Disclaimer

- Slides on construction. Still few references and numbers are missing…
  - Quoted as XXX or ??
  - WORK IN PROGRESS.
- Preliminary labels to be added in most plots !

Heavy quark production in high energy electron positron collisions

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ICHEP 2020 | PRAGUE

40th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

VIRTUAL CONFERENCE

28 JULY - 6 AUGUST 2020

PRAGUE, CZECH REPUBLIC

Outline of the talk

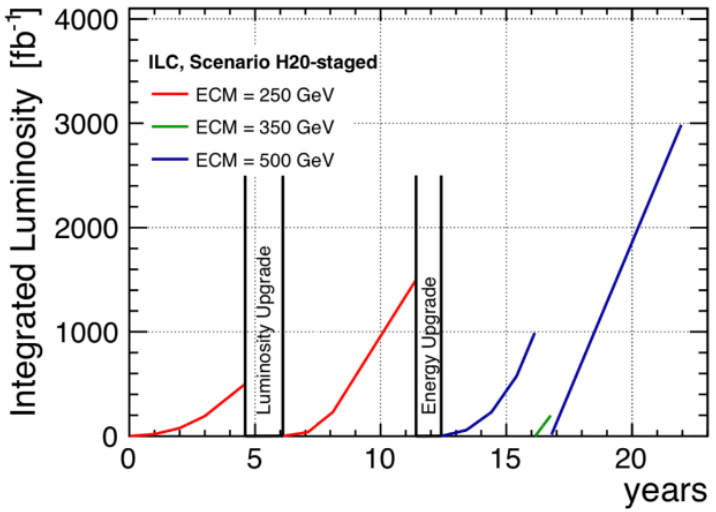
- What do we want to measure and why?
- Where? International Linear Collider, **ILC250**, and the International Large Detector **ILD**
- **top/b/c-quark electroweak couplings** extracted from **differential cross section** measurements
  - Experimental prospects based on full simulation and full systematic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

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)

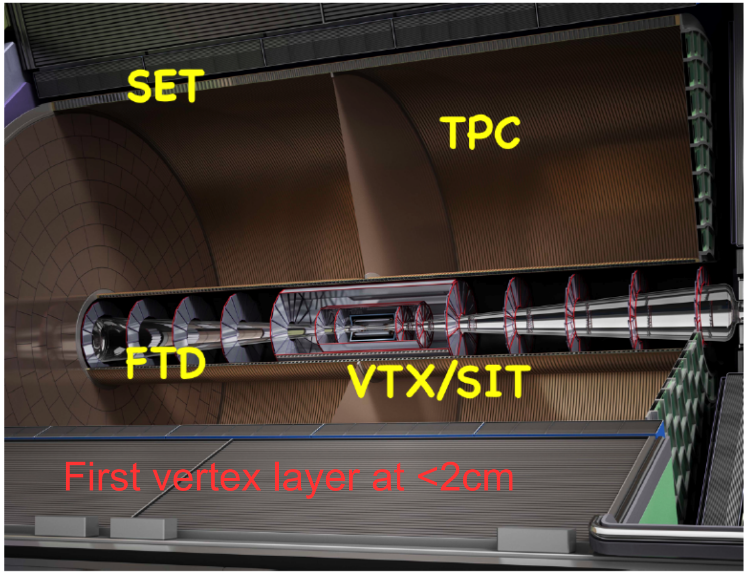
L upgrade: 5 Hz → 10 Hz; E upgrade: extend the linac

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

See XXX talk for more information on Linear Colliders and ILC

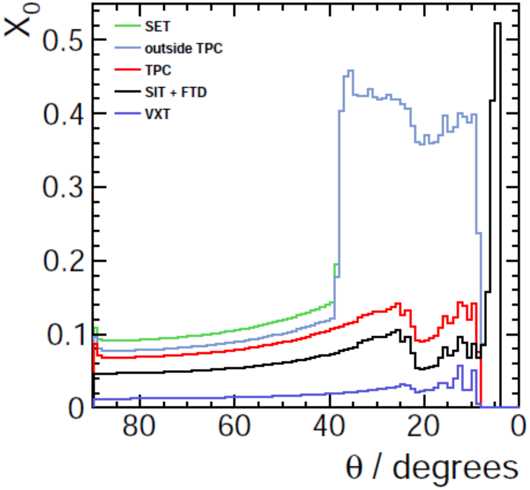
ILD highlights

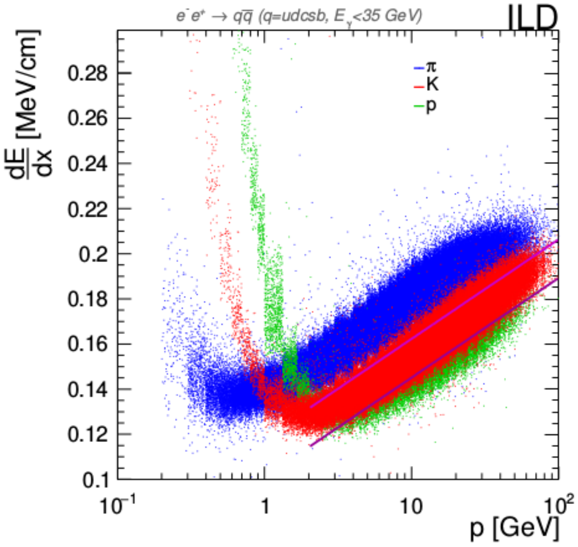
- **ILD snapshot**



- **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!)**

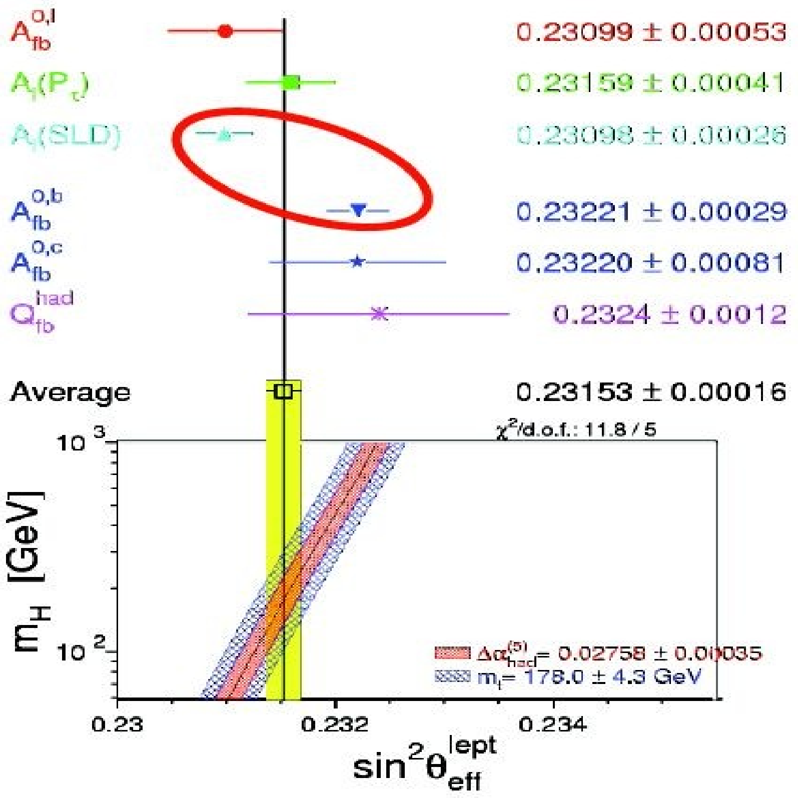




See T. Tanabe's talk on ILD

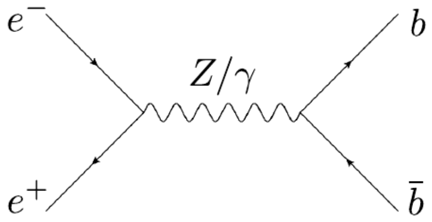
Motivation: LEP/SLC tension

- 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?



Two fermion processes

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



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

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

  - The helicity amplitudes Σ_{IJ}, contain the couplings g_L/g_R (or Form factors or EFT factors)

    For an EFT review see M. Perelló's talk and arxiv:1907.10619

  - Left/right asymmetries (characteristic for each fermion)

- 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.

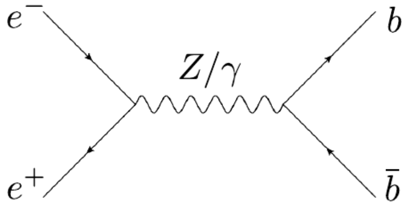
- **Only beam polarisation allows inspection of the 4 helicity amplitudes for all fermions**

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.



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

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

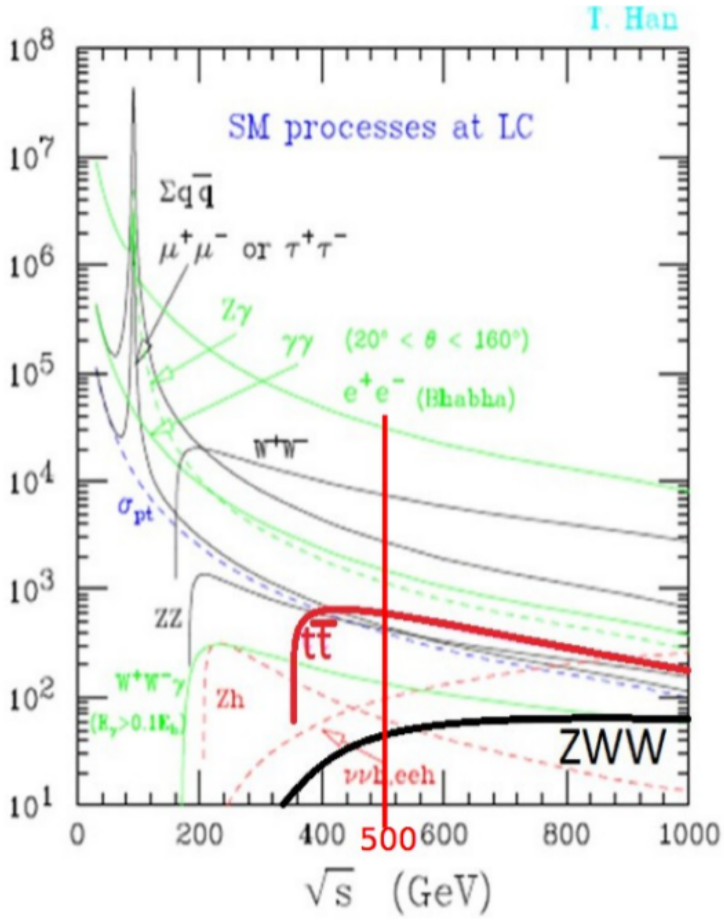
→ Angular Distribution.

Quark ID + charge measurement (quark – antiquark disentangling)

Gives access to all left/right couplings.

- These observables have been measured at **LEP/SLC at the Z-pole**
  - no access to the γ or Z/γ interferences
  - Moderated quark tagging and charge measurements.
  - Also moderated angular acceptance of the detectors: drop at cos(θ) ~0.6

Cross sections



$e^+e^- \to t\bar{t}$: 500 GeV | 352 GeV (unpol)

Channel	$\sigma_{unpol.}$ [fb]	$\sigma_{-,+}$ [fb]	$\sigma_{+,-}$ [fb]	352 GeV (unpol)
$t\bar{t}$	572	1564	724	450 fb
$\mu^+\mu^-$	456	969	854	
$\sum_{q=u,d,s,c} q\bar{q}$	2208	6032	2793	25.2 pb
$b\bar{b}$	372	1212	276	
γZ^0	11185	25500	19126	
W^+W^-	6603	26000	150	11.5 pb
Z^0Z^0	422	1106	582	865 fb
$Z^0W^+W^-$	40	151	8.7	
$Z^0Z^0Z^0$	1.1	3.2	1.22	
Single t for $e^+e^- \to e^-\bar{\nu}_e t\bar{b}$ [11]	3.1	10.0	1.7	

$e^+e^- \to b\bar{b}$: 250 GeV

Channel	σunpol fb	σL fb	σR fb
$b\bar{b}$	1756	5629	1394
$\gamma b\bar{b}$ (Z return)	7860	18928	12512
ZZ hadronic with $b\bar{b}$	196	549	236
HZ hadronic with $b\bar{b}$	98	241	152

$e^+e^- \to c\bar{c}$: 250 GeV

$$\sigma(P_{e^-} = -1, P_{e^+} = +1) \approx 8518\,\text{fb}$$

$$\sigma(P_{e^-} = +1, P_{e^+} = -1) \approx 3565\,\text{fb}$$

$$\sigma_{unpol.} \approx 3020\,\text{fb}$$

LCWS 2019

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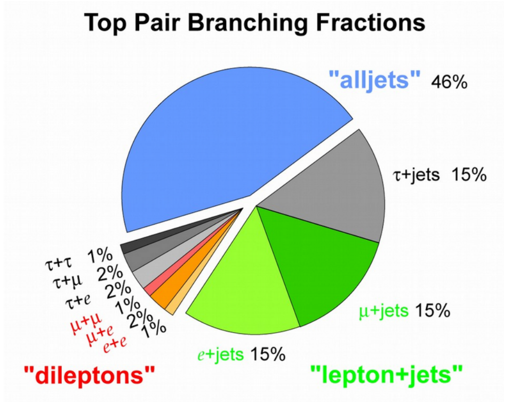
Slide borrowed from R. Poeschl (EF04 Snowmass process)

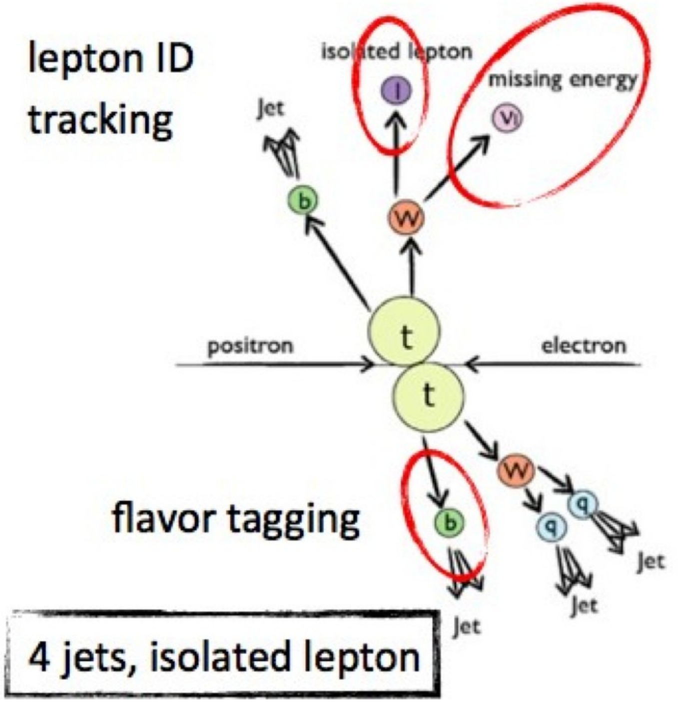
Top-quark reconstruction

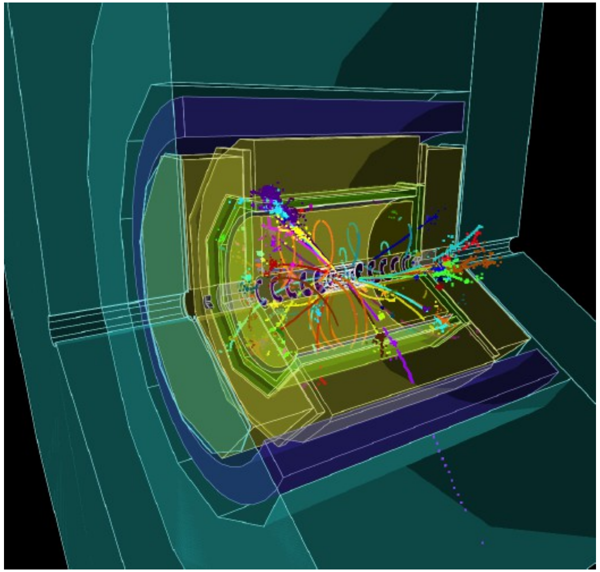
- **Tops decay** before hadronizing.
- Top-quark charge and direction information carried by its decay products
  - the b-jets (b-jet charge determination)
  - The W-boson product decays (leptonic channel and also c-decays !)



Final state reconstruction uses all detector aspects

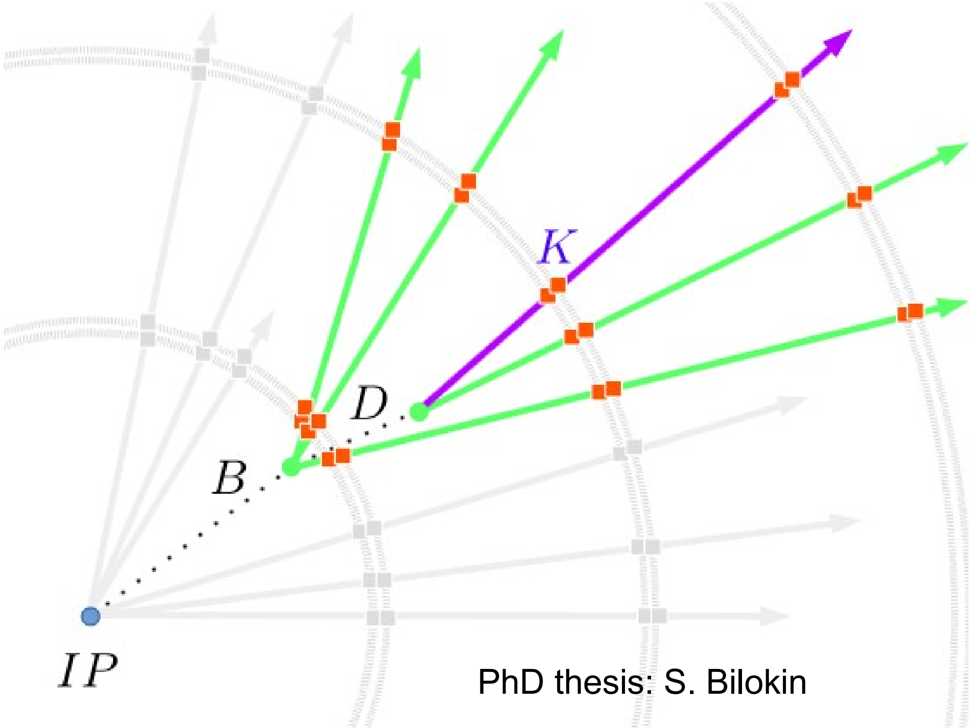
Results shown in the following (all quarks) are based on **full simulation** of **ILD**





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...

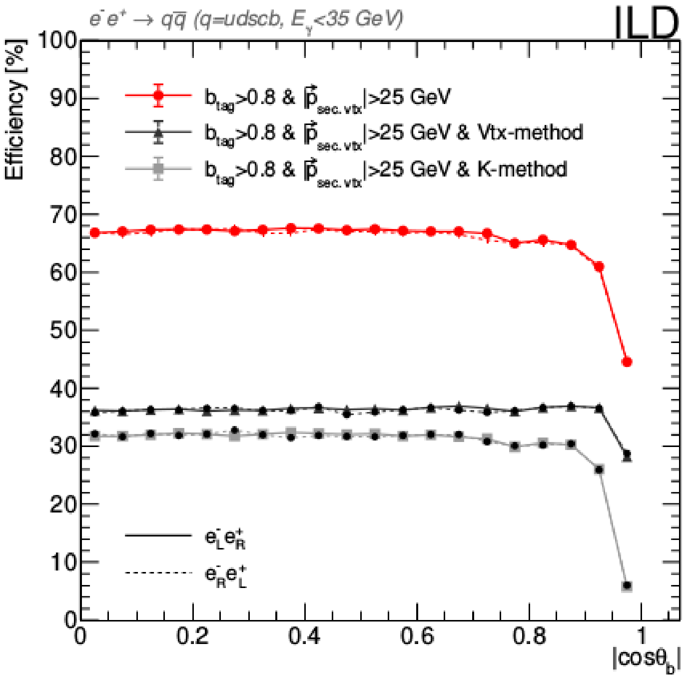


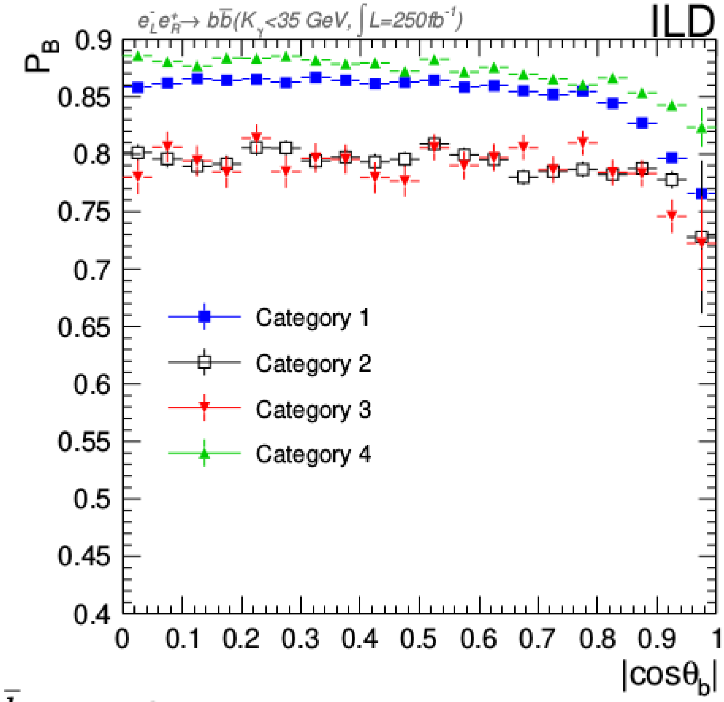
PhD thesis: S. Bilokin

- **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

Flavor tagging and charge measurement at ILD

- Individual efficiency for b-tag and charge measurements using vertex and Kaon charge
  - B-tagging efficiency larger than 65% (with minimal contamination from other quark flavors <1%)
  - charge measurement has >30% Efficiency and gives the correct charge with 80-90% probability (limited by B0 oscillations)
  - **Particle ID thanks to the TPC**





$e^+e^- \to b\bar{b}$: 250 GeV

Arxiv:1709.04289, ILD Paper in progress

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%

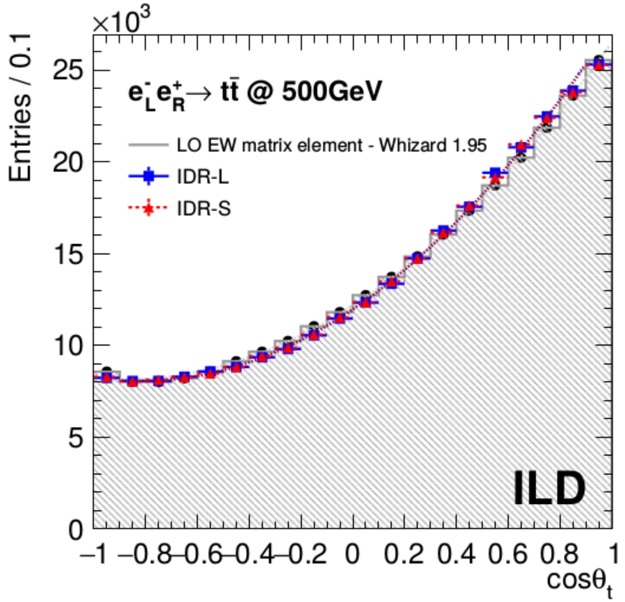
Total cross section

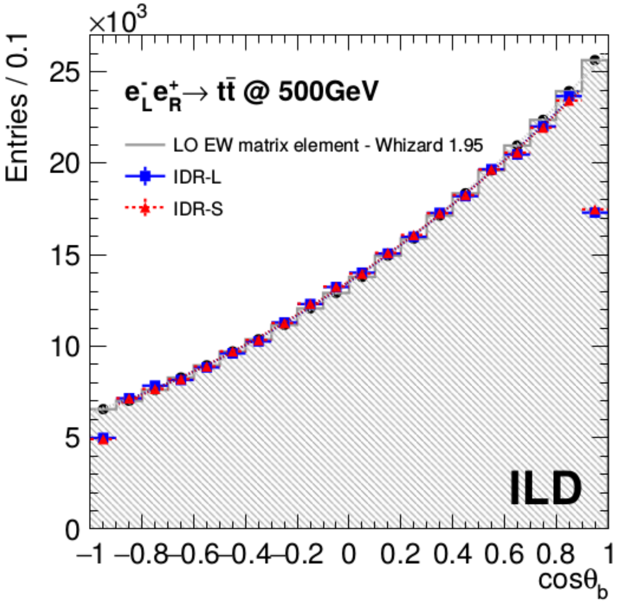
- Typical selection efficiencies fo the 75%
- Independent of beam polarisation

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

Top quark: results (1)

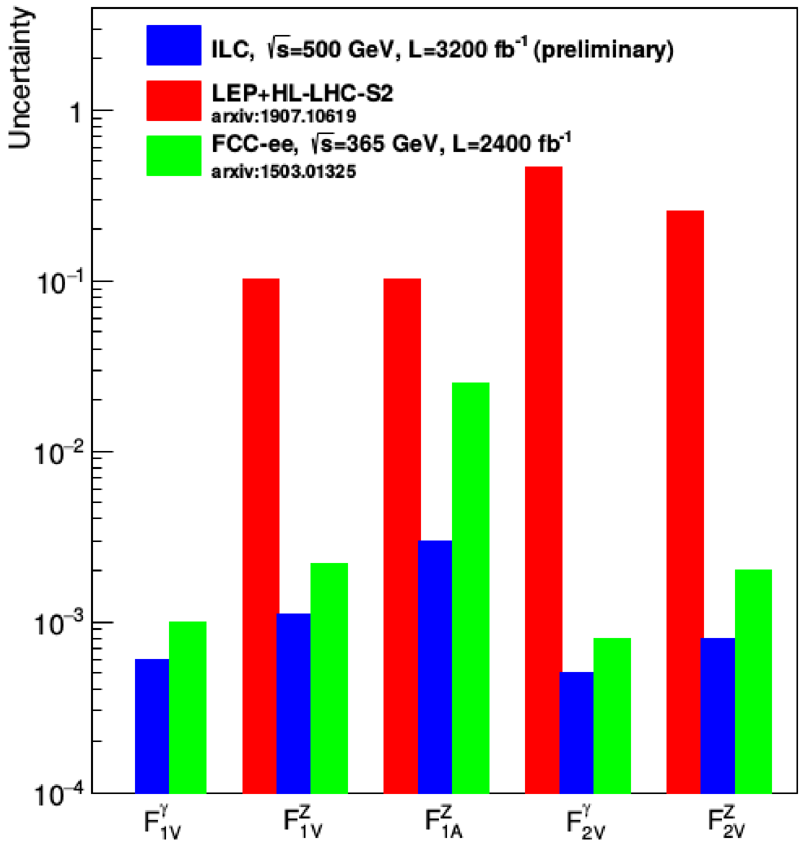




- Semi-leptonic channel
- Left polarisation
  - B-jet carries top direction information
  - Very useful for the hadronic channel!
- Right polarisation
  - W-carries the top direction information → **lepton charge and c/s tagging become important**

- Integrated Luminosity 4 fb^{-1}
- 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)

Top quark: results (2)



- 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.

b/c-quarks: reconstruction efficiencies

- 2 back-to back jets topology

Arxiv:1709.04289, ILD Paper in progress

- 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.

Solution: double tagging (and charge measurement) → ILD offers high efficiency and purity (see slide 12)

- New systematics when running far from the Z-pole:
  - Beam polarisation
  - Event selection → background **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

b/c-quarks: reconstruction efficiencies

Arxiv:1709.04289, ILD Paper in progress

- **Double tagging (and charge measurement) techniques require:**
  - **Preselection with similar efficiency for all quark flavours**
  - **Preselection that cut out the main backgrounds**
- Require dedicated studies with full simulations: done at ILD for b and c-quark
  - Profits from a highly efficient ISR photon identification (~XX %)

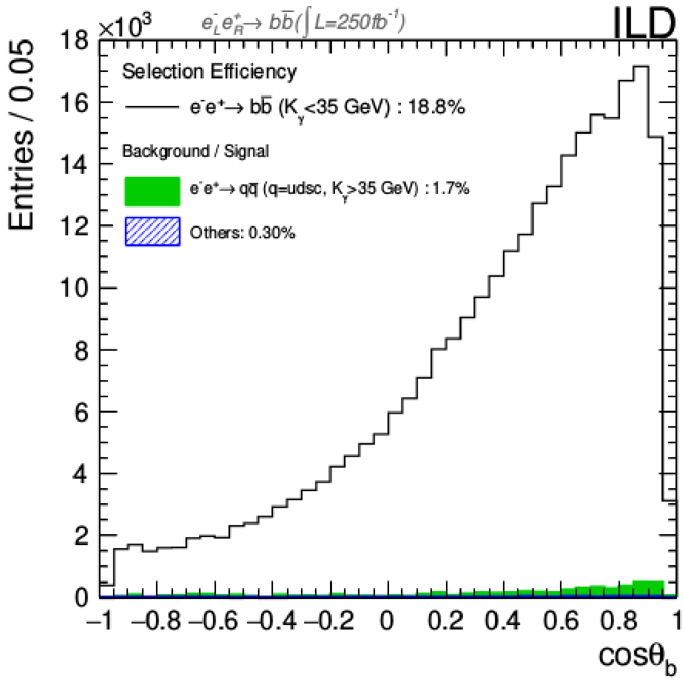
Efficiency of selection for $e_L^- e_R^+ \to X$ [%]

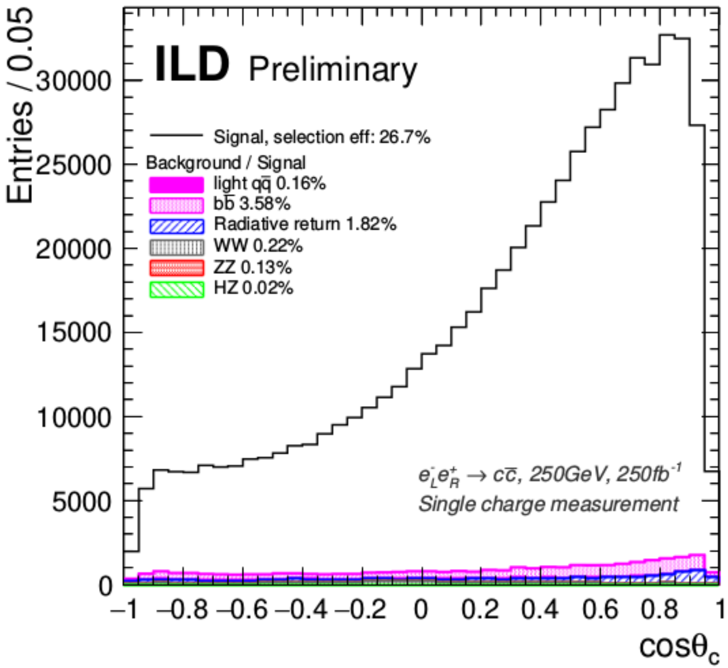
	$X = q\bar{q}$ ($E_\gamma < 35 GeV$)			$X = q\bar{q}$ ($E_\gamma > 35 GeV$)			
	$b\bar{b}$	$c\bar{c}$	$q\bar{q}$ (uds)	$q\bar{q}$ (udscb)	$X = ZZ$	$X = WW$	$X = HZ$
No cuts	100%	100%	100%	100%	100%	100%	100
Cut 1	84.5%	84.9%	86.4%	6.7%	12.3%	11.7%	12.6
+ Cut 2	82.8%	82.0%	80.3%	1.2%	12.1%	11.1%	11.8
+ Cut 3	72.1%	71.7%	71.3%	0.7%	2.5%	5.0%	4.5
+ Cut 4	71.5%	71.1%	70.7%	0.7%	1.6%	3.6%	3.8

$q\bar{q}$ signal — Rad. Ret. BKG — Other BKG

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



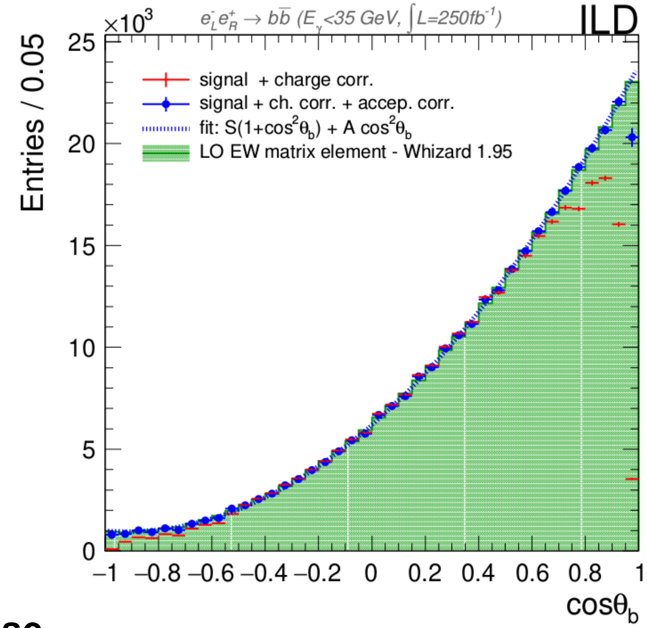


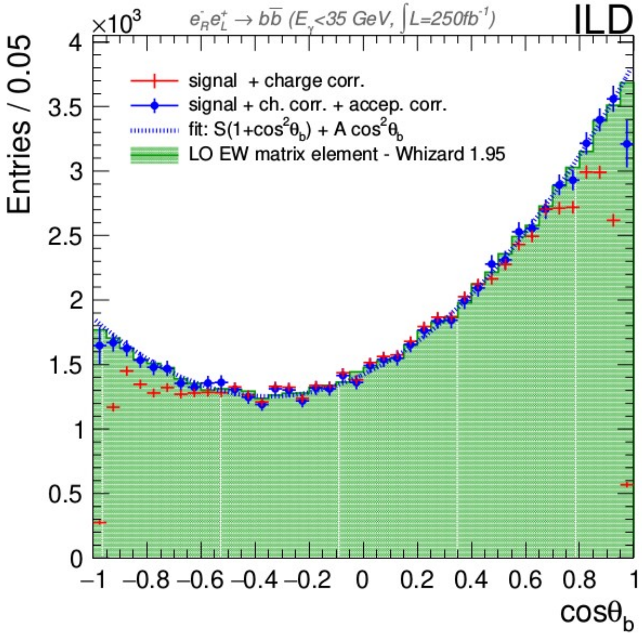
- Background ~free analysis!

Arxiv:2002.05805

Arxiv:1709.04289, ILD Paper in progress

b/c-quarks: Results (1)





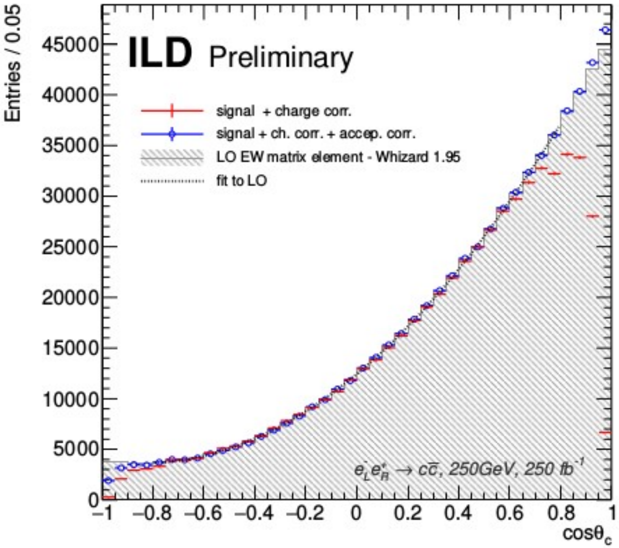
B-quark case

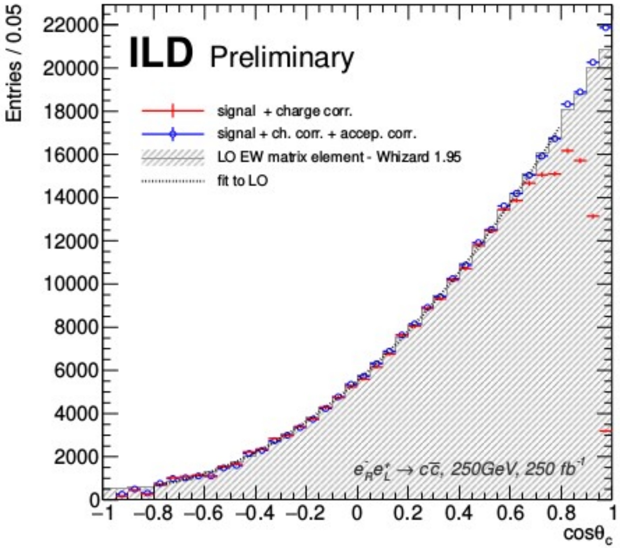
- **Full simulation studies for Rb and AFBb**
- **Full study of uncertainties (ILD note in progress)**
  - Statistics (and migrations)
  - Sytematics: tagging eff, correlations, beam polarisation, bkg estimation,...

HERE GOES A TABLE WITH
ALL UNCERTAINTIES BREAKDOWN
Per mile accuracy!

Arxiv:1709.04289, ILD Paper in progress

b/c-quarks: Results (2)



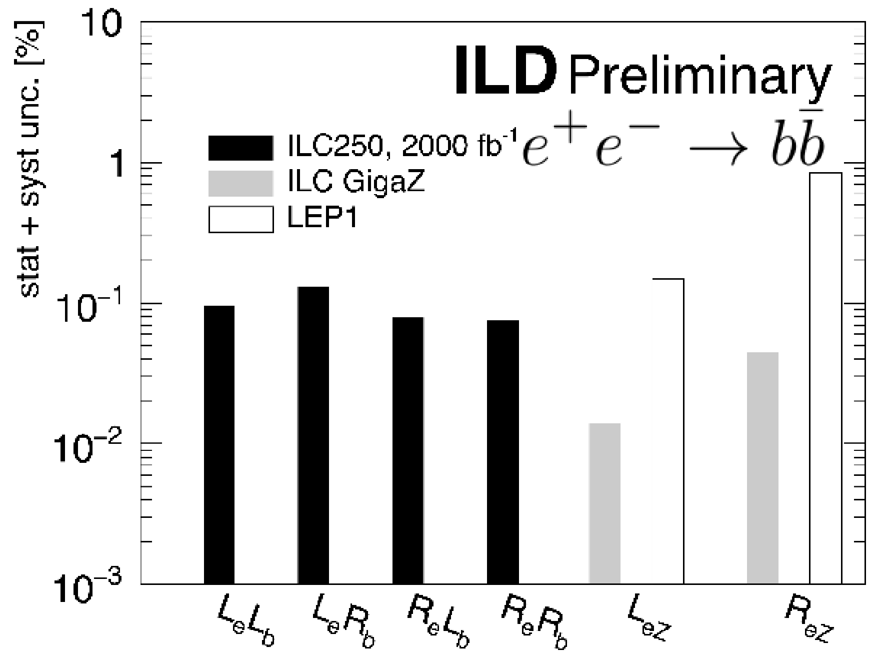


c-quark case

- 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

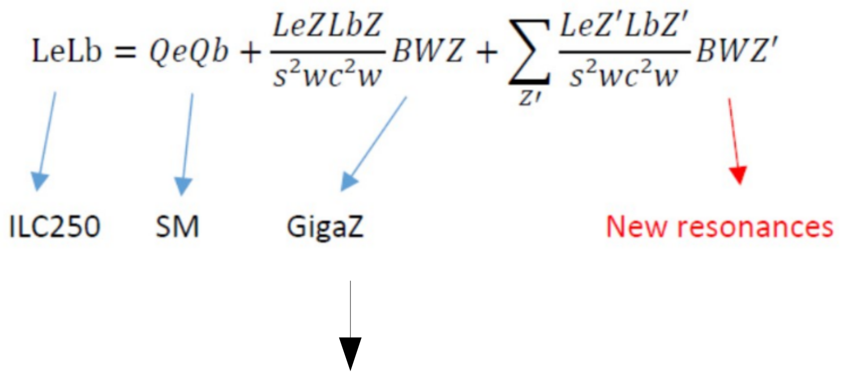
b/c-quarks: Results (3)



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!!**

New resonances

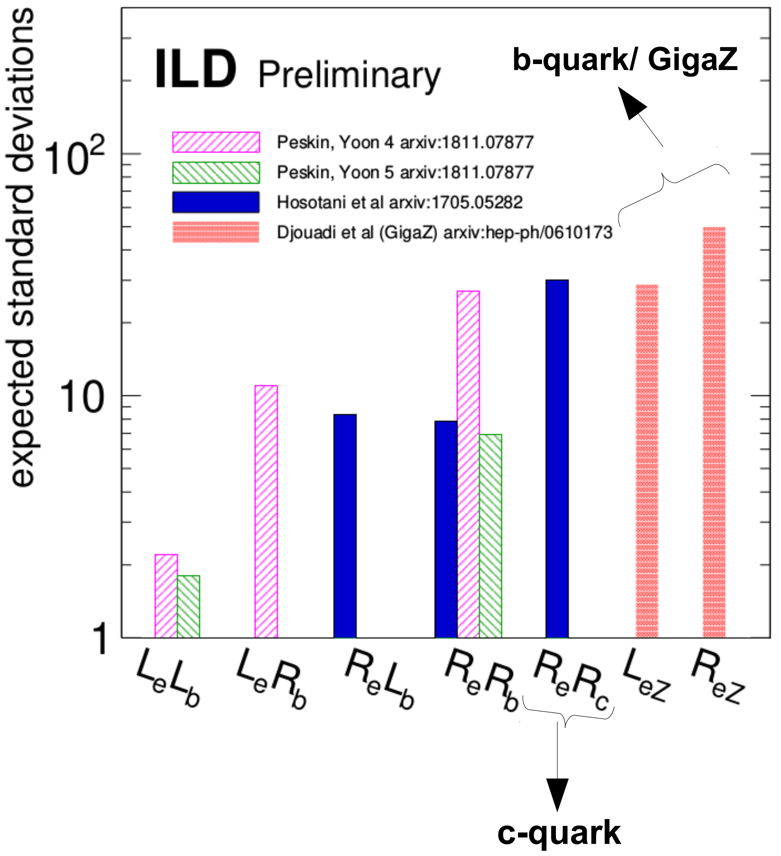


Sensitive to Z-Z' mixing effects

(that could explain AFBb measurement of LEP?)

Arxiv:1709.04289, ILD Paper in progress

b/c-quarks: Results (4) Potential for BSM discoveries



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).

- Many BSM predict deviations only for the right couplings

BEAM POLARISATION is crucial

- MODELS:
  - for Djouadi et al we assume **mZ'= 3 TeV**
  - for the Peskin et al we assumed two RS SO(5) scenarios labelled as Peskin 4 and Peskin 5
  - for Hosotani et al, we assumed mZ'= 8 TeV (three resonances) and not mixing at Z-pole

Power of discovery of new resonances mZ' ~ O(20-30) TeV at ILC250

Arxiv:1709.04289, ILD Paper in progress, Arxiv:2002.05805

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
  - **Full systematic studies 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

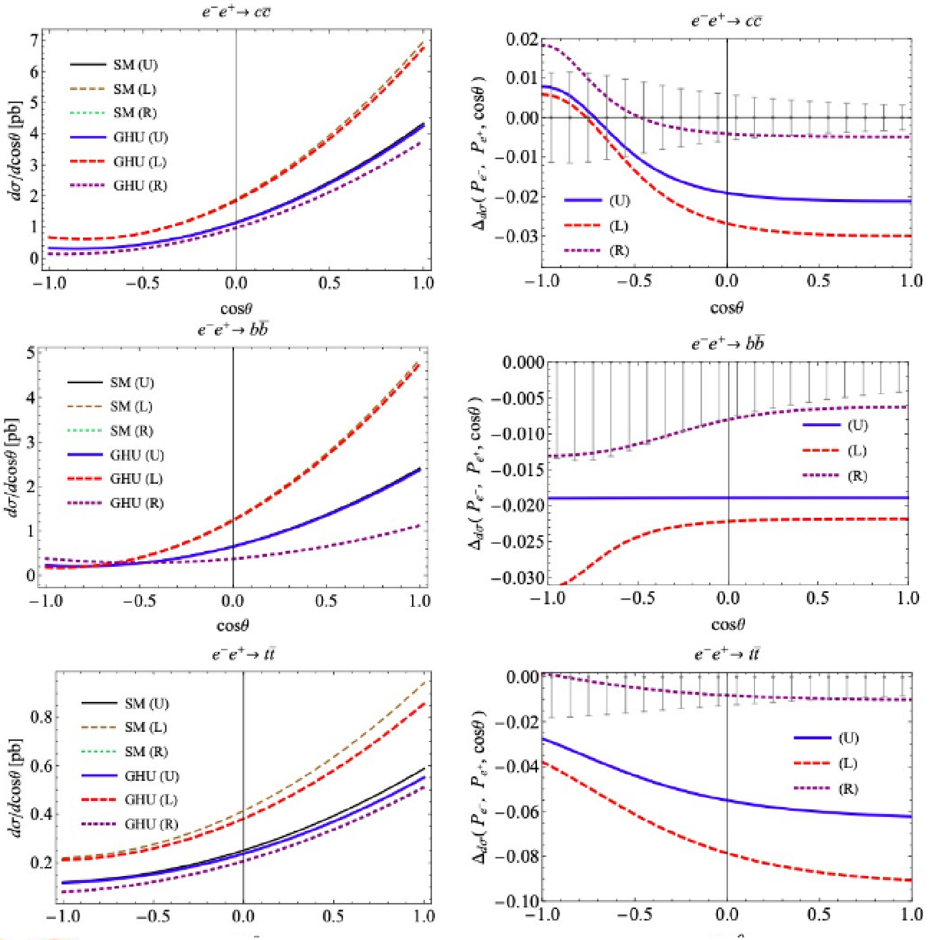
- Active phenomenological studies in terms of global analyses (EFT) and concrete models (not covered in this talk)
- Theory challenges (not covered in this talk)
  - Need at least NLO electroweak predictions (and MC programs) for correct interpretation of results

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)