Heavy quark production in high energy electron positron collisions

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VIRTUAL CONFERENCE

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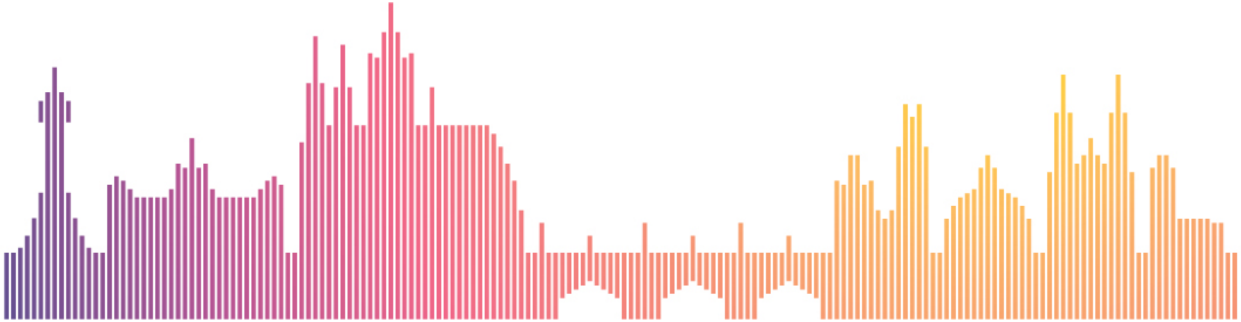
PRAGUE, CZECH REPUBLIC



Outline of the talk

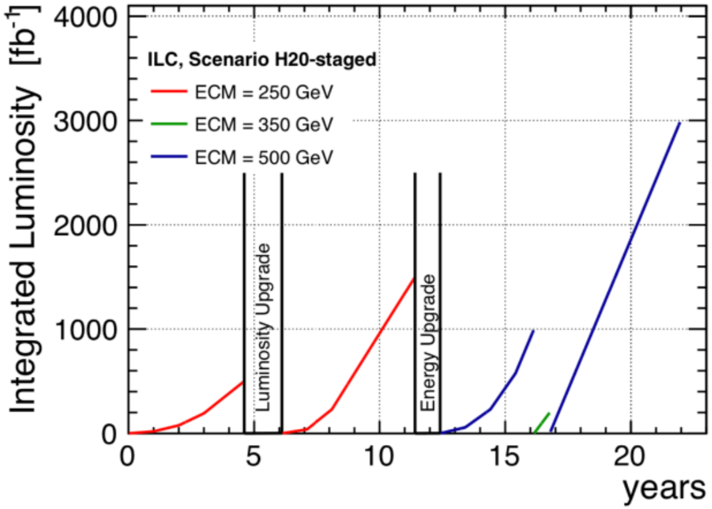
- What do we want to measure and why?
- Where? International Linear Collider, **ILC250**, and the International Large Detector **ILD**
- **top/b/c-quark electroweak couplings** extracted from **differential cross section** measurements
  - Experimental prospects based on full simulation including a comprehensive study of the systematic uncertainties

This talk

ILC physics program

- ILC is a Linear Collider Project, to be hosted in Japan.
  - **Matured technollogy: TDR (accelerator + detectors) since 2013**.
- **All Standard Model particles within reach of planned linear colliders**
- High precision tests of Standard Model over wide range to detect onset of New Physics
- **Machine settings can be “tailored” for specific processes**
  - **Centre-of-Mass energy**
  - **Beam polarisation** (straightforward at linear colliders)
- Background free searches for BSM through beam polarisation

current ILC run plan: (basis of projections)



250 GeV: 2 ab-1, 500 GeV: 4ab-1, 350 GeV: 0.2 ab-1

also, runs at 91 GeV (5B Z’s) and 1000 GeV (8 ab-1)

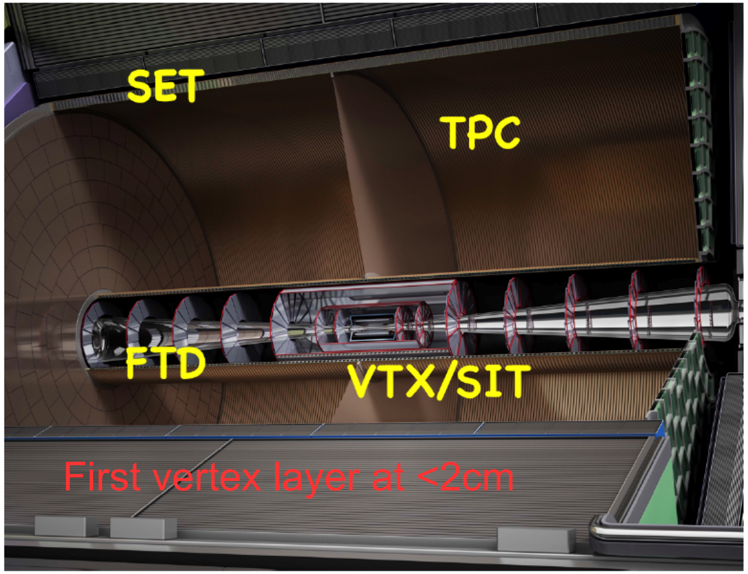
L upgrade: 5 Hz → 10 Hz; E upgrade: extend the linac

M. Peskin Snowmass (EF Workshop 21st July 2020)

See T. Tanabe and G. Wilson’s talks for more information on Linear Colliders and ILC

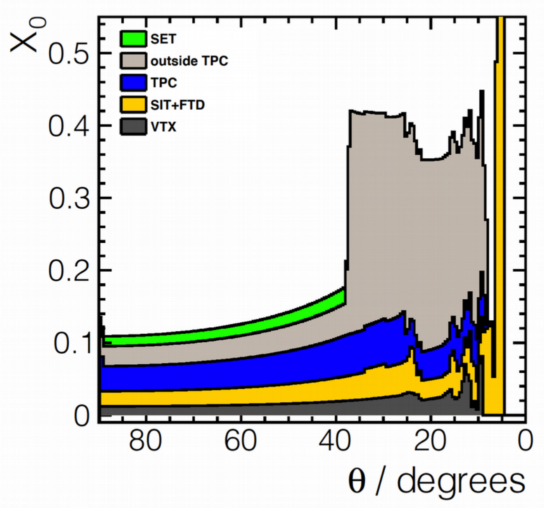
ILD highlights

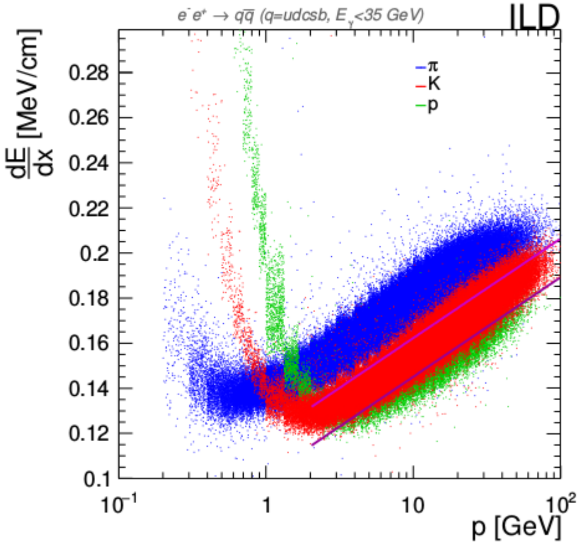
- **ILD snapshot**



- **High** angular **coverage** with **minimum material budget** and **PID (TPC)**

- ILC experiments, as the **ILD**, will provide excellent:
  - Beam IP constraint
  - **Secondary vertex separation and excellent flavour tagging**
  - Tracking **efficiency** (>99%)
- **Particle Flow optimized detector with high granularity calorimeters (>10^8 cells!)**





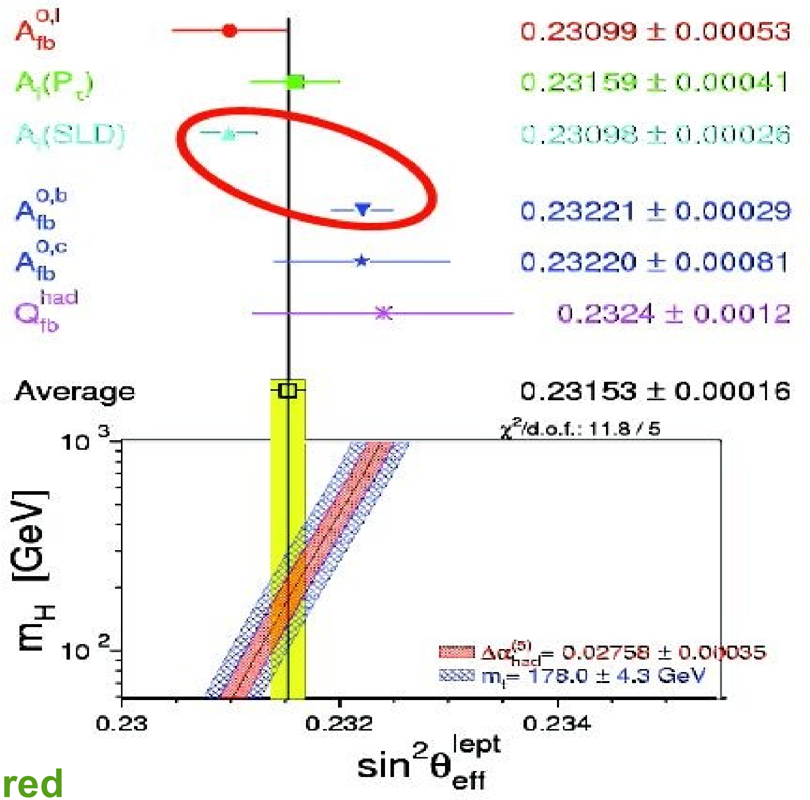
See T. Tanabe's talk on ILD

Motivation: LEP/SLC tension

- Current LEP & SLC best $sin^2\theta^l_{eff}$ **measurements** show **tension**
  - This measurement is the one with **largest tension with the SM fit.**
  - Most precise single Individual determination of $sin^2\theta^l_{eff}$

    from SLC → Left-right asymmetry of leptons
  - Most precise single Individual determination of $sin^2\theta^l_{eff}$

    from LEP → forward backward assymetry (b-quark)
- Heavy quark effect, effect on all quarks/fermions, no effect at all?



The **resolution** of this issue requires improving the the measurements precission an order of magnitude

Per mil level of experimental precision is required

Motivation: Two fermion processes

- Many **BSM scenarios** (i.e. Randal Sundrum, compositeness, Higgs unification models…) predict heavy resonances coupling to the (t,b) doublet and also lighter fermions (i.e. c/s quarks)
  - **BSM resonances** tend to **couple** to the **right components.**
  - Only (t,b) doublet

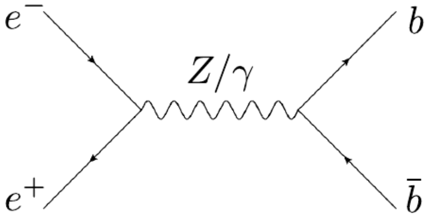
    → Peskin, Yoon arxiv:1811.07877
    → Djouadi et al arxiv:hep-ph/0610173
  - All fermions

    → Hosotani et al arxiv:1705.05282 arxiv:2006.02157
  - For an EFT review see M. Perelló's talk and arxiv:1907.10619
- **How do we probe these BSM scenarios ?**

Probe such BSM require at least per mil level of experimental precision
tt/**bb**/cc… (ss?) **Can we do it?**
(this talk)

Motivation: Two fermion processes

- Differential cross section for (relativistic) di-fermion production



$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to f\bar{f}) = \Sigma_{LL}(1+\cos\theta)^2 + \Sigma_{LR}(1-\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \to f\bar{f}) = \Sigma_{RR}(1+\cos\theta)^2 + \Sigma_{RL}(1-\cos\theta)^2$$

  - The helicity amplitudes Σ_{IJ}, contain the couplings g_L/g_R (or Form factors or EFT factors)
  - Left/right asymmetries (characteristic for each fermion)

- **Only beam polarisation allows inspection of the 4 helicity amplitudes for all fermions**

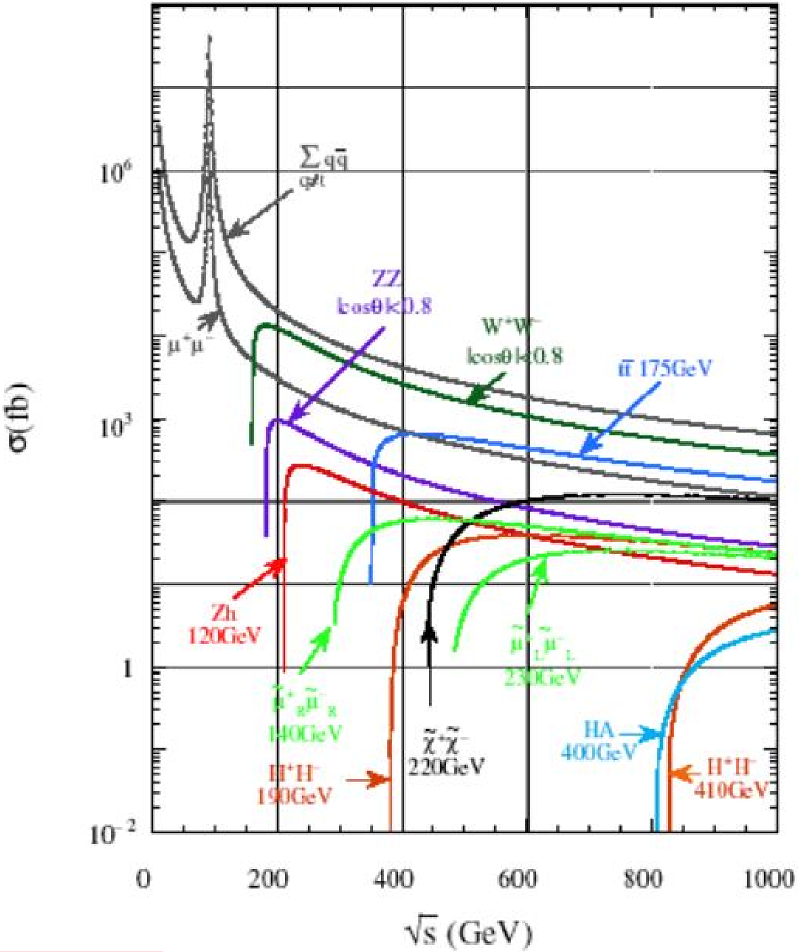
- **These processes have been deeply studied at LEP/SLC at the Z-pole**
  - no access to the γ or Z/γ interferences
  - Moderated quark tagging or charge measurements capabilities.
  - Also moderated angular acceptance of the detectors

Cross sections

$$\sigma_{e^- e^+ \to q\bar{q}}$$

	Channel	σ_{unpol} [fb]	$\sigma_{-,+}$ [fb]	$\sigma_{+,-}$ [fb]
500 GeV	q=t	572	1564	724
	q=b	372	1212	276
	q=u,d,s,c	2208	6032	2793
250 GeV	q=t	--	--	--
	q=b	1756	5677	1283
	q=c	3020	8518	3565
	q=u,d,s	6750	18407	5463

- **Beam polarisation also enhances the cross section values**



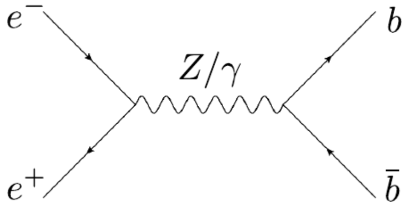
In this talk I concentrate on b-quark pair production at 250 GeV

Observables

- Quark (fermion) **electroweak couplings** can be **inferred from cross section, Rq** and forward backward asymmetry **AFB** observables.

$$R_q^0 = \Gamma_{q\bar{q}} / \Gamma_{had} (Z - pole)$$
$$\rightarrow R_q^{cont.} = \sigma_{q\bar{q}} / \sigma_{had} (s > Z - pole)$$

→ Quark identification. No need to measure an angular distribution, a priori.



$$\frac{d\sigma}{d\cos\theta}$$

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

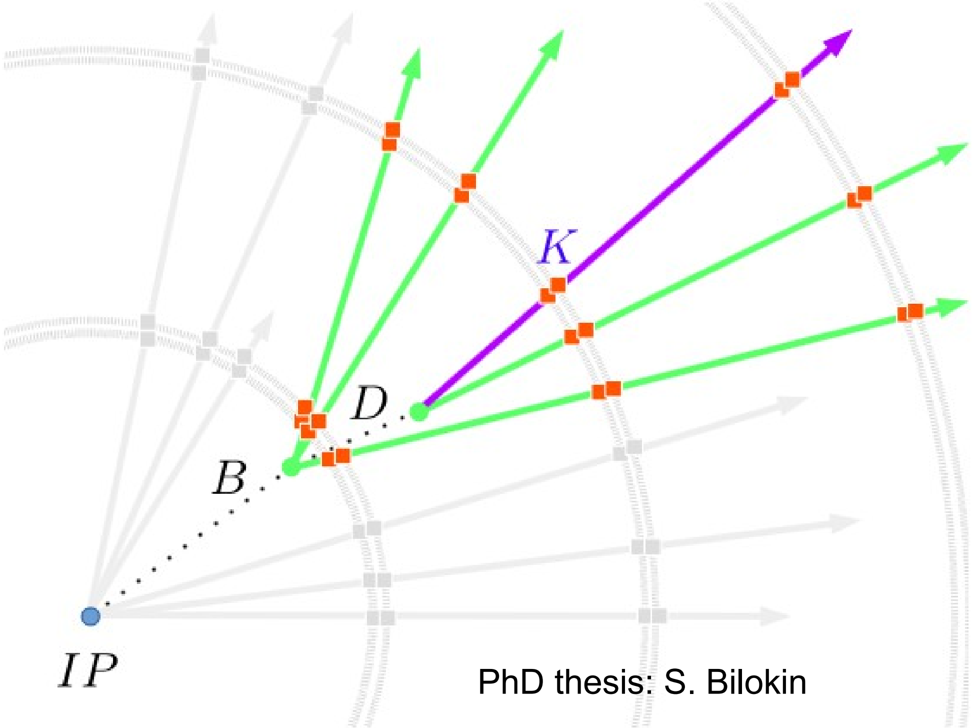
Angular Distribution.

Quark ID + charge measurement (quark – antiquark disentangling)

Gives access to all left/right couplings.

Flavor tagging and charge measurement

- **Flavor tagging**
  - Indispensable for analysis with final state quarks
- **Quark charge measurements**
  - Important for top-quark studies but Indispensable for ee→ bb/cc/ss...
- **Charge measurements:**
  - Vtx charge and **Kaon Identification**
  - High purity → control of the migrations **(double tagging)**
- **Future detectors** can base their entire measurements on double Tagging and vertex charge
  - LEP/SLC had to include single tags and semi-leptonic events



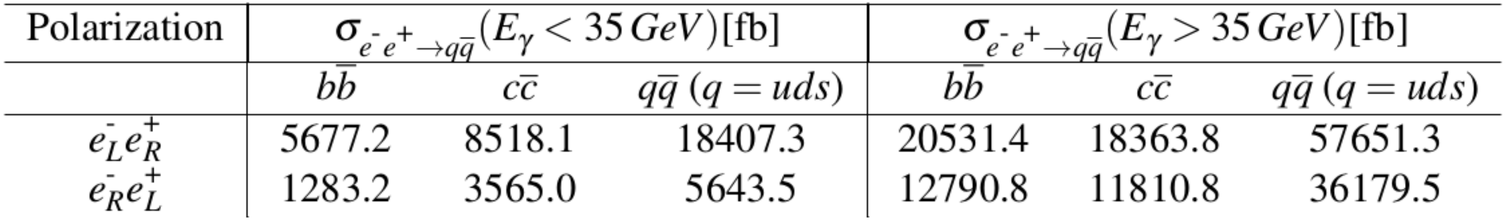
PhD thesis: S. Bilokin

b/c-quarks: reconstruction efficiencies

Arxiv:1709.04289, PoS(EPS-HEP2019)624
ILD Note in progress

- 2 back-to back jets topology
- Main source of systematics in LEP/SLC:
  - Uncertainties related to tagging efficiency
  - The tagging efficiency needs to be measured (not MC estimated) to reach the per mil level of accuracy.

- New systematics sources for LC operating polarised beams far from the Z-pole
  - Beam polarisation
  - Event selection → **backgrounds** **from radiative return** events and **WW/ZZ/HZ**



Polarization	$\sigma_{e^-e^+\to q\bar{q}}(E_\gamma < 35\,GeV)$[fb]			$\sigma_{e^-e^+\to q\bar{q}}(E_\gamma > 35\,GeV)$[fb]		
	$b\bar{b}$	$c\bar{c}$	$q\bar{q}\ (q = uds)$	$b\bar{b}$	$c\bar{c}$	$q\bar{q}\ (q = uds)$
$e^-_L e^+_R$	5677.2	8518.1	18407.3	20531.4	18363.8	57651.3
$e^-_R e^+_L$	1283.2	3565.0	5643.5	12790.8	11810.8	36179.5

$q\bar{q}$ signal

Rad. Ret. BKG

Up to x10 signal

Double Tag Method

- Needed to reach the per mil precision
- The sample consisted on events made of two hadronic jets (qqbar)
  - The LEP/SLC preselection consisted on a “simple” veto of Z→ leptons events
- The method is based on the comparison of single vs double tagged samples
  - f1= ratio of number jets that are tagged as b-jets
  - f2= ratio of events in which both jets are tagged as b-jets

To remove Luminosity dependence.

To remove modelling dependence on the efficiency of b-tagging

$$f_1 = \epsilon_b R_b + \epsilon_c R_c + \epsilon_{uds} R_{uds}$$

$$f_2 = \epsilon_b^2 (1+\rho_b) R_b + \epsilon_c^2 R_c + \epsilon_{uds}^2 R_{uds}$$

- Rb and ε_b are measured simultaneously.

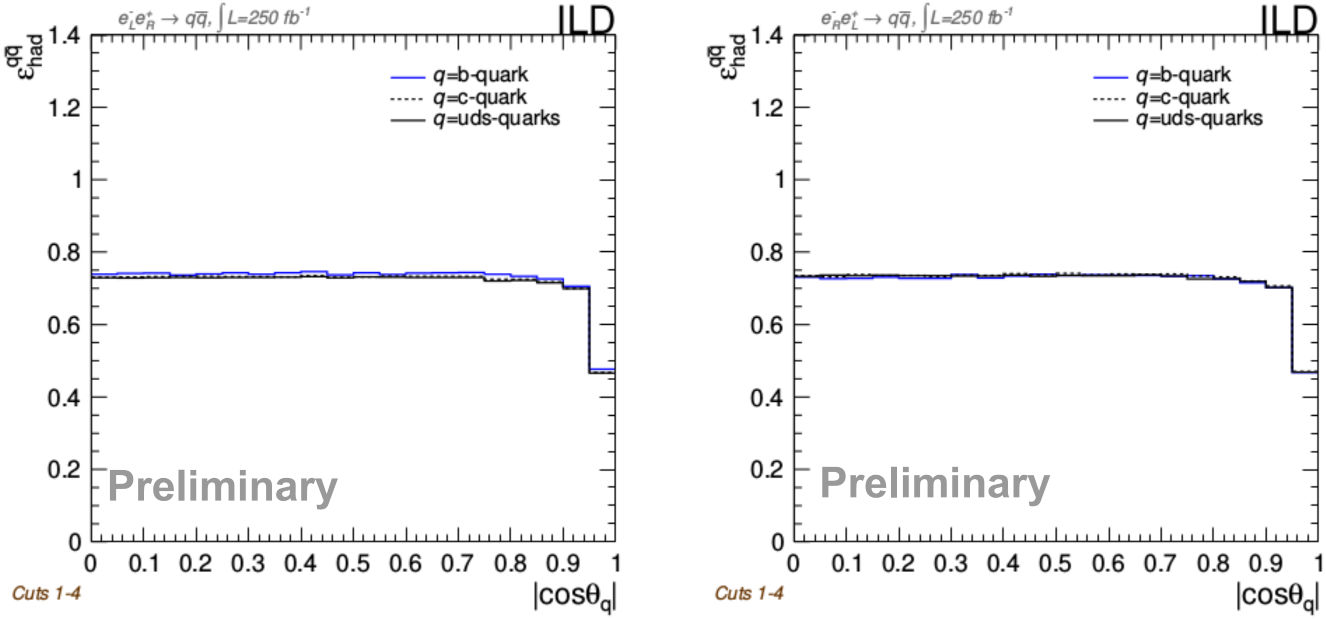
- **ε_b = b-tagging efficiency**
- ρ_b = b-tagging correlation factor
- ε_c = probability of tagging a c-quark jet as b-jet
- ε_{uds} = probability of tagging an uds-quark jet as b-jet

These values must be as small as possible and with small uncertainties

to not spoil our accuracy (not covered in this talk)

Double Tag Method

- **This method requires** (to minimise modelling uncertainties)
  - **Preselection with similar efficiency for all quark flavours**
  - Preselection that reduces to the minimum the main backgrounds
  - High quark tagging efficiencies with minimal mis-tagging efficiencies



Arxiv:1709.04289, PoS(EPS-HEP2019)624
ILD Note in progress

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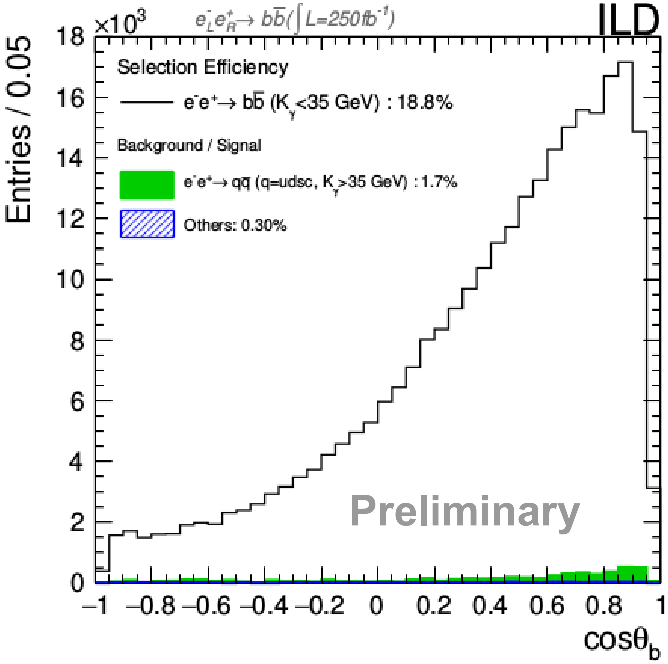

- Main bkg ee→ ZY(ISR)
  - ~x10 larger than signal
  - For **~90% of such ISR photons are lost in the beam pipe** → events filtered by energy (angular) conservation arguments
  - The **remaining ~10% are filtered by identifying photons** in the detector (efficiency of ~90%)
- Very small B/S ~2%

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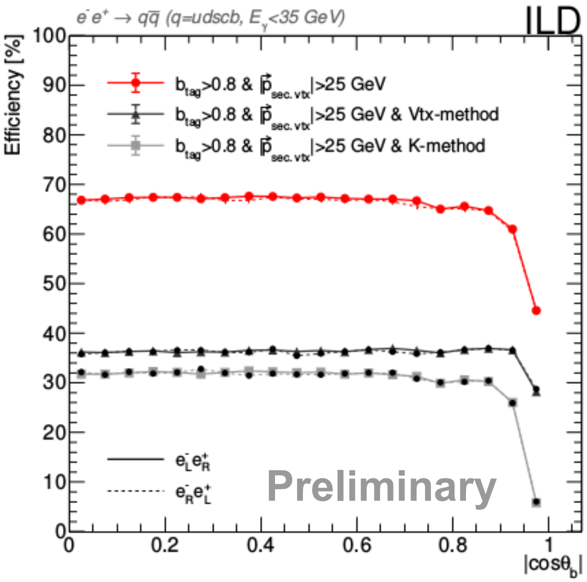
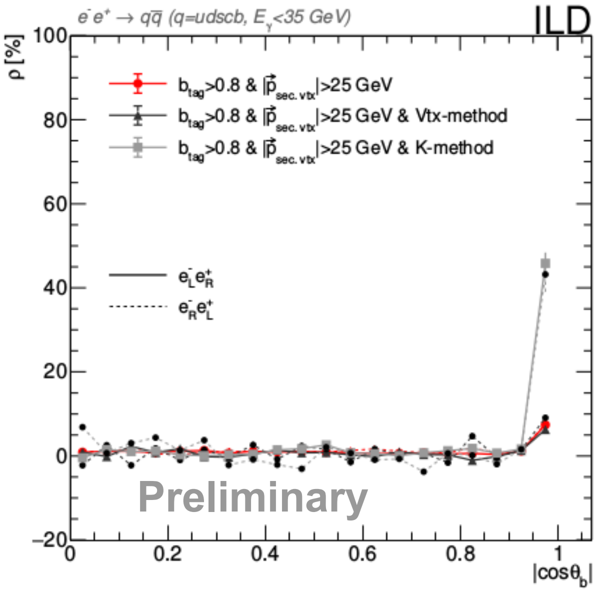




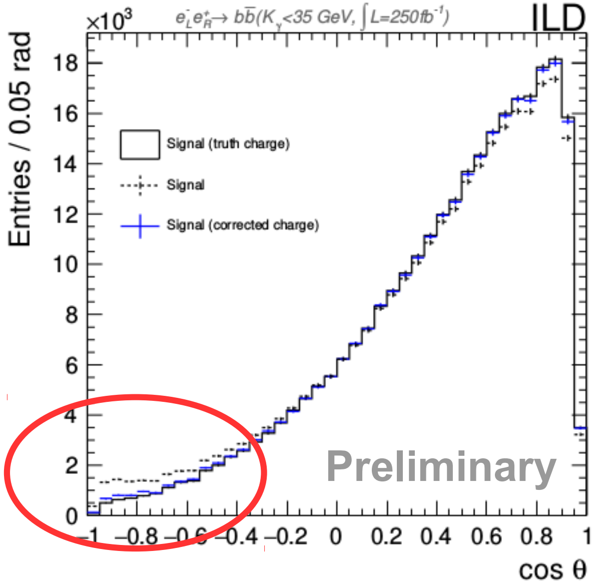
- **Excellent prospects for b-tagging** (or c-tagging) with very low correlation factor ~ 0 (~2% at LEP)
- **Differential measurements!**
  - Constant values for most of the angles
  - Drop of acceptance the very forward region → optimizations are under consideration
- **Miss-efficiencies very small**
  - <1% for c-quark
  - ~0% for uds

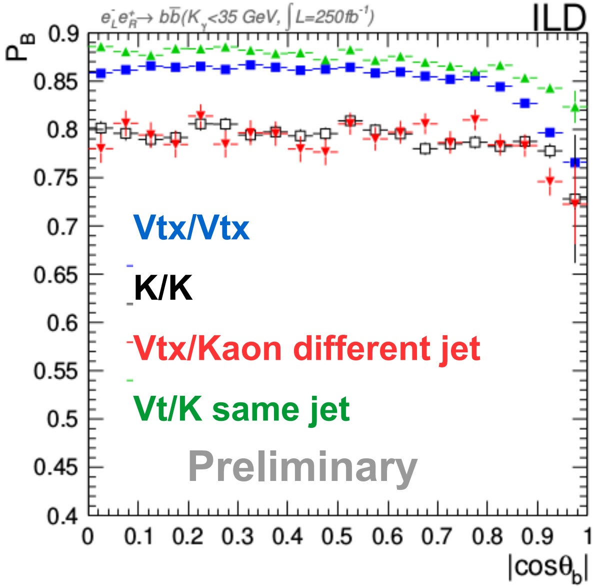
Arxiv:1709.04289, PoS(EPS-HEP2019)624
ILD Note in progress

Charge measurement: migrations

- Mis-measurements of the jet charge produce a flip of the sign in the differential distribution: **migrations**.
  - Mistakes due to lost tracks, mis-identification of kaons…
- Migrations look as “new physics” → we need to correct them
  - Using data: double charge measurements with same and opposite charges (see back-up slides)
  - We measure the probability to reconstruct correctly the charge (P_B) and use it for correction
  - **DATA DRIVEN METHOD.**

BSM or simple migrations?

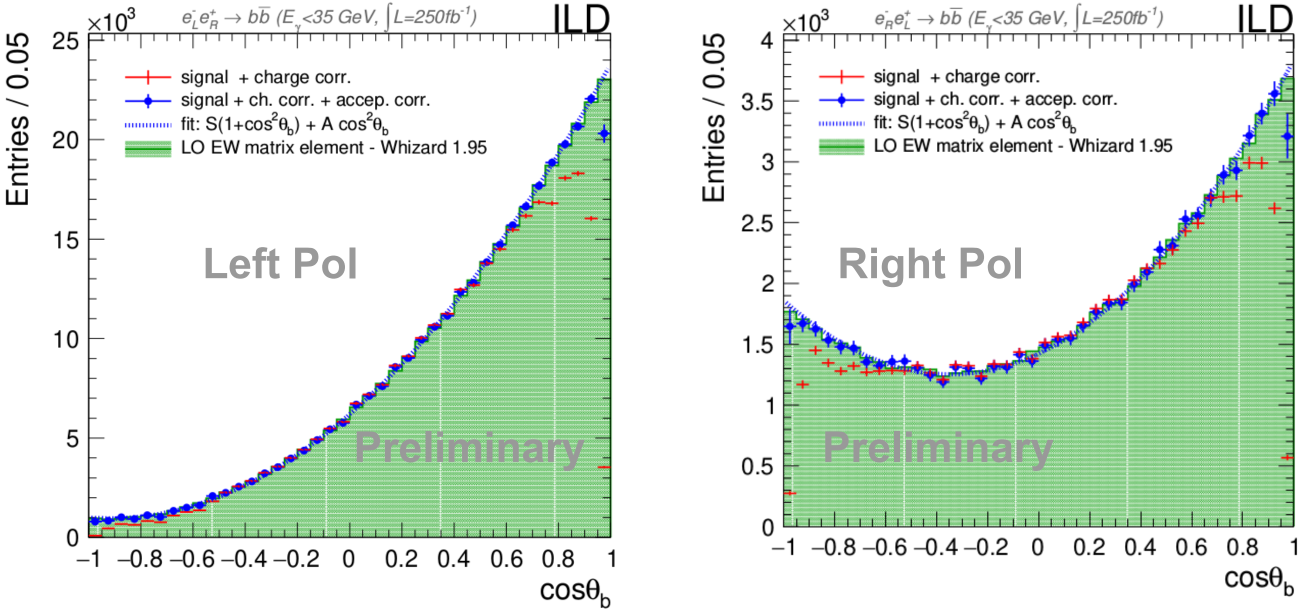




- **P_B limited by vertex reconstruction efficiency, Particle ID efficiency and B0 oscillations.**

Arxiv:1709.04289, PoS(EPS-HEP2019)624
ILD Note in progress

Results (1)



Excellent agreement between predicted and reconstructed distributions

- Gap between red dots and green histogram = acceptance drop.
- Blue dots = corrected acceptance
- The fit is restricted to |costheta|<0.8
  - *Minimal impact of the corrections*

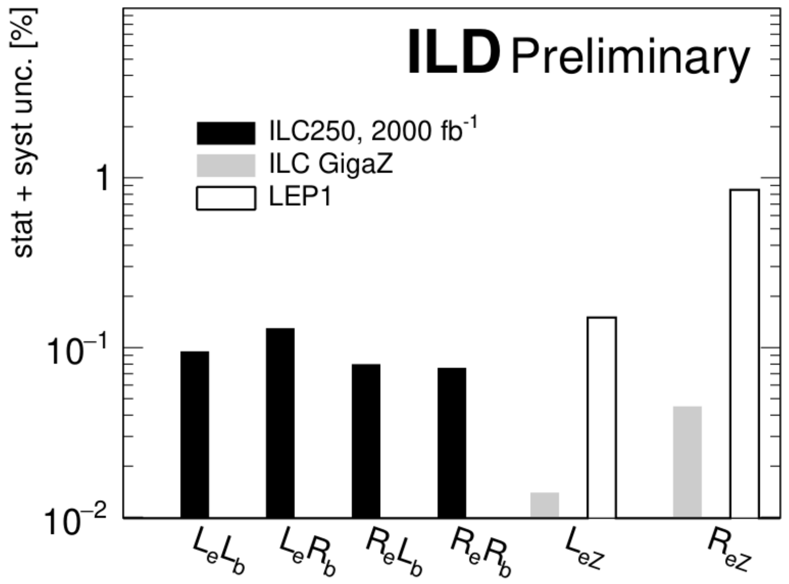
	Beam Polarisation	
	$(-+)$	$(+-)$
$\Delta R_b^{cont.}$	0.12 (stat.) ± 0.14 (syst.) %	0.15 (stat.) ± 0.13 (syst.) %
$\Delta A_{FB}^{b\bar{b}}$	0.30 (stat.) ± 0.05 (syst.) %	0.85 (stat.) ± 0.10 (syst.) %

Stat unc (2000 fb-1)

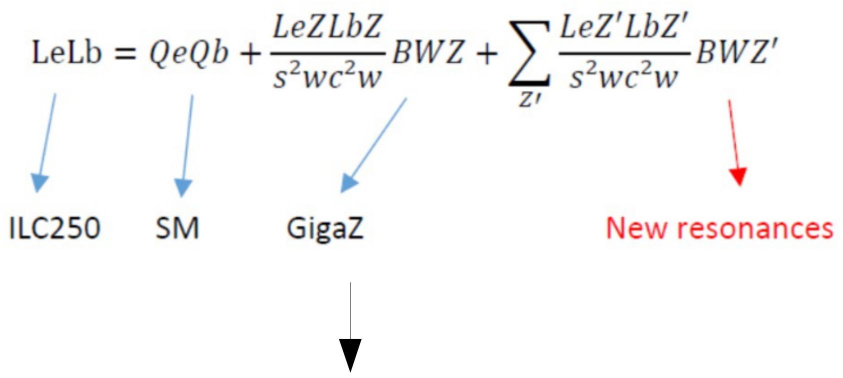
Syst unc.:
- Selection and background rejection
- quark tagging/mistagging (modelisation, QCD, correlations)
- Luminosity
- Polarisation

Arxiv:1709.04289, PoS(EPS-HEP2019)624
ILD Note in progress

Results (2)



Couplings (notation for new resonances)



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

Sensitive to Z-Z' mixing effects

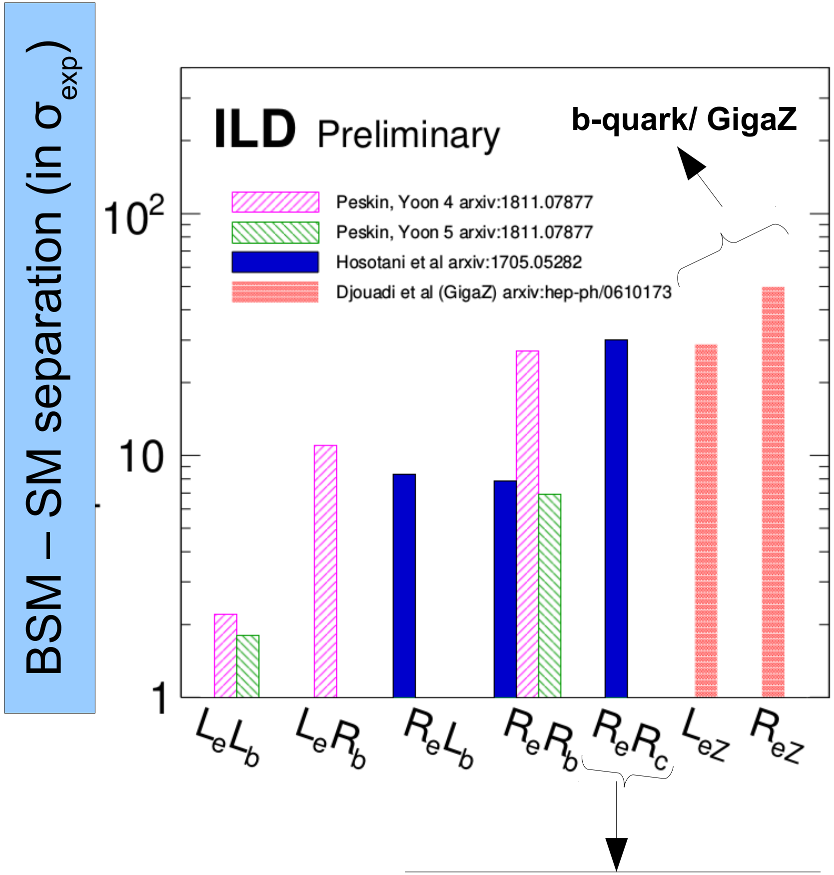
(that could explain AFBb measurement of LEP?)

Prospects for couplings determination are order of magnitude better than at LEP

- ► Resolution of the LEP/SLC anomaly
- ► **Full disentangling of helicity structure for all fermions only possible with polarised beams!!**

Arxiv:1709.04289, PoS(EPS-HEP2019)624
ILD Note in progress

Results (3) BSM benchmarks



c-quark Arxiv:2002.05805

- ▶ Many BSM predict deviations only for the right couplings

BEAM POLARISATION is crucial

Expected number of standard deviations for different **RS/compositeness BSM scenarios** when determining the different EW couplings to c- and b-quark at **ILC250** (with GigaZ input).

- Models that predict multi-TeV Z’ resonances
- With or without mixing at Z-pole
- See backup for more details on the models

Potntial for discovery of new resonances mZ’ ~ O(20-30) TeV at ILC250

Arxiv:1709.04289, PoS(EPS-HEP2019)624
ILD Note in progress

Top quark: results (1)

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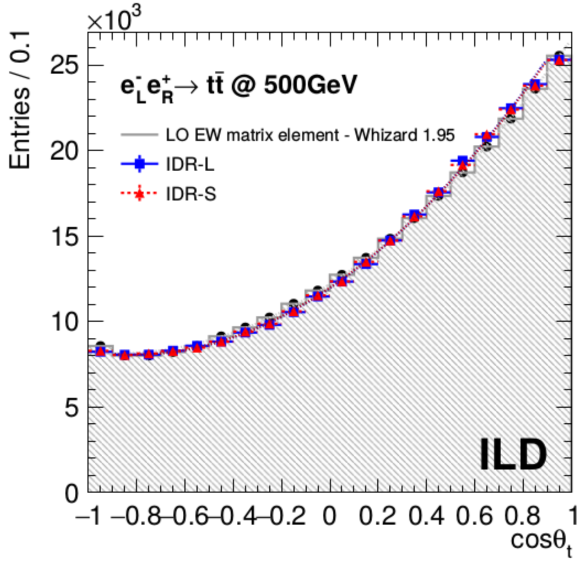
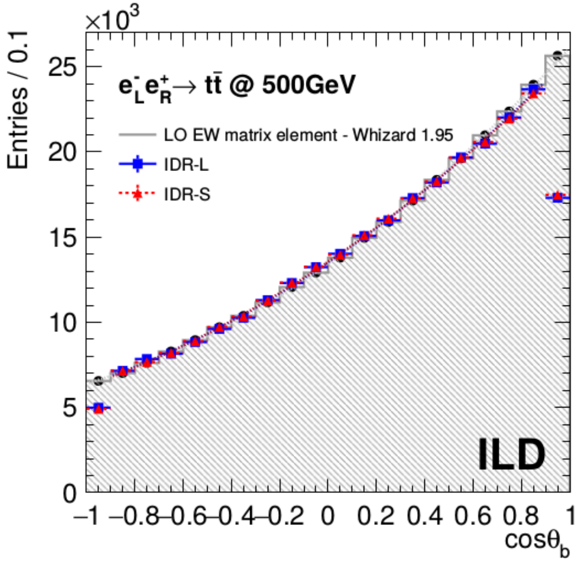




- Semi-leptonic channel
- Left polarisation plots
  - B-jet carries top direction information
  - Very useful for the hadronic channel!
- Right polarisation (not shown)
  - W-carries the top direction information → **lepton charge and c/s tagging become important**

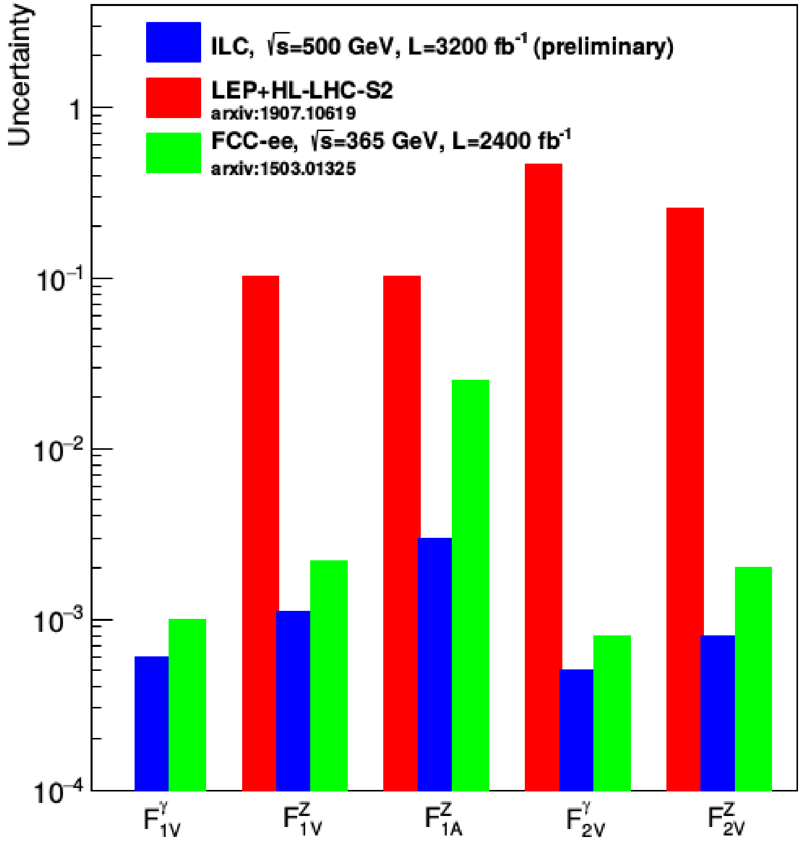
- Integrated Luminosity 4 fb^{-1}
- Thanks to the jet charge calculations capabilities, we could use all decay channels.
- Efficiencies of 75% (cross section) and 30% (differential cross section)
- Exact reproduction of generated spectra
  - Statistical precision on cross section: ~0.1% Statistical precision on A FB : ~0.5%

Can expect that systematic errors will match statistical precision (but needs to be shown)

IDR-L/S
Are two detector
Concepts compared
In the ILD
Interim Design Report ILD
Arxiv:2003.01116

Top quark: results (2)

ILD-PHYS-PUB-2019-007



- e+e- collider way superior to LHC (√s = 14 TeV)
- Final state analysis at FCCee (polarisation)
  - Also possible at LC => Redundancy

- Two remarks:
  - 500 GeV is nicely away from QCD Matching regime

    Less systematic uncertainties
  - The determination of axial form factors highly benefit from higher energies

- See M. Perelló's talk to interpret this plot in terms of EFT Wilson coefficients.

Summary / conclusions

- ILC is ideally suited for precision measurements of two-fermion final states
- **ILC will have the answer whether new physics acts on heavy doublet (t,b) only or on all fermions**
  - Will/would probe helicity structure of electroweak fermion couplings over at least one order of magnitude in energy (Z-Pole -> ~1 TeV)
- **Achievable experimental precisions ~0.1 – 1%**
  - Demanding analysis requiring the full detector capabilities: Vertex charge and particle ID, PFO for final state jets, etc
  - **Comprehensive assessment of the systematic uncertainties done (b-quark)** or in progress (top and charm)
- **Effects may become already visible at 250 GeV stage for b quark and c quarks (and other light fermions)**
  - **Amplification of effects at higher energies**
  - **Clear and unique pattern thanks to polarised beams**

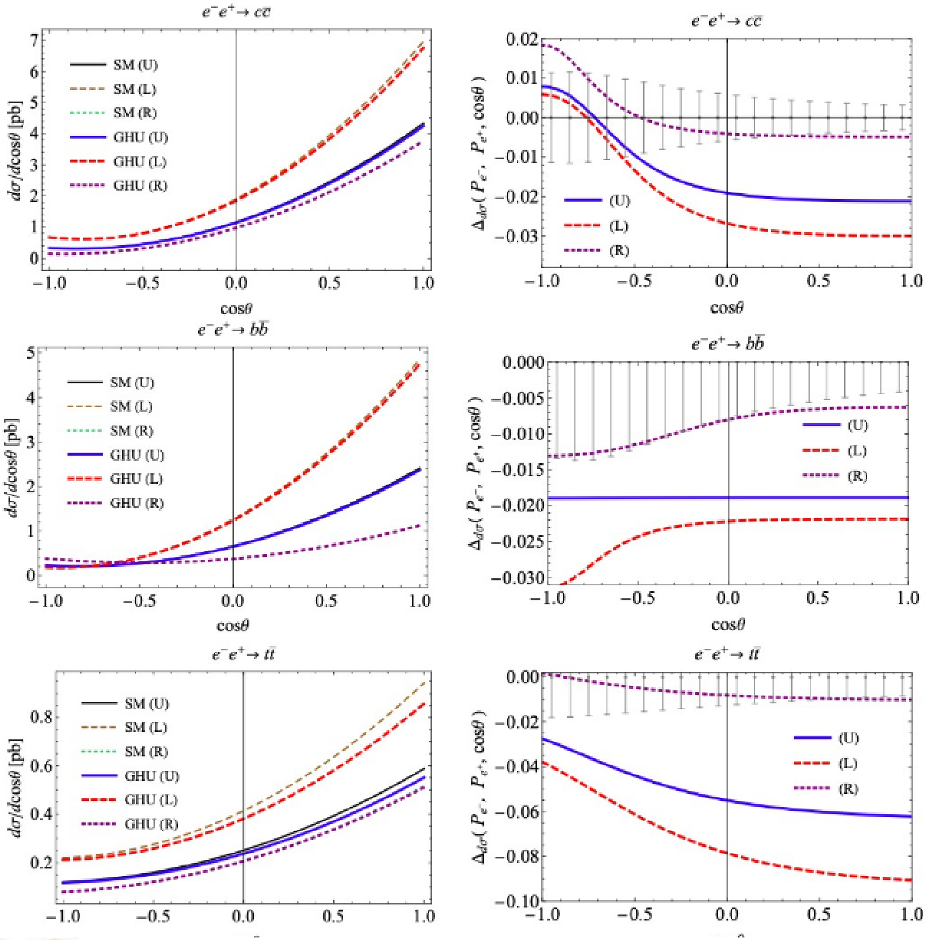
- Active phenomenological studies in terms of global analyses (EFT) and concrete models (not covered in this talk)
- Theory challenges (not covered in this talk)
  - Need at least NLO electroweak predictions (and MC programs) for correct interpretation of results

Thanks for your attention.

Back-up slides

- WORK IN PROGRESS

a BSM example: GUT Inspired Grand Higgs Unificaton Model



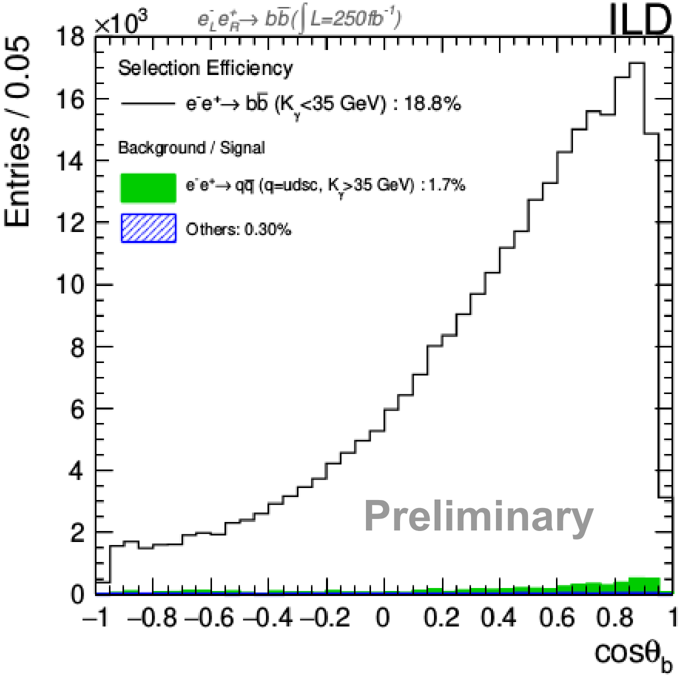
arxiv:2006.02157

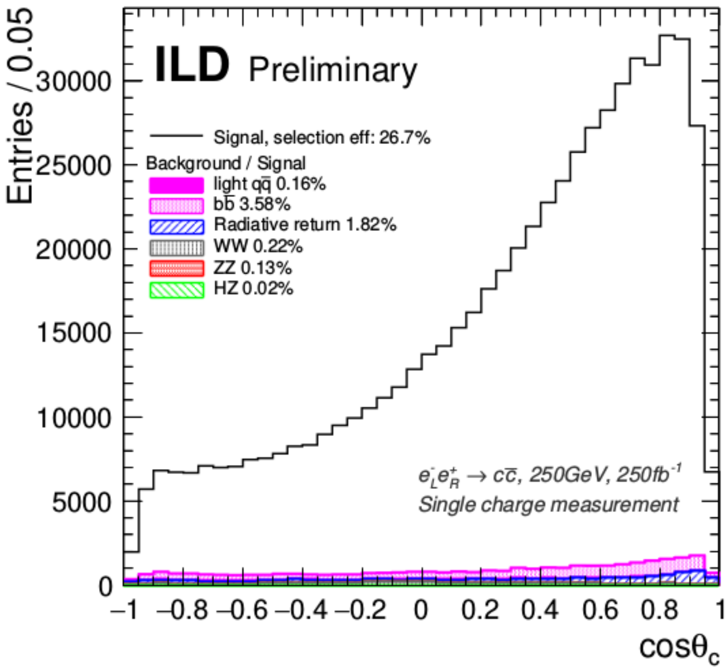
- Model parameter is Hosotani angle θ_H yielding the Higgs-Potential as consequence of Aharanov-Bohm Phase in 5th dimension
- Model defined in Randall-Sundrum warped extra dimensions
  - KK excitations of gauge bosons and new bosons modify fermion couplings
- Predictions for ILC
  - m_{KK} = 13 TeV and θ_H = 0.1
- Deviations from SM of the order of a few %
  - Effects measurable already at 250 GeV
  - Effects amplified by beam polarisations
  - Effects for tt, bb and cc (and other light fermions)
- One concrete example for importance to measure full pattern of fermion couplings
  - Full pattern only available with beam polarisation

Slide borrowed from R. Poeschl (EF04 Snowmass process)

b/c-quarks: reconstruction efficiencies

- After the preselection, we apply the b/c tagging including charge measurement for differential cross sections.
  - Efficiencies for inclusive cross section are ~x2 larger



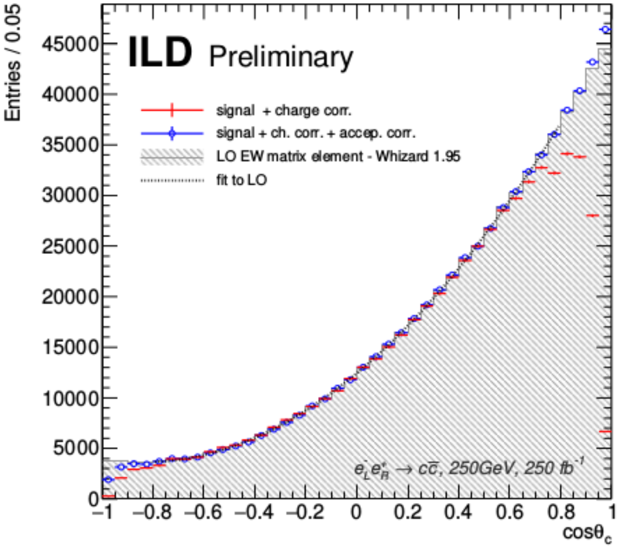


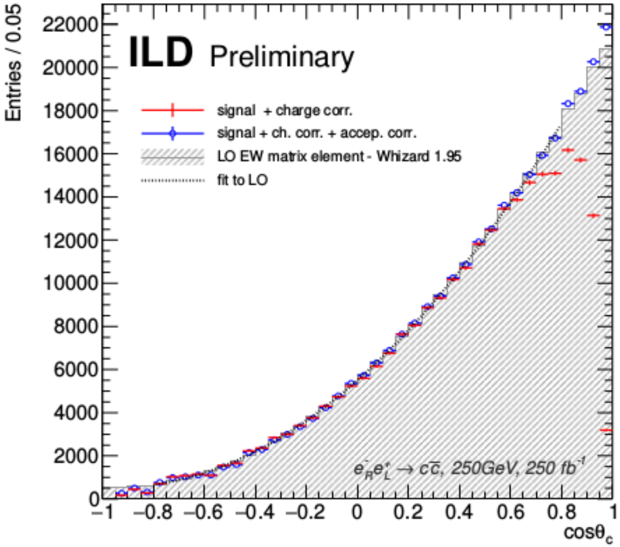
- Background ~free analysis!

Arxiv:2002.05805

Arxiv:1709.04289, ILD Paper in progress

b/c-quarks: Results (2)



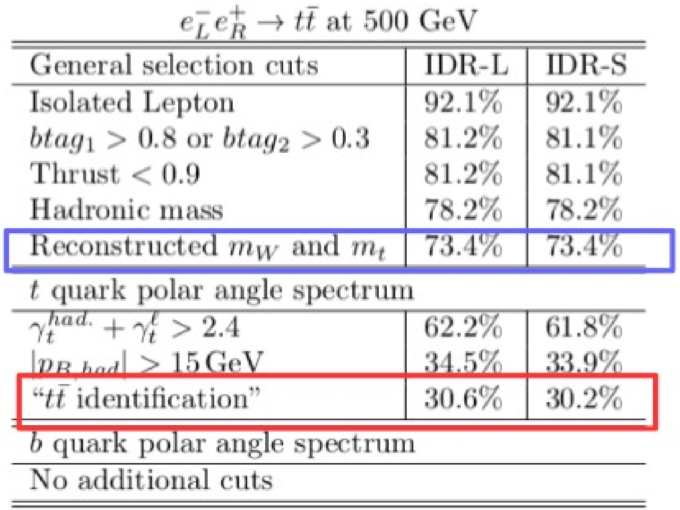


c-quark case

- Similar precisions (work in progress)
- Lower tagging efficiency compensated by higher statistics for both polarisations.
- Kaon Identification becomes the most promising channel for the charge measurement

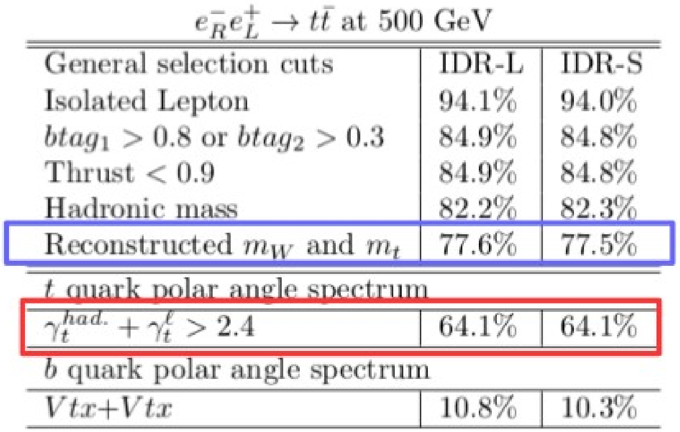
Arxiv:2002.05805

Top-quark: Reconstruction efficiencies



$e^-_L e^+_R \to t\bar{t}$ at 500 GeV

General selection cuts	IDR-L	IDR-S
Isolated Lepton	92.1%	92.1%
$btag_1 > 0.8$ or $btag_2 > 0.3$	81.2%	81.1%
Thrust < 0.9	81.2%	81.1%
Hadronic mass	78.2%	78.2%
Reconstructed m_W and m_t	73.4%	73.4%
t quark polar angle spectrum		
$\gamma_t^{had.} + \gamma_t^{\ell} > 2.4$	62.2%	61.8%
$\lvert p_{B,had}\rvert > 15\,\mathrm{GeV}$	34.5%	33.9%
"$t\bar{t}$ identification"	30.6%	30.2%
b quark polar angle spectrum		
No additional cuts		



$e^-_R e^+_L \to t\bar{t}$ at 500 GeV

General selection cuts	IDR-L	IDR-S
Isolated Lepton	94.1%	94.0%
$btag_1 > 0.8$ or $btag_2 > 0.3$	84.9%	84.8%
Thrust < 0.9	84.9%	84.8%
Hadronic mass	82.2%	82.3%
Reconstructed m_W and m_t	77.6%	77.5%
t quark polar angle spectrum		
$\gamma_t^{had.} + \gamma_t^{\ell} > 2.4$	64.1%	64.1%
b quark polar angle spectrum		
$Vtx{+}Vtx$	10.8%	10.3%

Total cross section

- Typical selection efficiencies fo the 75%
- Independent of beam polarisation

Differential cross section

- Differences for beam polarisations
- Left hand polarisation more vulnerable to migrations
- Requires information from the hadronic state
- Vertex / Kaon as in the bb-case