Can ILC observe fermions as composite particles ?

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Introduction

- Recall the two possible solutions to the **hierarchy** problem after the Higgs discovery

  SUSY and **compositeness**

- SUSY (still ?) OK but without an interpretation of the hierarchy of fermion masses

- Compositeness has several incarnations

- I will choose the **RS model**, which has several variants

- It predicts a rich spectrum of KK particles but direct discovery at LHC is not guaranteed since **precision measurements** from LEP-SLC tend to predict heavy vector KK bosons at ~10 TeV

- Usually **b/t** couple to KK particles but 'ordinary fermions' could also manifest significant deviations

RS in short
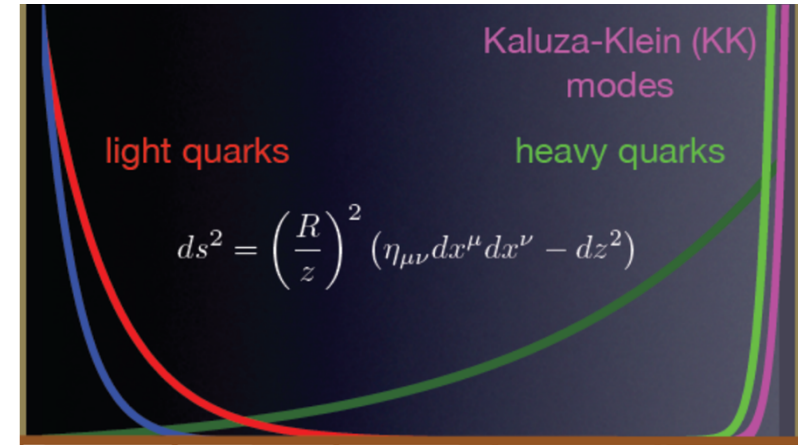
- It solves the hierarchy problem through exponential damping of the Planck scale to the EW scale
- It can describe fermion mass hierarchy by **geometry** in the extra dimension
- It naturally calls for **non-universal fermion couplings**
- **b/t** more coupled to KK than light quarks
- μ-τ could also be preferentially coupled to KK to explain the **B factory anomalies** arXiv:1709.05100
- It also calls for a **stabilizing mechanism** for the extra dimension resulting into the **radion** (also called dilaton) a scalar which could be light, below 100 GeV, and discovered at ILC and LHC e.g. in RZ or 2 photons (**arXiv:1712.06410**)

Measuring fermionic final states
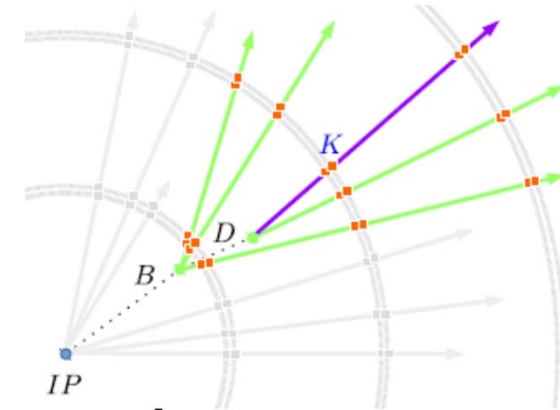
- Main tools
- **Beam polarisation**, e-80% and e+30%, for a **model independent** extraction of all amplitudes
- **High luminosity**, 2000 fb-1 at 250 GeV
- An excellent tracking detector to reconstruct secondary vertices and determine the charge of the b quark using **charged B mesons**
- A capability to identify **charged kaons**, giving the b quark charge with ~80% purity, is provided by the large TPC of ILD
- Very significant improvements with respect to LEP2 detectors specially a gain of 1000 on the luminosity !

Experimental aspects for bb

- The b charge is needed to draw **dσ/dcos**θ

- **dE/dx from TPC** in ILD gives a clean K/pi separation over a wide momentum range

- Very demanding on **μvertex** efficiency given the high multiplicity of B decays ~5

- A very detailed description can be found in the PhD document of S. Bilokin and in **arXiv:1709.04289**

- Double b charge tag needed to reach full purification using simple **counting techniques** comparing B+B- to B+B+ and B-B-
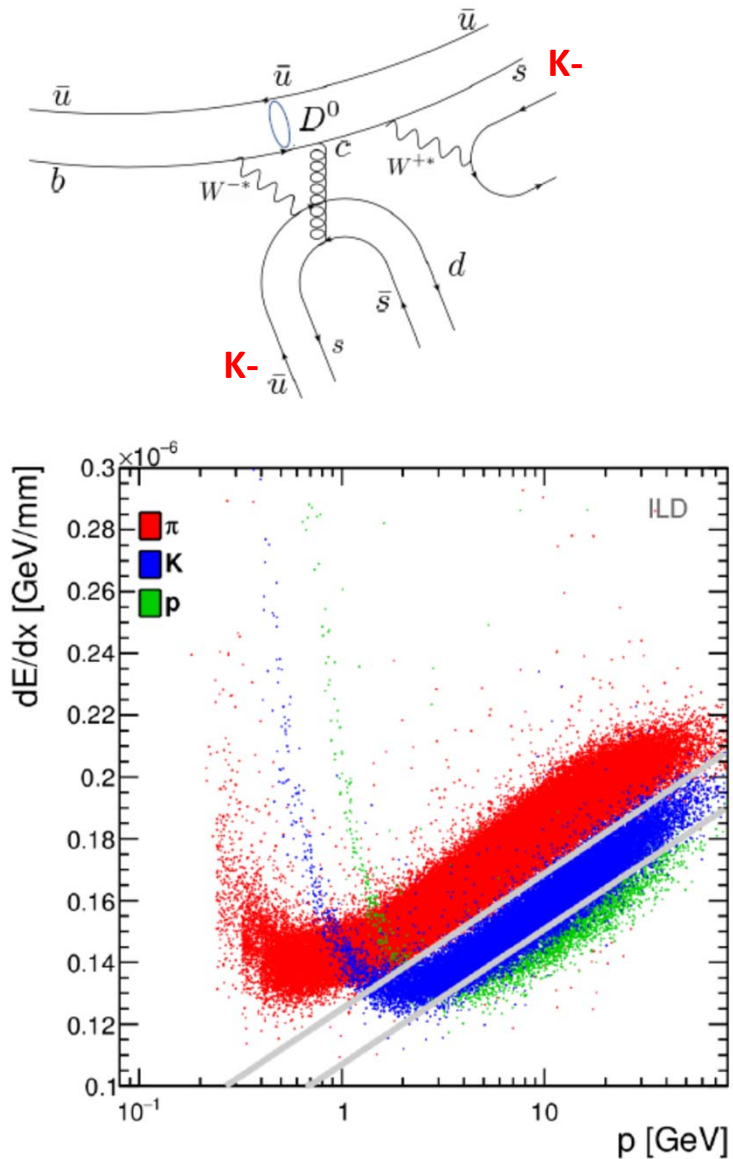
Results

- Very asymmetric angular distribution sensitive to b charge reconstruction

- After **data based corrections**, the angular distribution becomes ~identical to the generated one for |cosθ|<0.8

- Inefficiencies in the fwd region can be handled adjusting the theoretical distribution by **S(1+cos²θ)+Acosθ** in the fully efficient angular region

- This work has served as a **benchmark** for tracking, dE/dx reconstruction in ILD

**e-L**
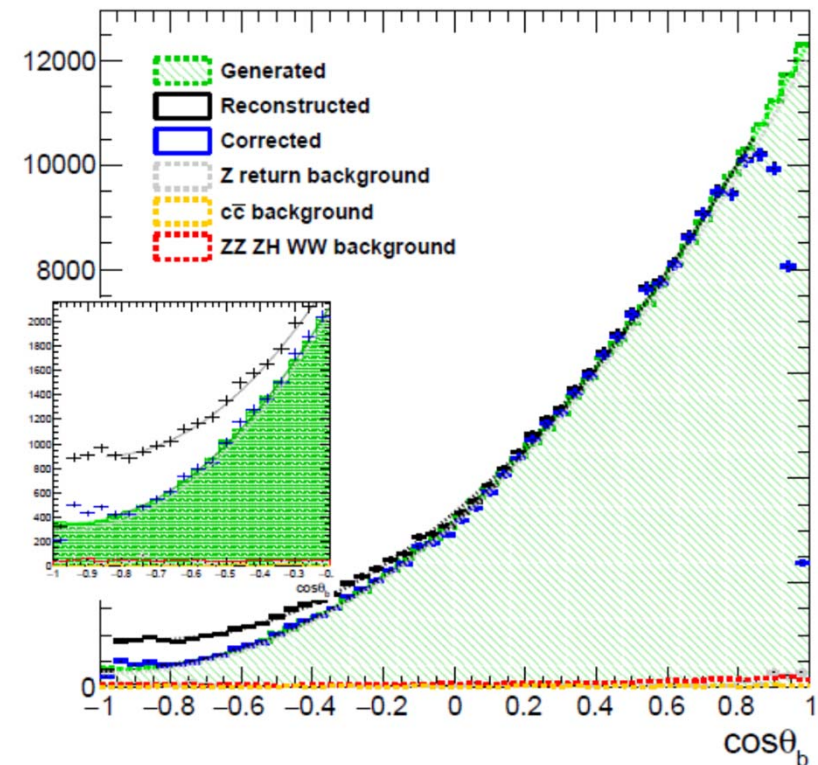
Model independent Interpretation

- Measuring the angular distribution for e-R

$$d\sigma/d\cos\theta = (1+\cos^2\theta)(ReRb^2+ReLb^2)$$
$$+2(ReRb^2-ReLb^2)\cos\theta$$

- With eL/R one can extract $ReRb^2$ $ReLb^2$ $LeLb^2$ and $LeRb^2$ at % level

- Assuming that **ee couplings are standard** one can also extract **gbRZ** and **gbLZ** and solve the LEP1 puzzle

- This assumption is untrue in some RS models

- As shown in **arXiv:1804.02846**, it will be possible to measure ee coupling in **ee->ee** and validate this hypotesis
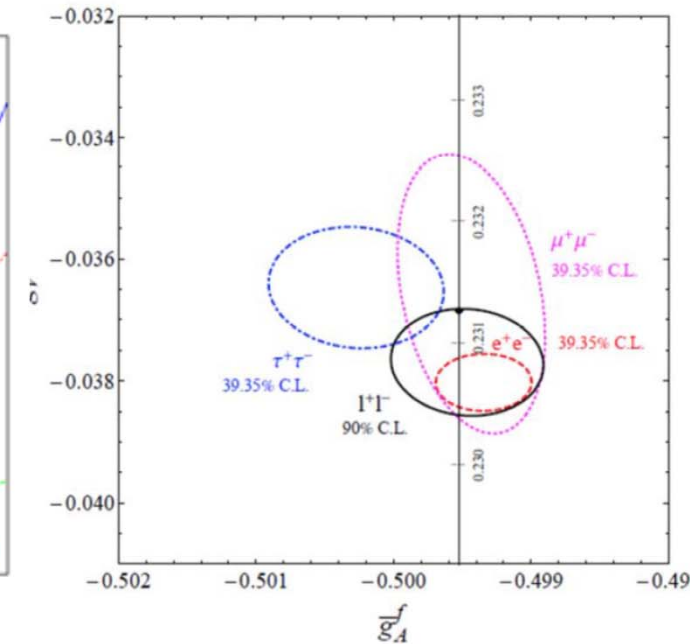

ee->bb

500 fb-1   2000 fb-1   LEP1
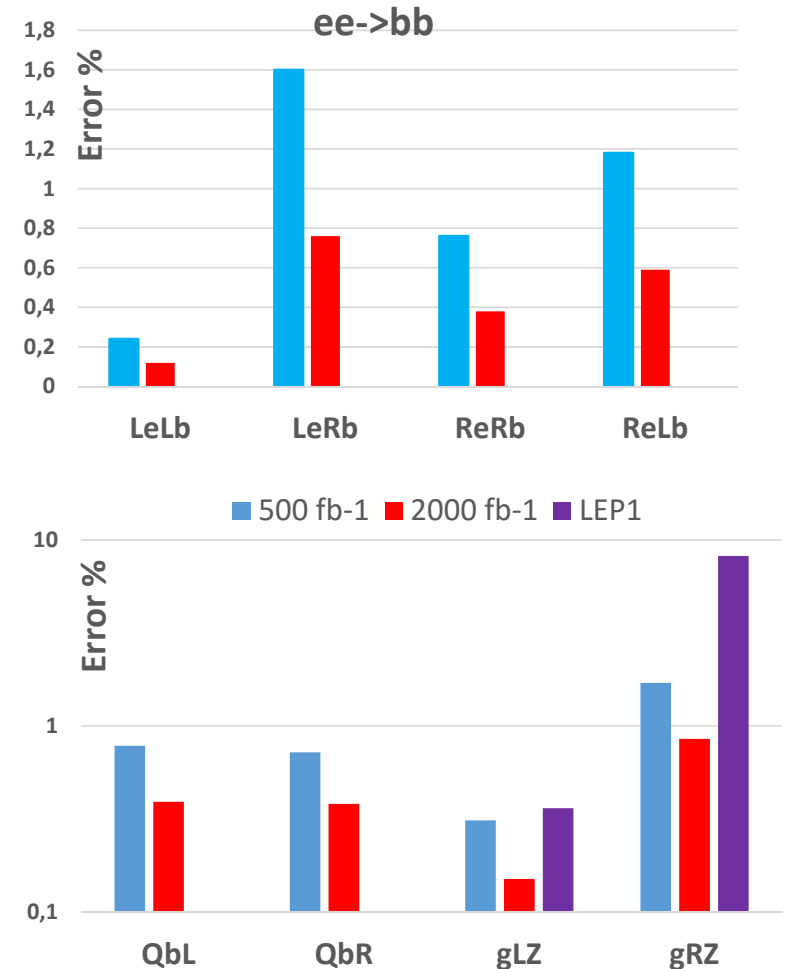
ee->ee measurements

- There is good sensitivity to BSM physics through **t-channel** interference **arXiv:1804.02846**

- The main challenge is to cope with the very high rate in the forward region both theoretically and experimentally keeping **errors at ~0.1%**

- LEP1 provides a precise measurement of the Zee coupling
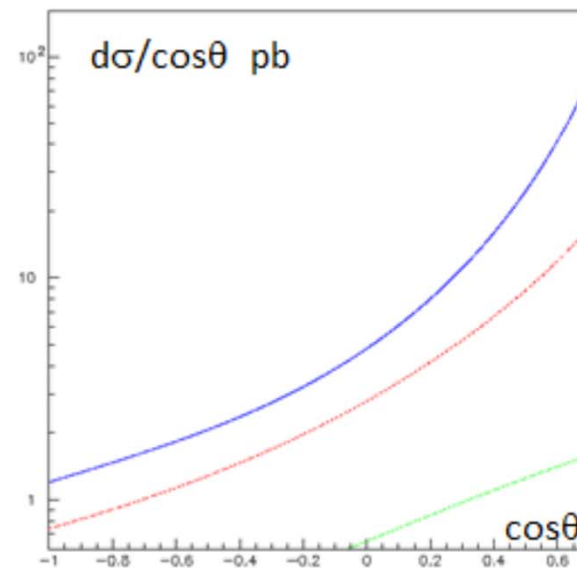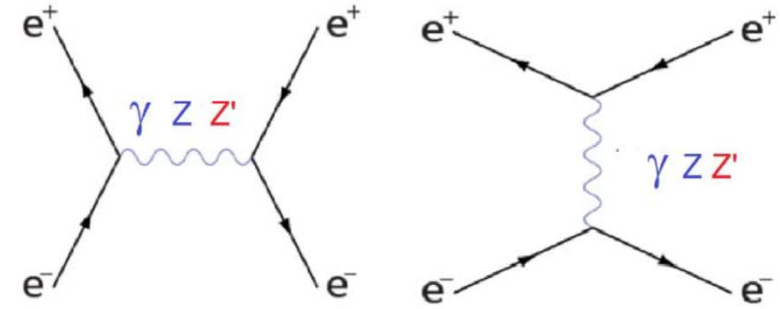
γ **exchange**
γ-**Z interference**

LEP1

GHU coverage and comparison to LHC direct reach

- In Gauge-Higgs-Unification, **arXiv: 1705.05282**, **H** appears as the 4th gauge component and **gauge symmetry** protects its mass from radiative corrections (hierarchy problem)

- **Extended symmetry** (S,T) allows γ_{KK} Z_{KK} Z_R down to 5-10 TeV

- **All right-handed fermions** are close to the EW brane and interact with KK bosons

- The **GHU** model provides an interesting playground to illustrate the power of ILC. It predicts deviations both for t/b and **lepton couplings**

- ILC surpasses LHC direct searches and will be able to predict the masses of heavy resonances
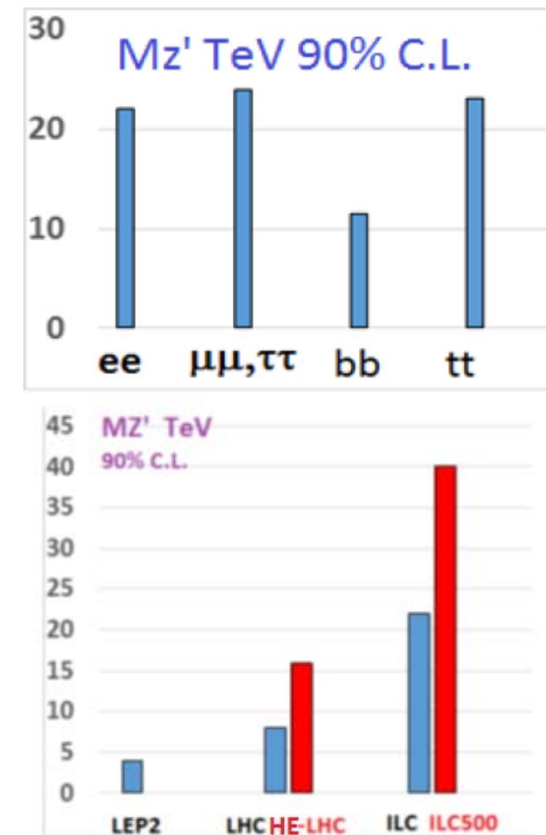
Two RS scenarios

- **GHU** affects all flavours
- This model depends on **one free parameter** and can therefore be overconstrained at ILC
- It will allow to predict the Z' masses
- Another prediction stems from the AFBb anomaly observed at **LEP1** which was interpreted as due to Z-Z' mixing **hep-ph/0610173**
- These scenarios can be tested on ee-> bb with full statistical significance
- They are clearly distinguishable
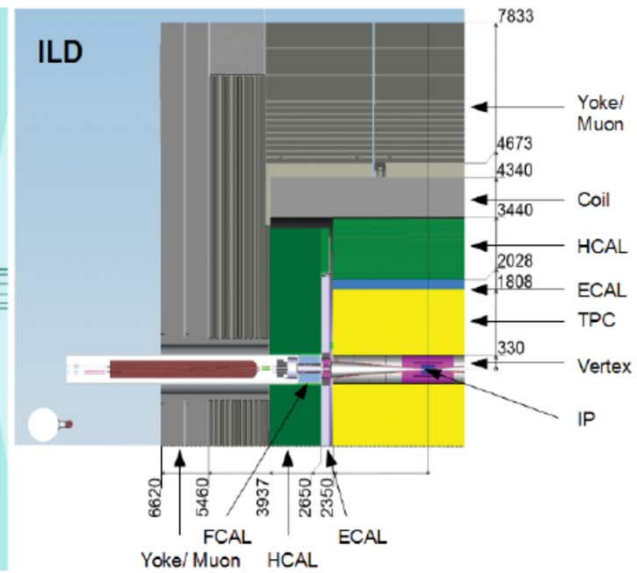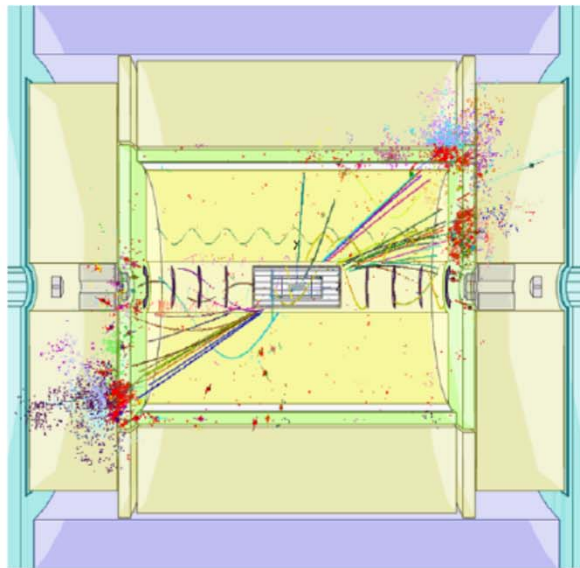- ee->ee allows to measure ee anomalies only present in GHU
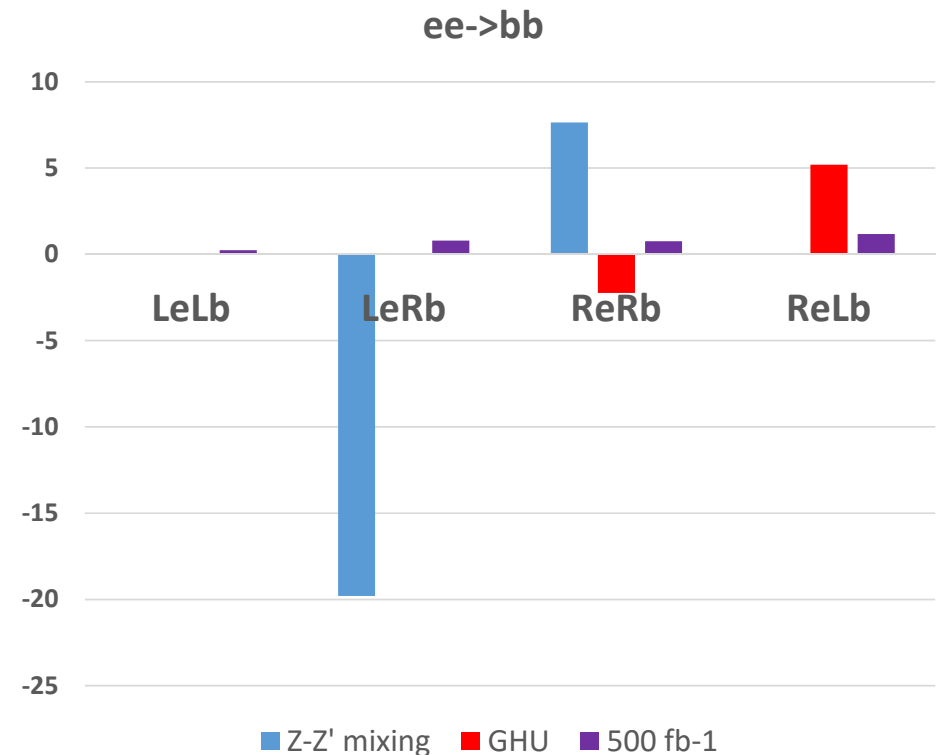
Conclusion

- **ILC250 with x1000 the luminosity of LEP2 and beam polarisation** is the ideal instrument to understand a composite scenario as suggested by LEP1 and B factories anomalies

- This is illustrated by the two RS scenarios presented in this talk

- dE/dx K identification and very good **µvertex** efficiency are needed for ee->bb (and tt) measurements

- **Leptons** (not only b/t !) could also manifest significant deviations

- Expected accuracy below % allows to extend the mass domain of RS models **well beyond the reach of LHC**

- Progress is also needed to reduce **theoretical uncertainties** at the same level, in particular for what concerns **EW corrections** for ee->tt, bb, ee…

- These examples show how ILC could predict heavy resonances and pave the way for the **next hadron collider**

THAT'S ALL FOLKS

ILD
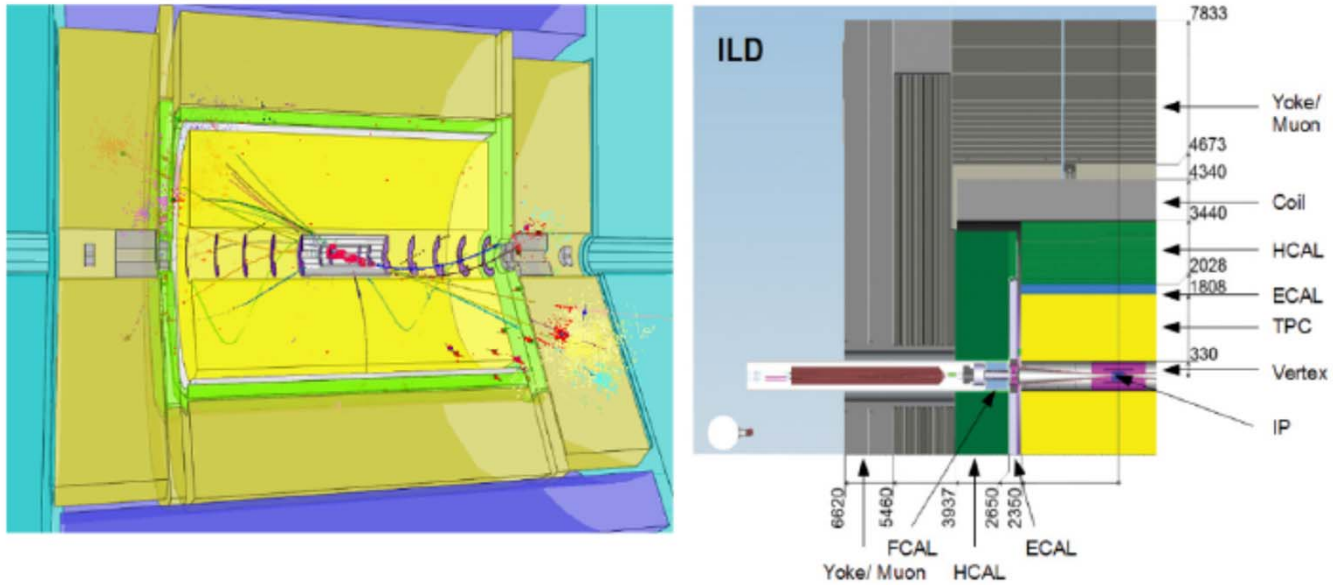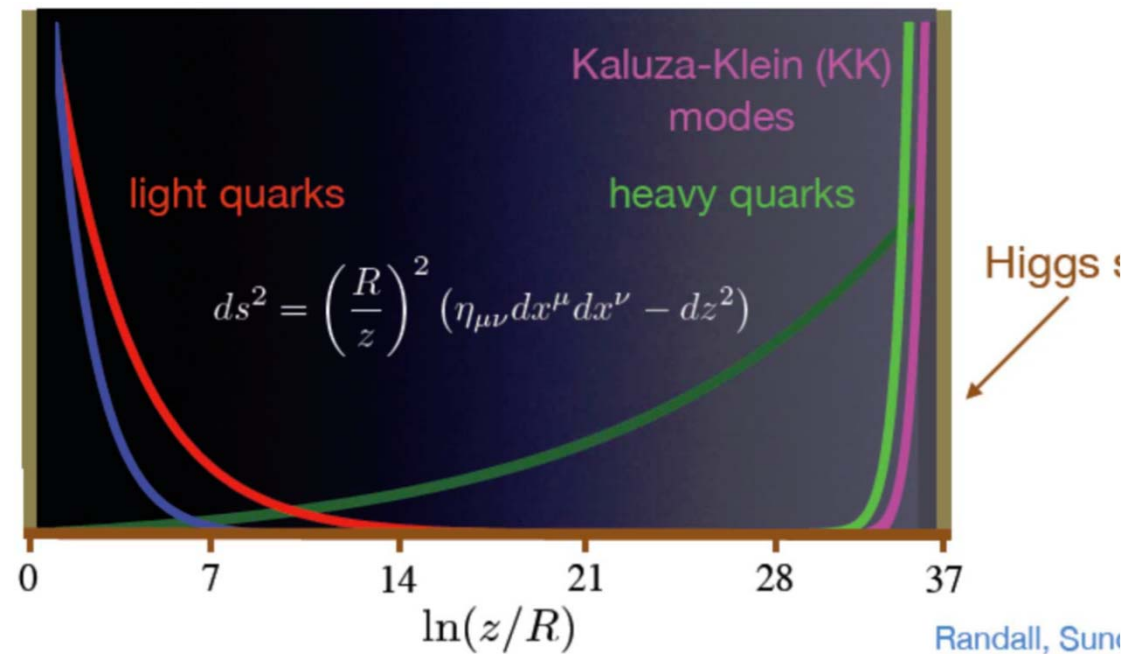

Figure 3: *Event display of the $e^+e^- \to b\bar{b}$ process in a full simulation of the ILD detector (left) and schematic view of the ILD concept [2] (right).*

ILD

Yoke/Muon
Coil
HCAL
ECAL
TPC
Vertex
IP

7833
4673
4340
3440
2028
1808
330

6620
5460
3937
2650
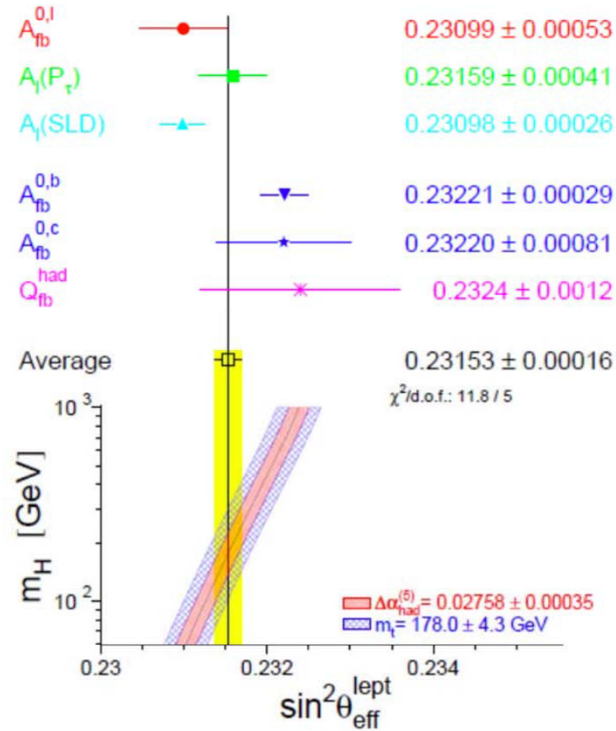2350
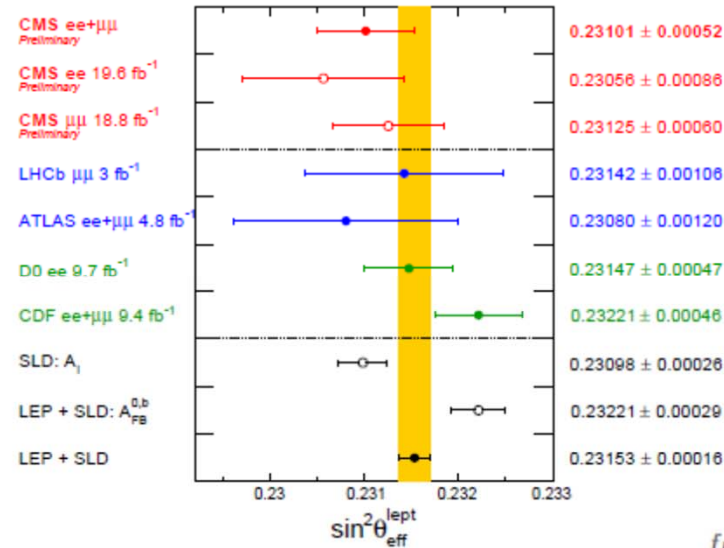
FCAL
Yoke/ Muon   HCAL   ECAL

RS for pedestrians

- *Extra dimension with **warped space** between two branes in the extra dimension*

- *Solves **hierarchy** : $M_W = M_P exp(-2k\Delta y)$ where $k\Delta y \sim 35$ with $k \sim 1/M_P$, Δy distance between the two branes*

- *Describes geometrically the **hierarchy** between fermion masses: light fermions close to the Planck brane are light and elementary, the heavy ones see the Higgs on the other brane called the EW brane*

- *The need to stabilize this brane requires an extra scalar field called the **radion***

Kaluza-Klein (KK) modes

light quarks   heavy quarks

$$ds^2 = \left(\frac{R}{z}\right)^2 \left(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2\right)$$

Higgs

0   7   14   21   28   37

$\ln(z/R)$

Randall, Sund

The b/τ anomalies at LEP

- Can be reproduced in a RS approach

0610173

0312023
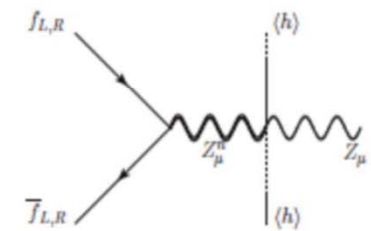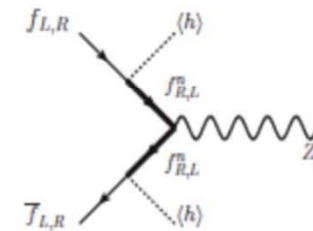
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$$\frac{\mathcal{B}(W \to \tau\nu_\tau)}{[\mathcal{B}(W \to e\nu_e) + \mathcal{B}(W \to \mu\nu_\mu)]/2}\bigg|_{\mathrm{LEP}} = 1.077 \pm 0.026,$$

Beware EW corrections

- Subtantial EW corrections were found (GRACE) for ee->tt with L polar **arXiv:1706.03432**

- Similar diagrams can contribute to ee->bb

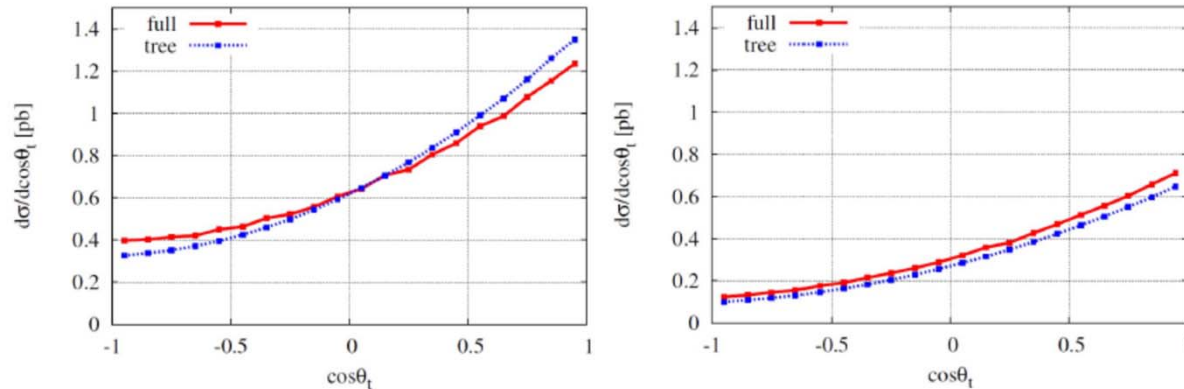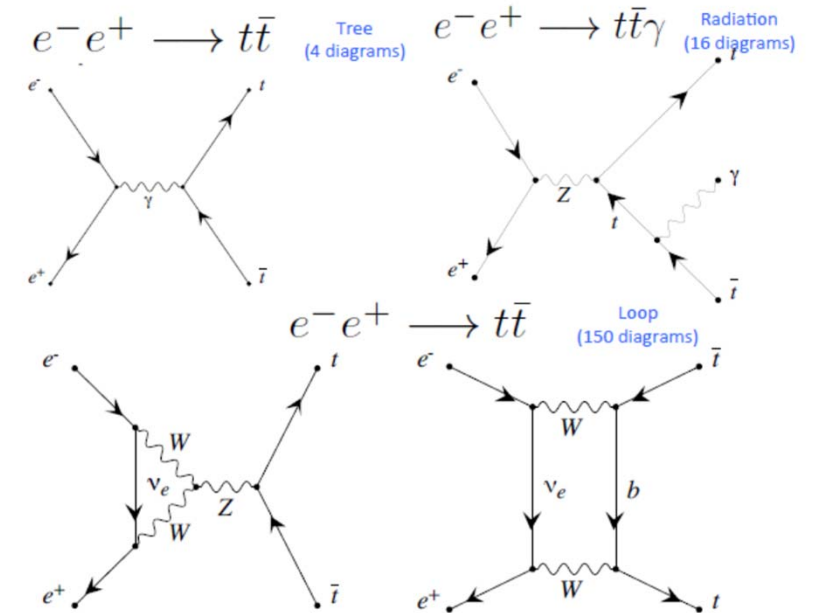- Calculations are needed to match the predicted statistical accuracies

Figure 4: Angular distributions of the production angle of top quark θ_{top} at a CM energy of 500 GeV with $e_L^- e_R^+$ polarization (left) and $e_R^- e_L^+$ polarization (right). The dotted lines show tree-level results wheres the solid lines show full electroweak-corrected results.

GHU

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	$g_{Z^{(1)}f}^L$	$g_{Z^{(1)}f}^R$	$g_{Z_R^{(1)}}^L$	$g_{Z_R^{(1)}f}^R$	$g_{\gamma^{(1)}f}^L$	$g_{\gamma^{(1)}f}^R$
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
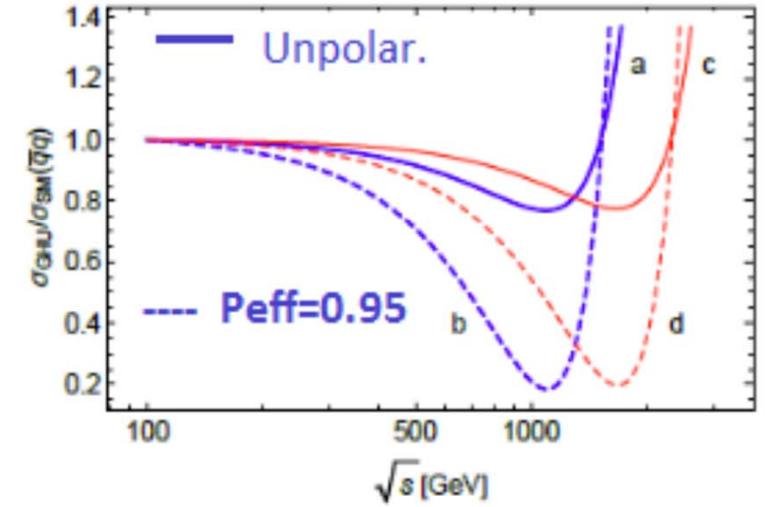
at ILC Peff=0.89

Table 1: Masses and widths of Z' bosons, $Z^{(1)}$, $\gamma^{(1)}$, and $Z_R^{(1)}$ ($N_F = 4$)

θ_H [rad.]	$\frac{z_L}{10^4}$	m_{KK} [TeV]	$m_{Z^{(1)}}$ [TeV]	$\Gamma_{Z^{(1)}}$ [GeV]	$m_{\gamma^{(1)}}$ [TeV]	$\Gamma_{\gamma^{(1)}}$ [GeV]	$m_{Z_R^{(1)}}$ [TeV]	$\Gamma_{Z_R^{(1)}}$ [GeV]
0.115	10	7.41	6.00	406	6.01	909	5.67	729
0.0917	3	8.81	7.19	467	7.20	992	6.74	853
0.0737	1	10.3	8.52	564	8.52	1068	7.92	1058

Z-Z' mixing and propagators

- **Z-Z' Mixing ~energy independent**   **Propagator ~s**

$$Q_{ij} = Q_\gamma^e Q_\gamma^f + \frac{Q_Z^{e_i} Q_Z^{f_j}}{s_W^2 c_W^2} \frac{s}{s - M_Z^2 + i\Gamma_Z M_Z} + \sum_V \frac{g_V^2}{e^2} Q_V^{e_i} Q_V^{f_j} Q_V(c_{e_i}) Q_V(c_{f_j}) \frac{s}{s - M_V^2}$$

- Easy to separate the 2 contributions operating at two energies
- $\delta Q_{ij}(250) - \delta Q_{ij}(500)/4 \sim 3/4 MIX_{ij}$
- Mixing should manifest itself only for bb and tt since LEP1 tells us that leptons show no measurable effect
- As for EFT one cannot deduce M^2V not knowing the coupling constants

Search for a light radion at ILC and LHC

arXiv:1712.06410

- Indication at LEP2 in Zφ(95) and at CMS φ(95)->2γ

- Radion solution for ξ=-0.47

- Complementarity between ILC and LHC

Rγγ and κ² predictions for φ(95) versus the mixing parameter for a vacuum expectation Λ=TeV. Blind zones are in red for ILC and in blue for HL-LHC. ξ=-0.47 (black line) gives a solution consistent with LEP2 and CMS indications and with Higgs measurements.