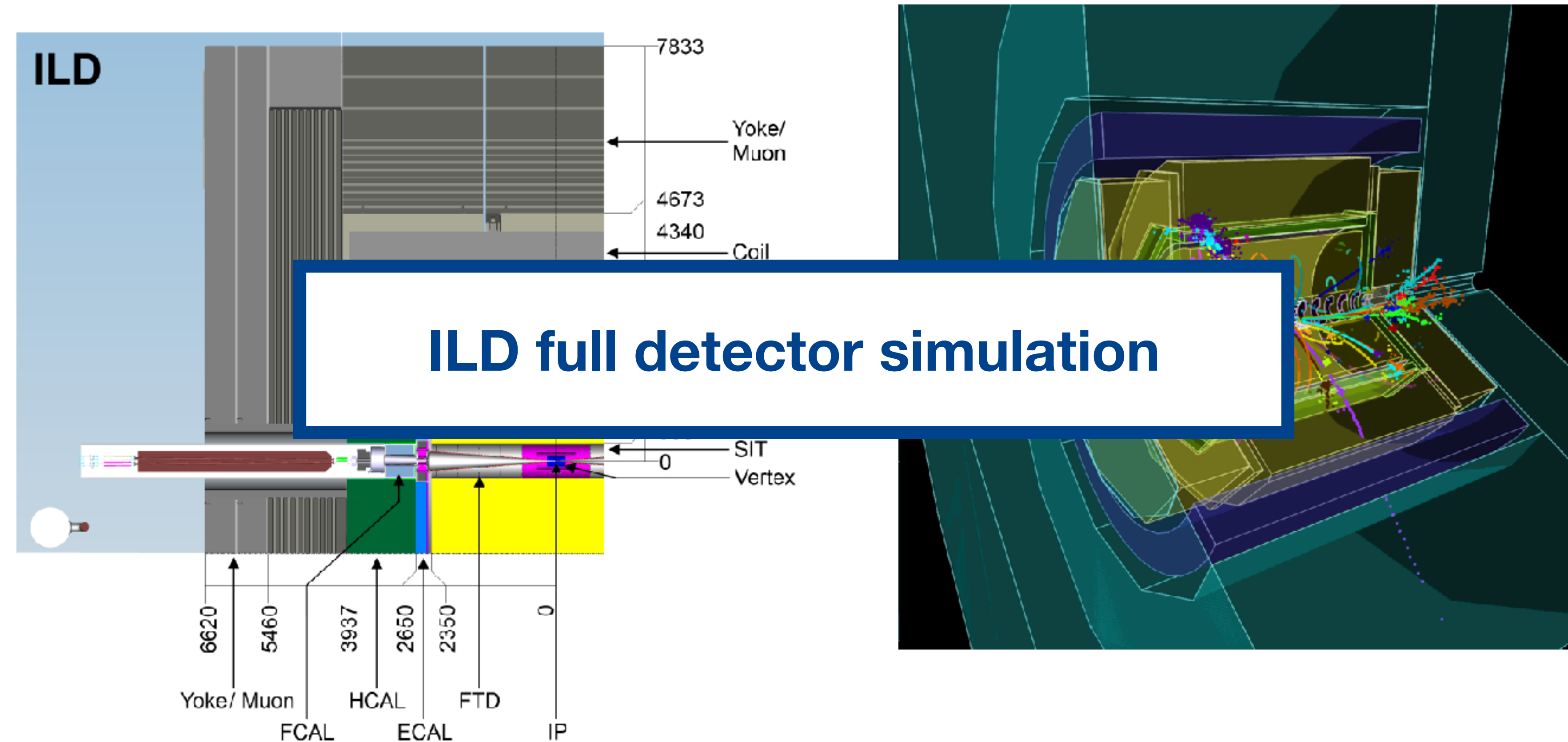


Figure 6: Quadrant view of the ILD detector (left) and a 3D event display of $e^+e^- \rightarrow t\bar{t}$ event (right) [6]

Particle Identification

- **Kaon** is the primary identifier of the s-quark.
 - **dE/dx distance** identification from the **TPC**.

- **Bethe-Bloch formula**

$$\frac{dE}{dx} \approx \frac{z^2}{\beta^2} \ln(a\beta^2\gamma^2) \quad p = m_0\beta\gamma c$$

- **dE/dx distance**

$$\text{signed} \left[\left(\frac{(dE/dx - dE/dx_{exp-kaon})}{\Delta_{dE/dx}} \right)^2 \right]$$

- Kaons' dE/dx distribution overlaps with the ones for **pion** and **proton** which becomes the primary background.

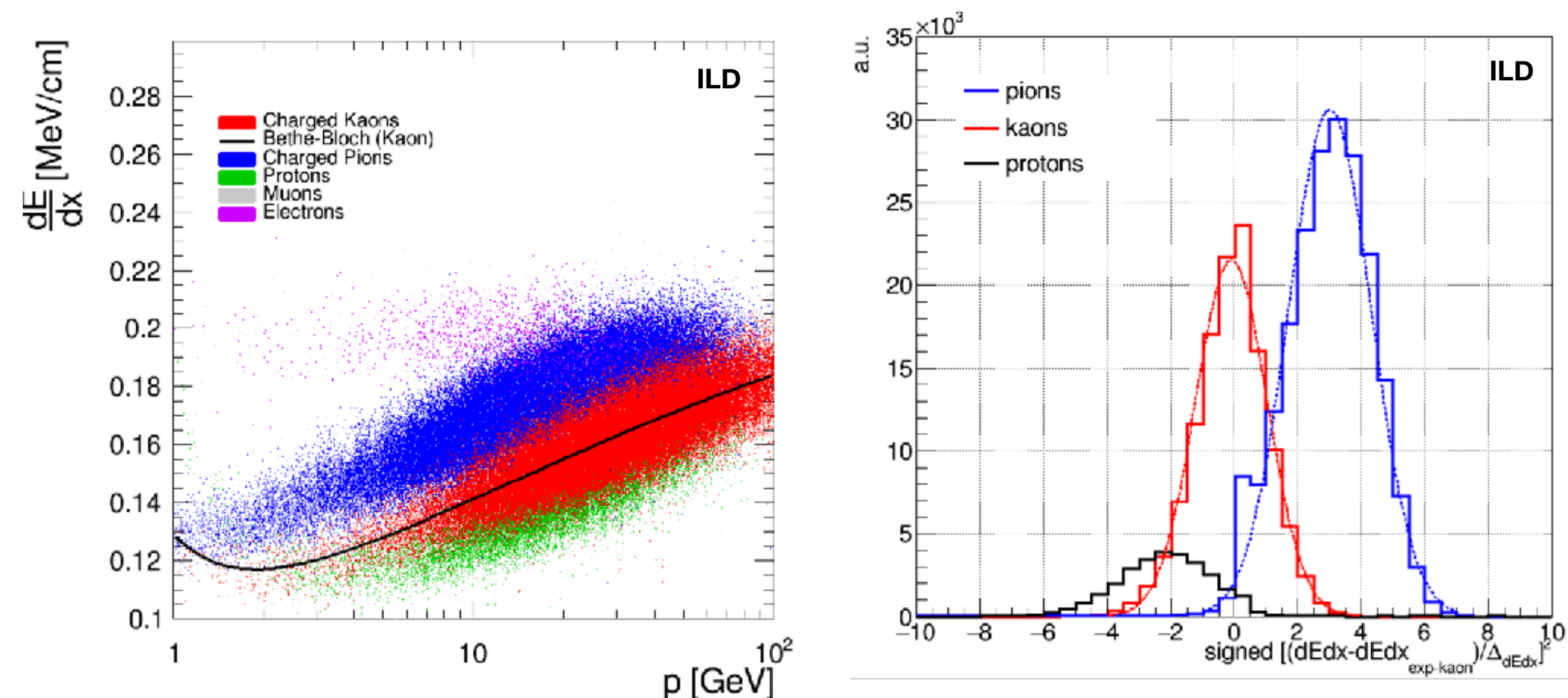


Figure 7: dE/dx vs momentum distribution of particles observed in TPC (left) and their dE/dx distance (right)

S-Quark Pair Production

- In the $s\bar{s}$ analysis, **leading Kaon** is used as a primary identifier of s-quark.
 - **Leading particle** is the particle with the highest momentum within a jet.
 - Leading particle is then identified as kaon using dE/dx identification method.
- Angular distribution of $s\bar{s}$ events can be an estimator on forward-backward asymmetry observable.
- Drop in the reconstruction at the edge of the polar angle originates from the detector acceptance.

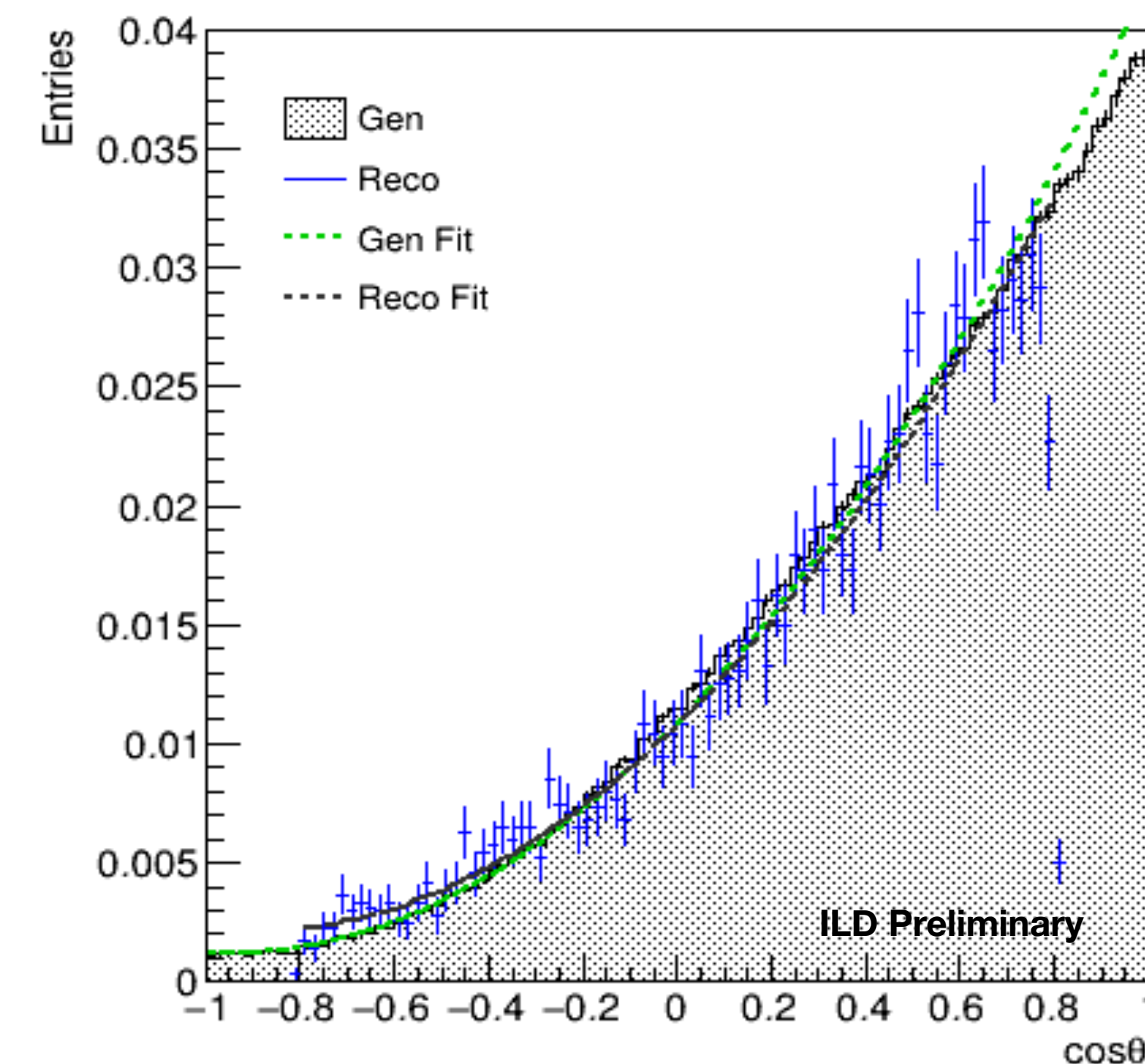
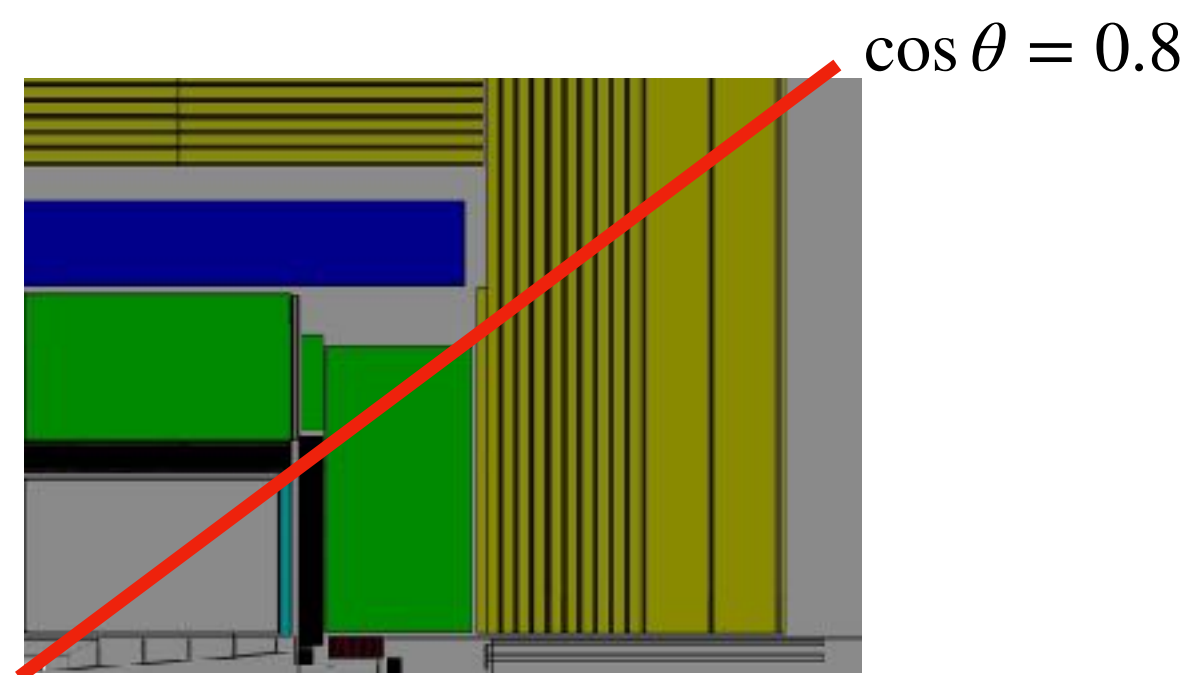


Figure 8: Polar angle distribution of reconstructed $s\bar{s}$ in pure $s\bar{s}$ sample with $\sqrt{s} = 250$ GeV.

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)

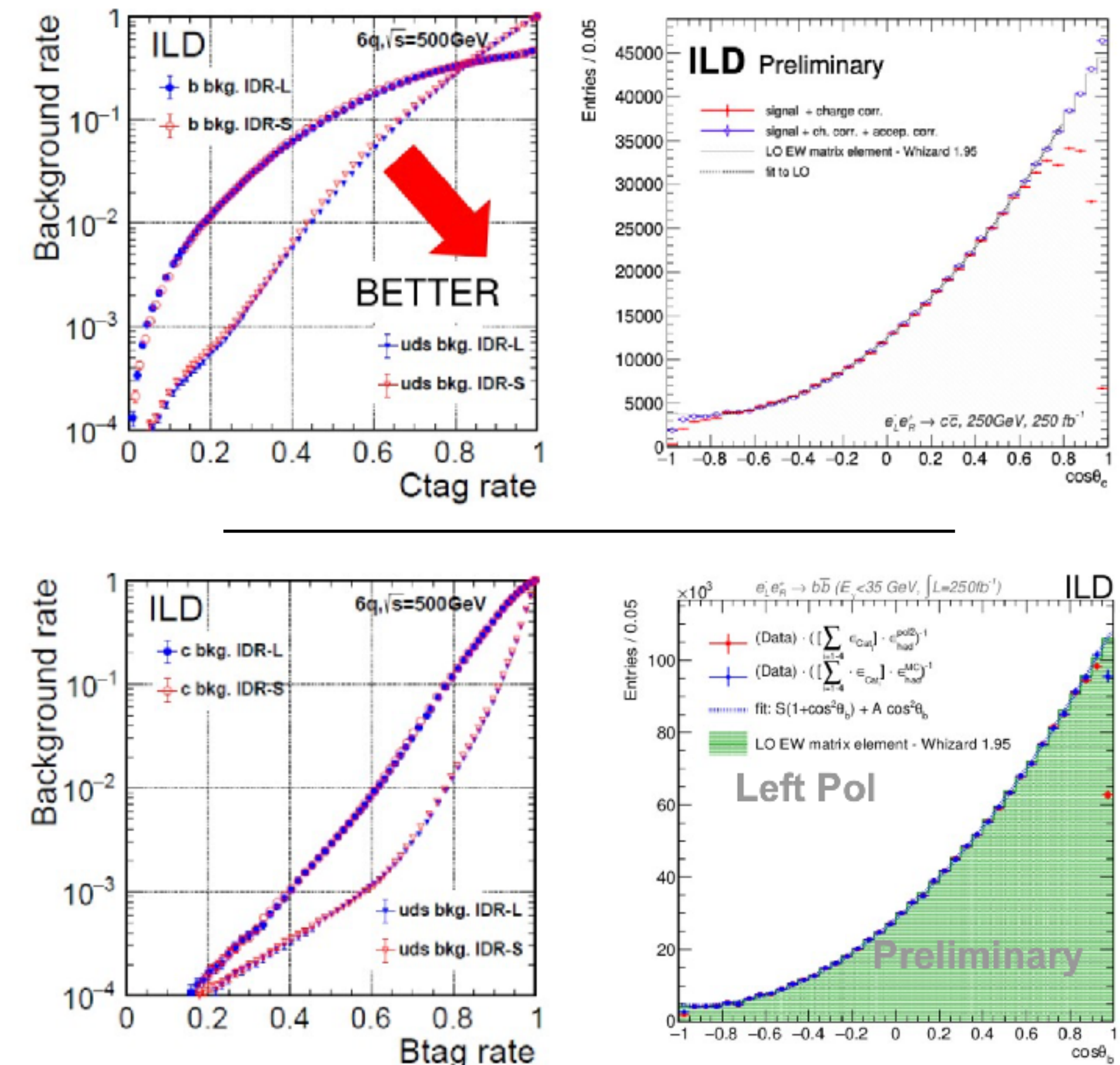


Figure 9: c and b background rate vs c and b tag rate (left) and reconstructed b and c polar angle for $e_L^- e_R^+$ polarization (right) [7]

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.

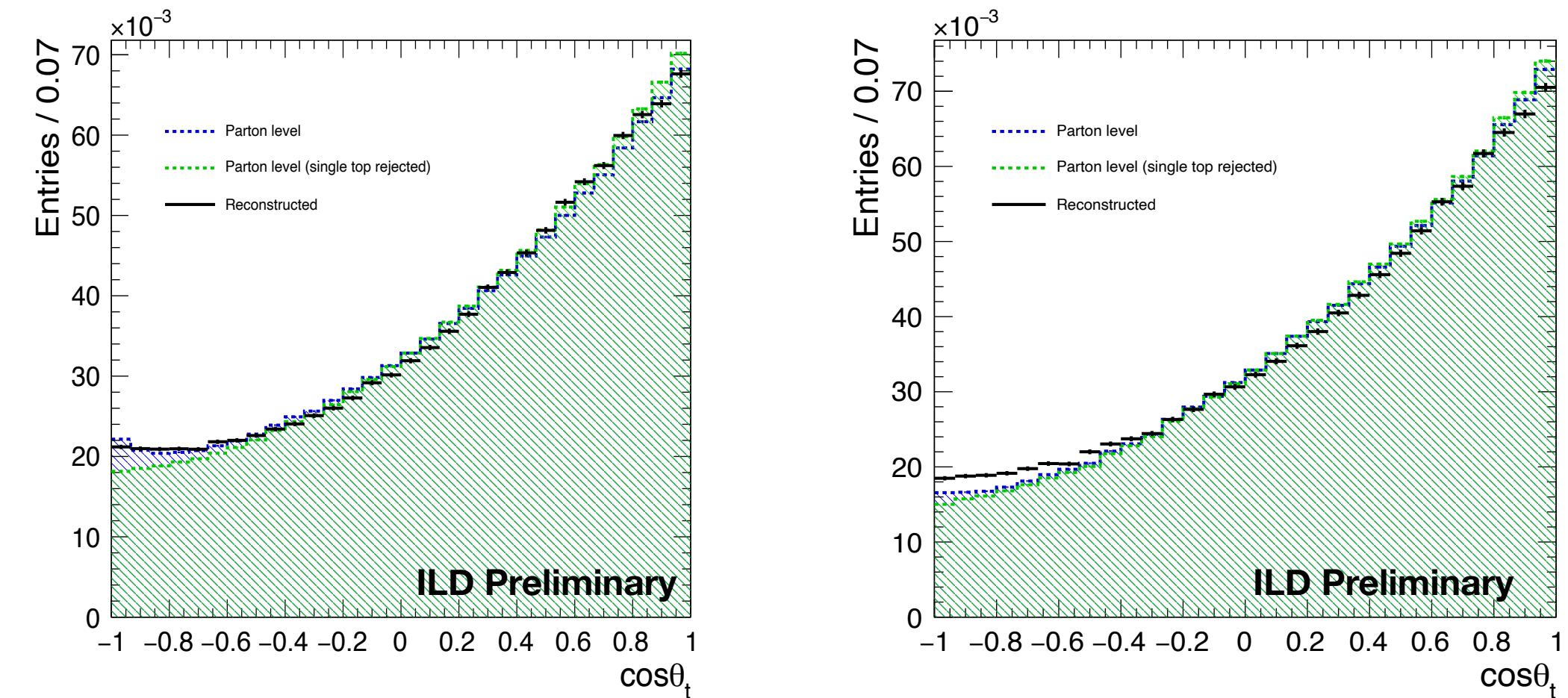
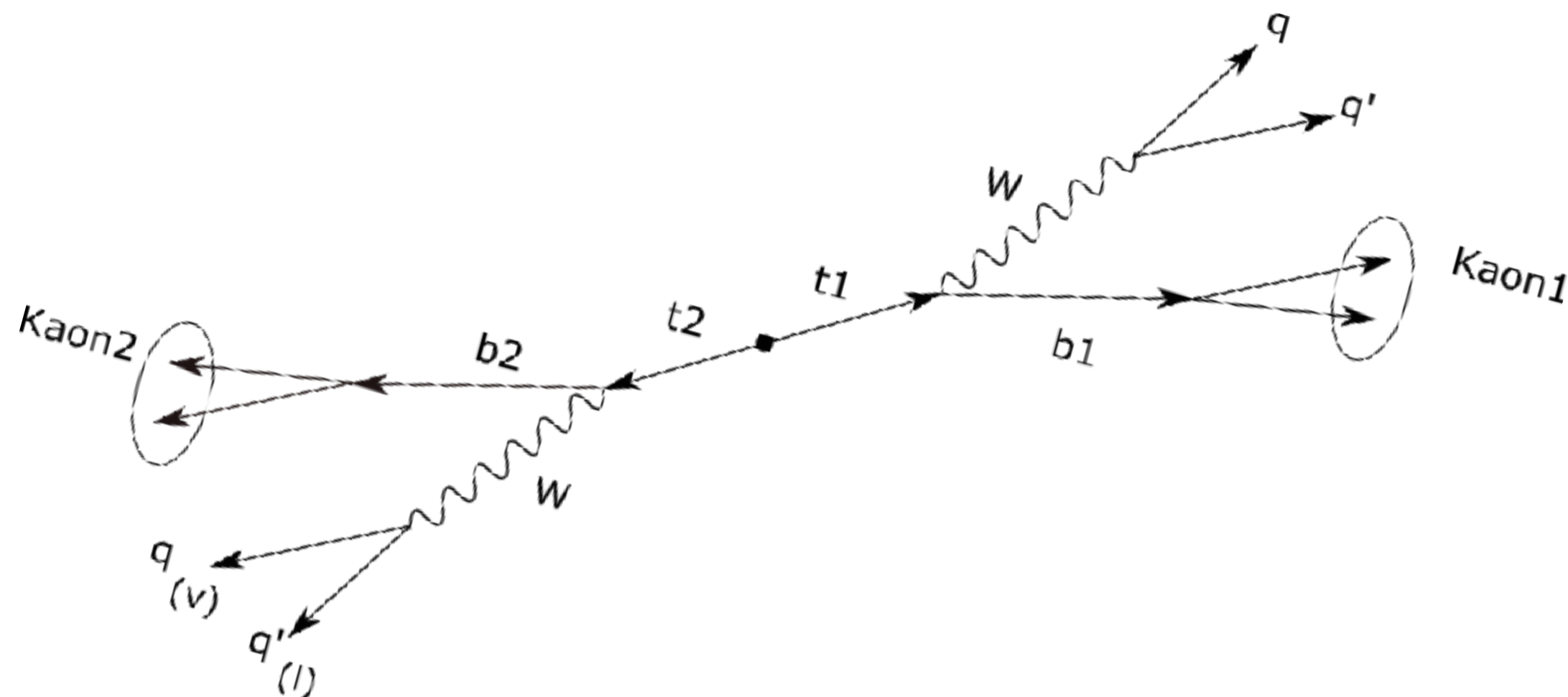


Figure 9: Polar angle distribution of $e^+e^- \rightarrow t\bar{t}$ semi-leptonic channel for $e_L^- e_R^+$ (left) and $e_R^- e_L^+$ (right) polarization.

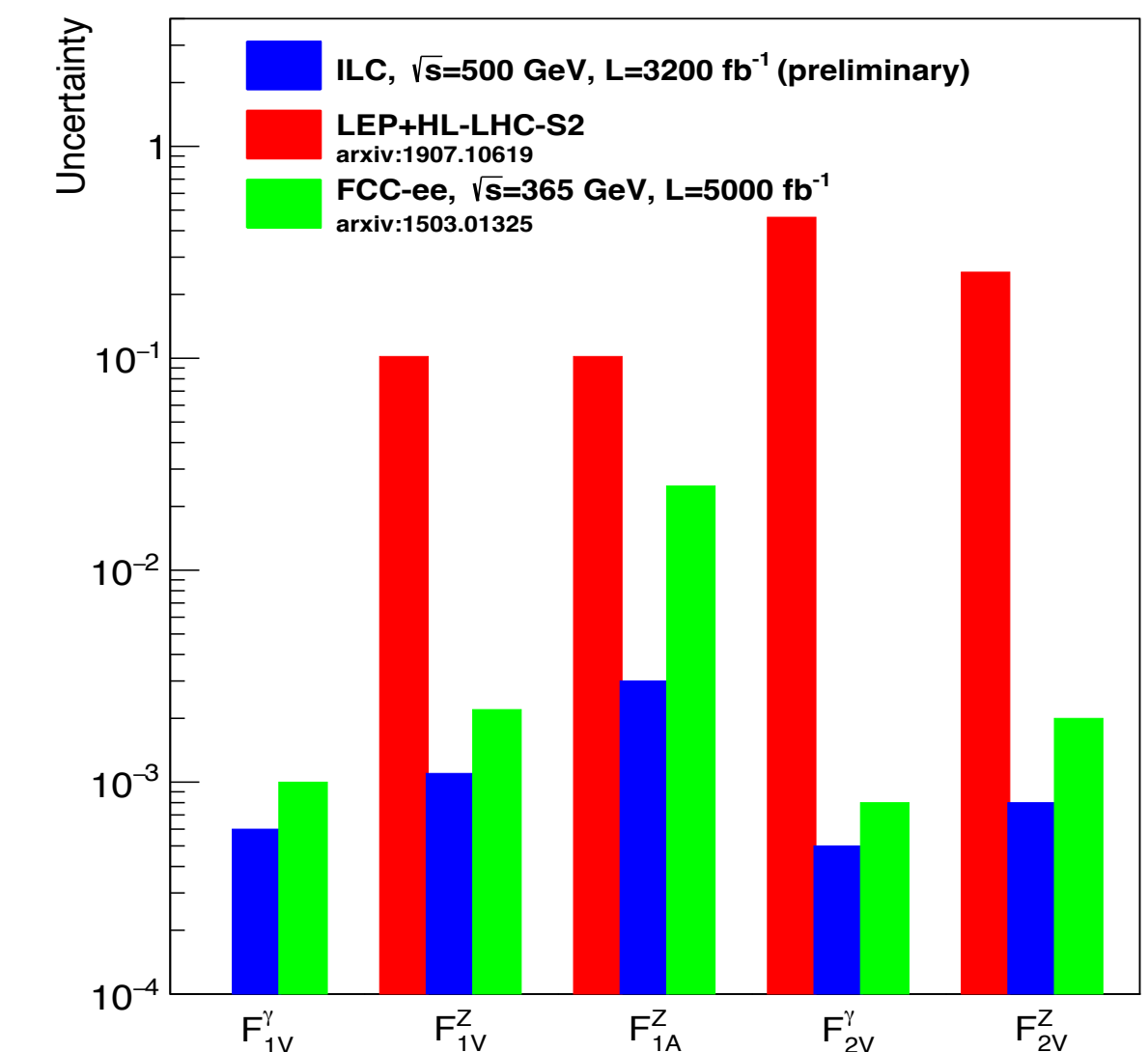
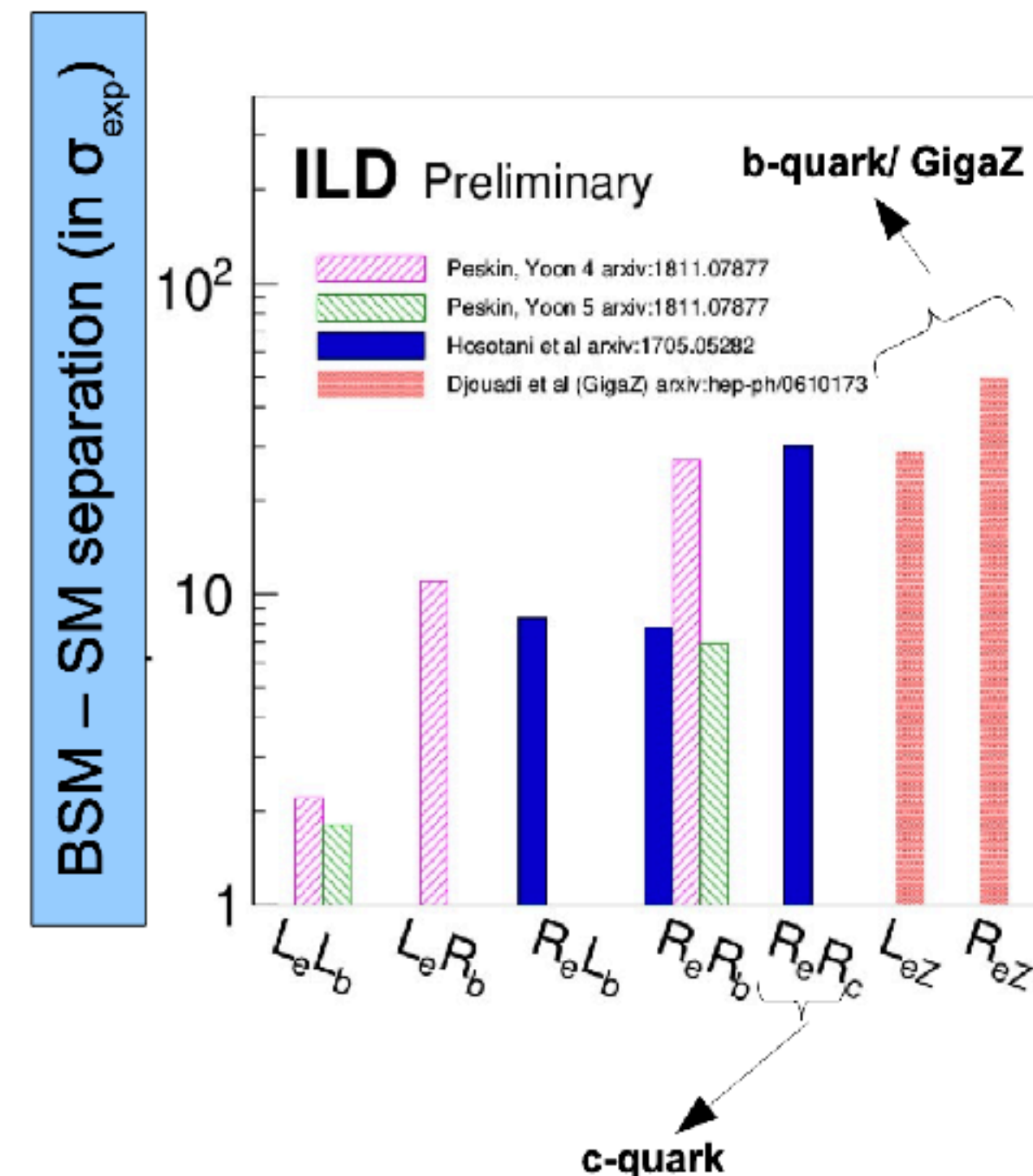
	Final States	# of jets	B.R.
Full Leptonic	$t\bar{t} \rightarrow (b\ell\bar{\nu})(\bar{b}\ell\nu)$	2 jets + 2 ℓ	10.5%
Semi Leptonic	$t\bar{t} \rightarrow (b\ell\bar{\nu})(\bar{b}q\bar{q}')$	4 jets + 1 ℓ	43.8%
Full Hadronic	$t\bar{t} \rightarrow (bq\bar{q}')(b\bar{q}q')$	6 jets	45.7%

Deviation from BSM

- Many BSM theories predict deviation of EW couplings of fermion pairs from the SM
 - Plot (left) [8] shows the BSM deviations from the SM for different Models in c/b-quark pair production at **ILC 250**
 - Can only be achieved with **beam polarization** achieved by the ILC

Precision

- ILC has its advantage over LHC experiments on precision measurements of EW coupling
 - Plot (right) [9] shows uncertainties of form factors associated with the vertex function on $t\bar{t}$.
 - It reveals that ILC is capable of measuring form factor with precision up to 10^3



- **Probing the BSM from the fermion pair production at ILC**
 - Four processes working in progress ($s\bar{s}$, $c\bar{c}$, $b\bar{b}$, $t\bar{t}$)
- **Key characteristics of ILC/ILD to facilitate the precision measurements**
 - Beam polarization
 - Particle Identification with dE/dx information
- **Each process with unique approach to the analysis**
 - $s\bar{s}$: Primarily rely on kaon identification from dE/dx measurements
 - $c\bar{c}/b\bar{b}$: c,b-tag as a result of multivariate analysis from LCFIPlus
 - $t\bar{t}$: Reconstruction after combining b-jet with W constituents ($q\bar{q}$ for hadronic, $\ell\bar{\nu}_\ell$ for leptonic)

- Probing the BSM from the fermion pair production at ILC

- Four processes $H \rightarrow s\bar{s}$ is $(s\bar{s}, c\bar{c}, b\bar{b}, t\bar{t})$

- Key characteristics of

- Beam polarization
- Particle Identification

Strange quark as a probe for new physics in the Higgs sector

Jul 8, 2022, 6:00 PM

15m

Bologna, Italy

Parallel Talk

Higgs Physics

Higgs Physics

Speaker

Valentina Maria Martina Cairo (CERN)

- Each process with unique

Description

- $s\bar{s}$: Primarily rely on the universality of the Higgs Yukawa couplings and their universality. Key information in our understanding of this question arises from studying the coupling of the Higgs boson to second generation quarks. Some puzzles in the flavor sector and potential additional sources of CP violation could also have their origins in an extended Higgs sector.
- $c\bar{c}/b\bar{b}$: c,b-tag as rare Higgs decay modes to charm or strange quarks are very challenging or nearly impossible to detect with the current experiments at the Large Hadron Collider, where the large multi-jet backgrounds inhibits the study of light quark couplings with inclusive $H \rightarrow q\bar{q}$ decays. Future e+e- machines are thus the perfect avenue to pursue this research. Studies were initiated in the context of Snowmass2021 (<https://arxiv.org/abs/2203.07535>) with particular emphasis on the Higgs coupling to strange quarks and the related flavour tagging challenges.
- $t\bar{t}$: Reconstruction of top quark pairs. This gave light to the development of a novel algorithm for tagging jets originating from the hadronisation of strange quarks (strange-tagging) and the first application of such a strange-tagger to a direct Higgs to strange ($h \rightarrow s\bar{s}$) analysis.

The analysis is performed with the future International Large Detector (ILD) at the International Linear Collider (ILC), but it is easily applicable to other Higgs factories. The $P(e^-, e^+) = (-80\%, +30\%)$ polarisation scenario was used for this preliminary result, corresponding to $\sqrt{s} = 250$ GeV of the initial proposed $\sqrt{s} = 500$ GeV of data which will be collected by ILD during its first 10~years of data taking at $\sqrt{s} = 250$ GeV. The study includes as well a preliminary investigation of a Ring Imaging Cerenkov system (RICH) capable of maximising strange-tagging performance in future Higgs factory detectors.

Search for non-Standard Model interactions of the top quark at ILC

Jul 8, 2022, 7:05 PM

1h 25m

Bologna, Italy

Poster

Top quark and EW P...

Poster Session

Speaker

Dr Adrian Irlas (FIC)

Description

Top quarks and in general heavy quarks are likely messengers to new physics. The scrutiny of these particles' properties must be completed by the measurement of electroweak $q\bar{q}$ production at high energies, in particular for the top-quark. The International Linear Collider will offer favorable low-background environment of e+e- annihilation combined with a high-energy reach. This talk will review the opportunities for precision measurements of the top and heavy quarks properties at the International Linear Collider, including the search for BSM contributions and CP violation in the top sector.

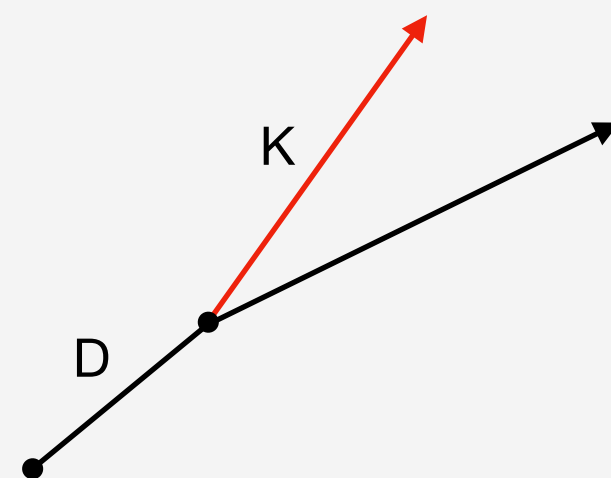
In-person participation Yes

$\ell\bar{\nu}_\ell$ for leptonic)

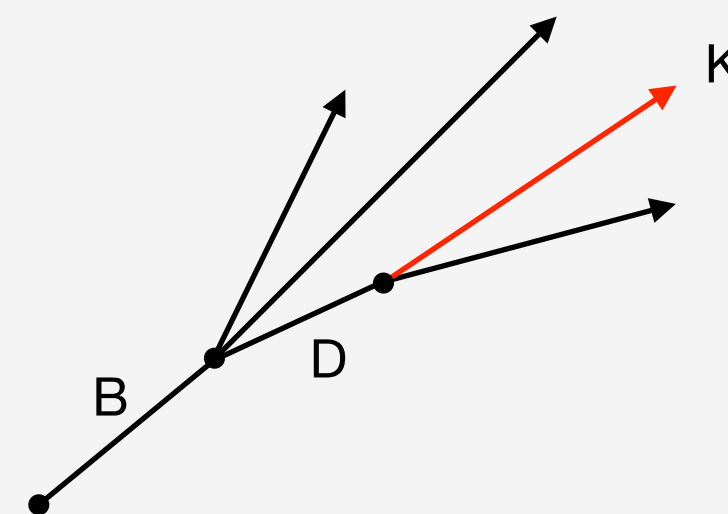
- [1] [Richard, F. \(2014\). Present and future constraints on top EW couplings](#)
- [2] [Zarnecki, A. F. \(2020\). On the physics potential of ILC and CLIC. PoS, CORFU2019:037.](#)
- [3] [Adolphsen, C. et al. \(2013\). The International Linear Collider Technical Design Report - Volume 3.II: Accelerator Baseline Design](#)
- [4] [Han, T. \(2005\). Collider phenomenology: Basic knowledge and techniques. In Theoretical Advanced Study Institute in Elementary Particle Physics: Physics in D 4, pages 407–454.](#)
- [5] [Bilokin, S. \(2018\). Third Generation Quark and Electroweak Boson Couplings at the 250 GeV stage of the ILC \[Conference presentation\], ICHEP 2018, Seoul, Korea.](#)
- [6] [Abramowicz, H. et al. \(2013\). The International Linear Collider Technical Design Report - Volume 4: Detectors.](#)
- [7] [Irles, A. \(2018\). Flavor-Tagging of Quark Pairs at e+e- Higgs/Top Factories \[Conference presentation\], HIGGS 2021, NY, USA.](#)
- [8] [Irles-Quiles, A., Poeschl, R., and Richard, F. \(2019\). Determination of the electroweak couplings of the 3rd generation of quarks at the ILC. In 2019 European Physical Society Conference on High Energy Physics, volume EPS-HEP2019, page 624, Ghent, Belgium.](#)
- [9] [Pöschl, R. \(2022\). Top and heavy quark studies at linear colliders. PoS, EPS-HEP2021:491.](#)

Backup

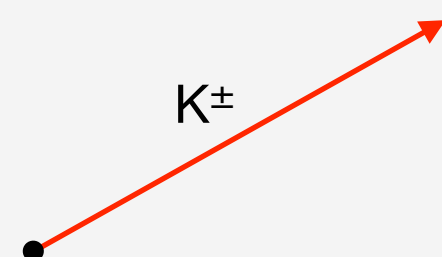
c-jet



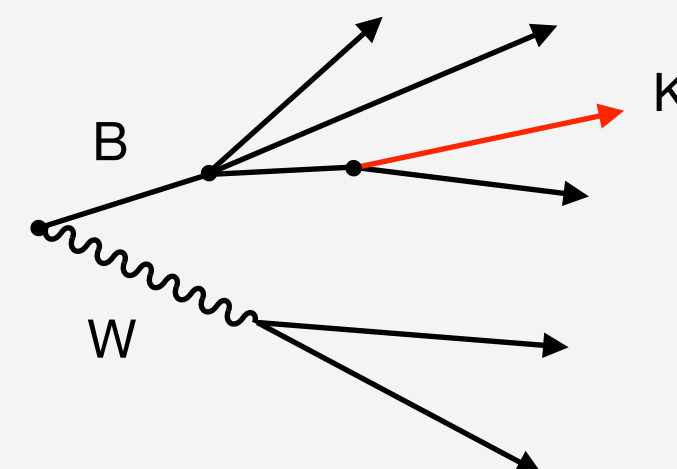
b-jet



s-jet



top



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Momentum check	53,227
TPC hit check	27,921
Offset check	26,848
dEdx dist min check	4,211
Opp K SPFO check	3,036
Migration	86 (2.8%)

Purity : 97.3% **Efficiency : ~1.0%**

