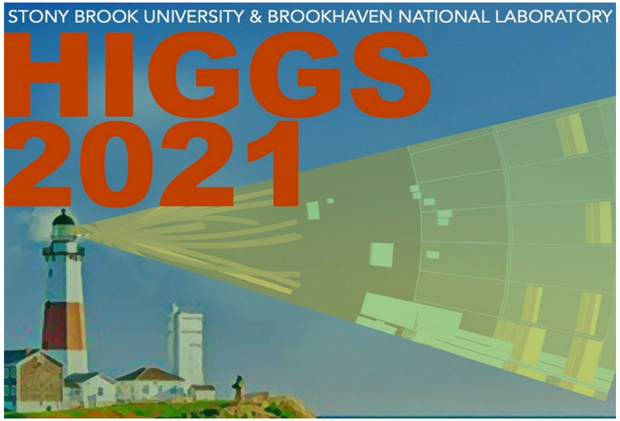
Flavor-Tagging of Quark Pairs at e+e- Higgs/Top Factories

Adrián Irles *(AITANA group at IFIC – CSIC/UV)* **on behalf of:**

the **ILC International Development Team** Physics and Detector Working Group
the **ILD concept group**
*and the **IJCLab/Tohoku/Valencia HQ-ILC team***



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MATTER AND TECHNOLOGY

ILD

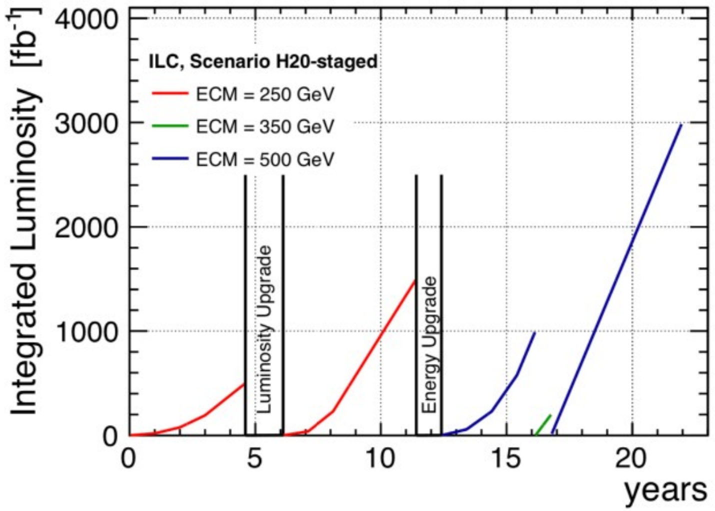
This talk (250 GeV)

ILC physics program

- **All Standard Model particles within reach of planned linear colliders**
- **Machine settings can be "tailored" for specific processes**
  - **Centre-of-Mass energy**
  - **Beams polarisation** (straightforward at linear colliders)
- Background free searches for BSM through beam polarisation

- **First phase at 250GeV**
  - A Higgs Factory **and much more!**

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

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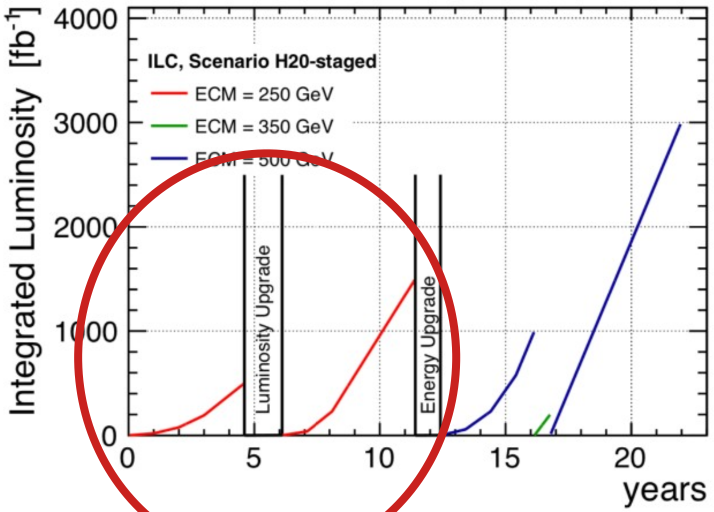

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ILC250 → this talk

Motivation: BSM Z' resonances

- 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 coupling to (t,b) doublet
    - → Peskin, Yoon arxiv:1811.07877
    - → Djouadi et al arxiv:hep-ph/0610173
  - Coupling also to lighter fermions
    - → Hosotani et al arxiv:1705.05282 arxiv:2006.02157

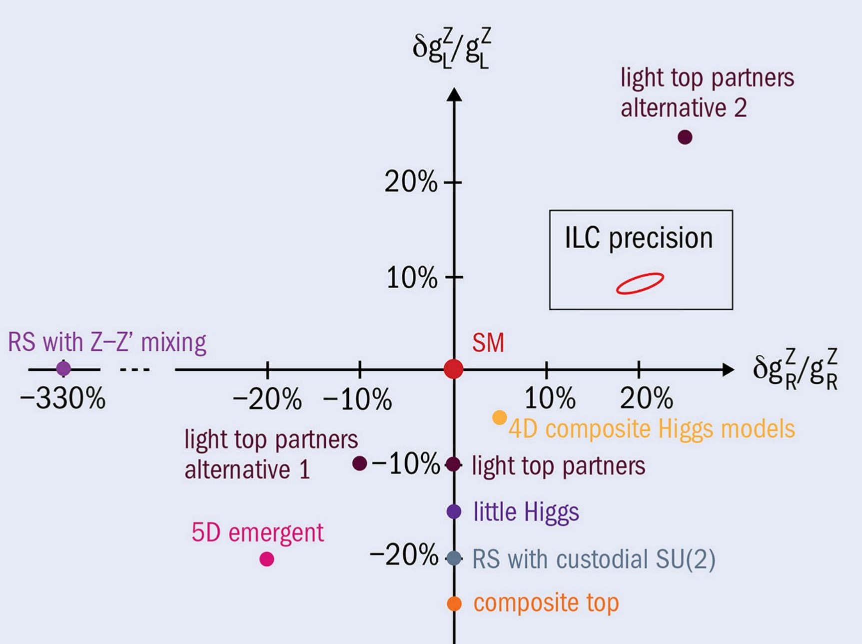


Figure from F. Richard

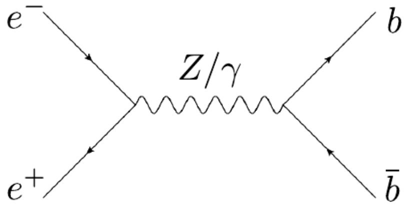
Probe such scenarios require at least per mil level for experimental precision
tt/**bb**/cc… (ss?) **Can we do it?**
(this talk)

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 (but possible)



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

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

→ Angular Distribution.

Quark ID + charge measurement (quark – antiquark disentangling)

Gives access to all left/right couplings.

Normalized quantities are highly preferred: to control (remove) **systematic uncertainties**

(few) Experimental challenges

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- **C-quark pairs**

- **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 ac curacies

- **s-quark pairs (in progress)**

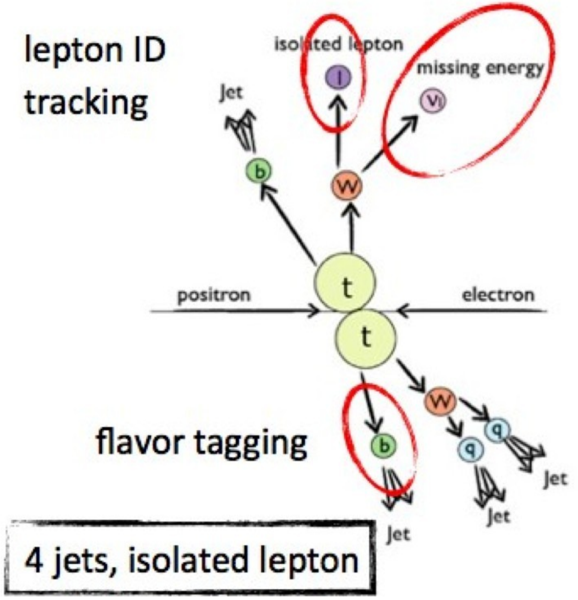
- **B-quark pairs**

- **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 in b-hadron decays → **K-method (requires PID)**

PID is very useful

- **top-quark pairs... decay before hadronizing**



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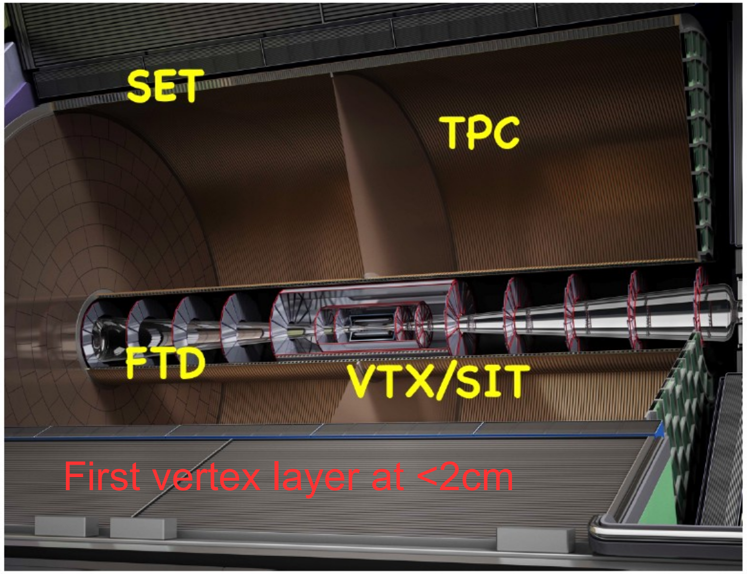
ILD highlights

▶ ILD snapshot



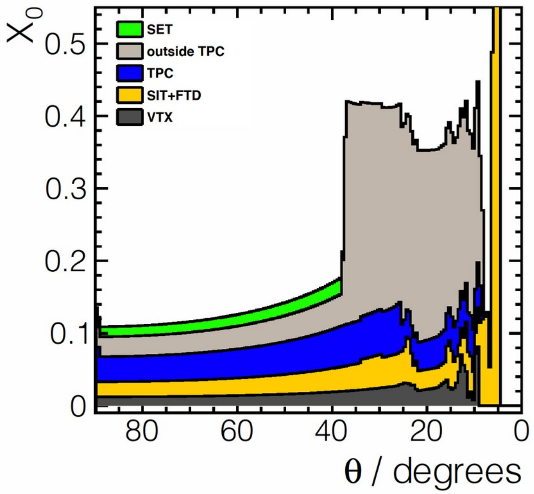
▶ **High** angular **coverage** with **minimum material budget** and **PID (TPC)**

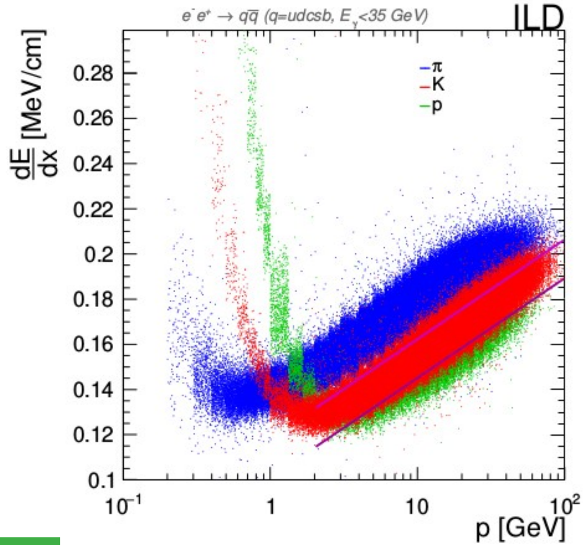
▶ **Linear Colliders offer tiny beam spots**

▶ ILC experiments, as the **ILD**, will provide excellent:

- Beam IP constraint
- **Tracking efficiency (>99%)**
- **Secondary vertex separation and excellent flavour tagging**

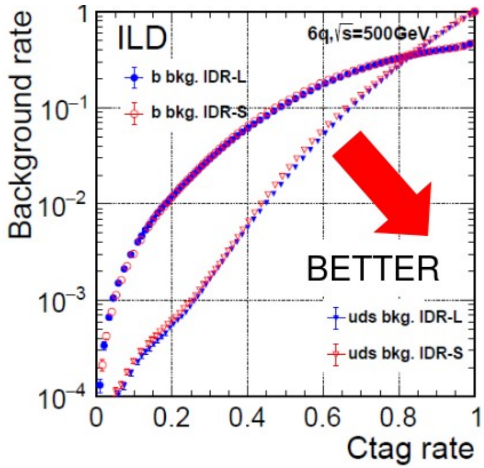
▶ **Particle Flow optimized detector with high granularity calorimeters ($>10^8$ cells!)**

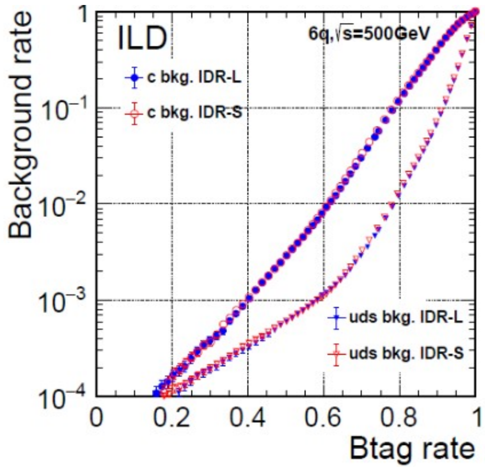




ILD: Interim Design Report arXiv:2003.01116

Flavour tagging





▶ Dedicated tools for vertexing and flavour tagging: LCFIPlus (for lepton colliders)

- A high-purity secondary vertex finder based on build-up vertex clustering,
- a jet clustering algorithm using vertex information
- and multivariate jet flavor tagging for the separation of b -jetsand c jets

Design goals

- Impact parameter resolution
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)$ µm
- Transverse momentum resolution
  $\sigma(1/p_T) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_T \sin^{1/2}\theta)$

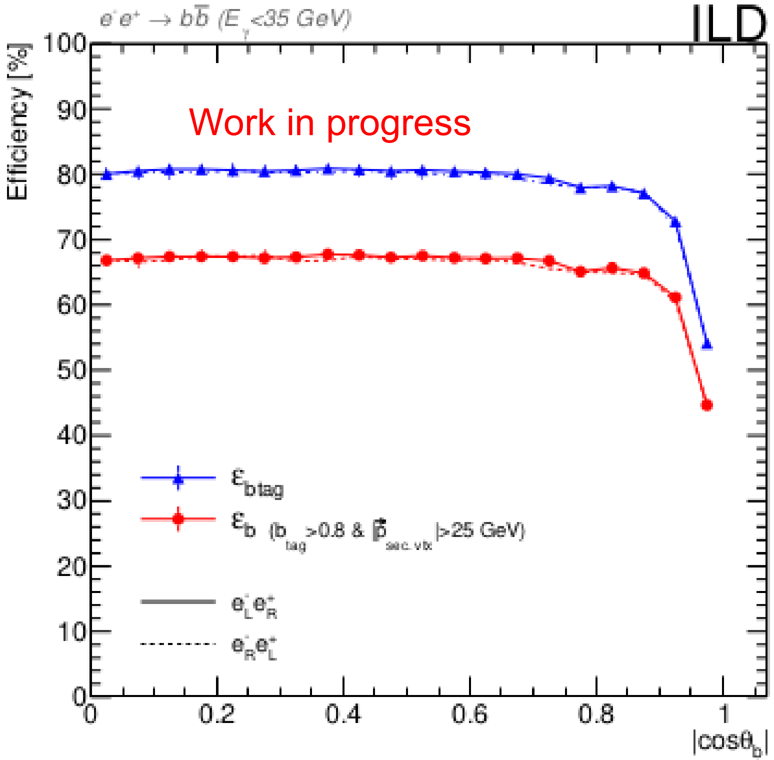
Experiment	*b*-quark Eff. [%]	*b*-quark Pur. [%]	light quarks Eff. [%]	light quarks Pur. [%]
DELPHI [19]	47%	86%	51%	82%
ILD (this note)	80%	98.7%	58%	96.1%

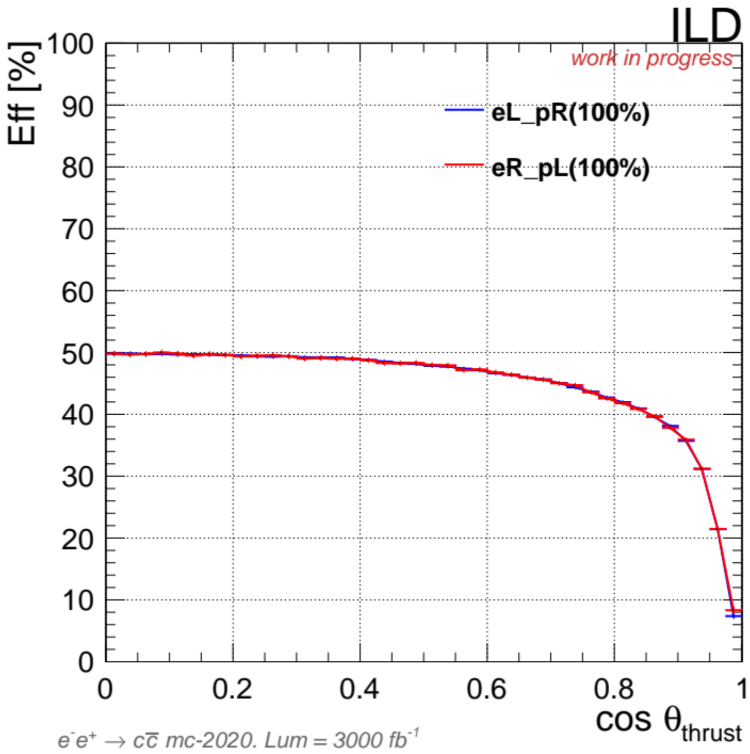
LCFIPlus: Nucl.Instrum.Meth.A 808 (2016) 109-116

Double Tag Method

▶ **The efficiency of quark tagging can be measured with the single vs double tagging,**

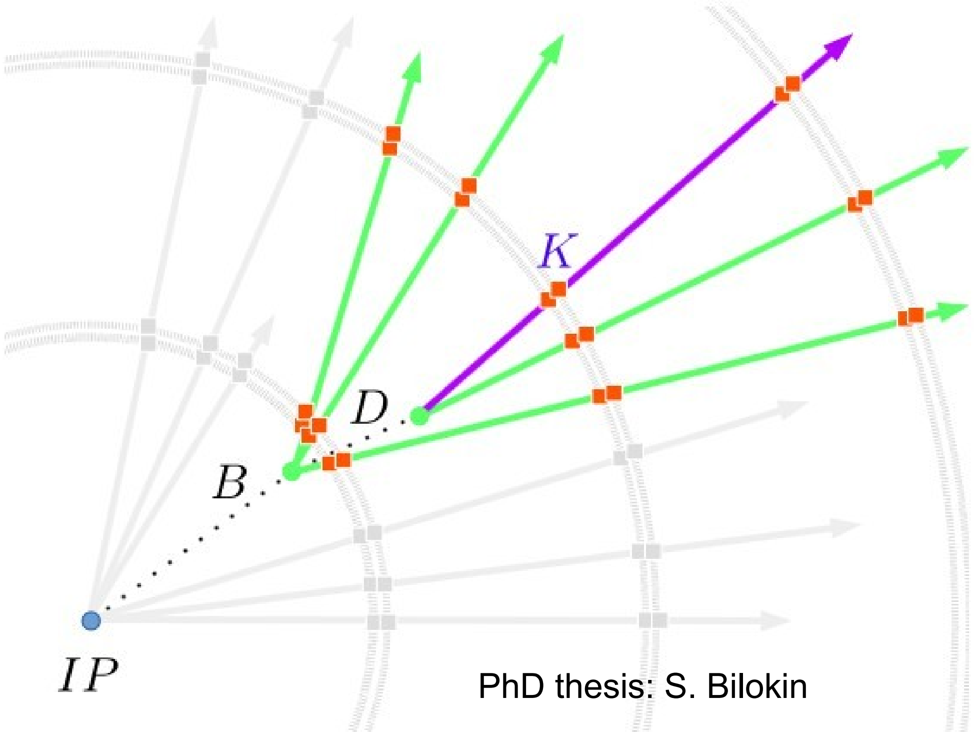
- We don’t need to rely on MC which cannot provide per-mile level accuracy
- Other quark contamination bellow the 1% level (almost zero for uds)





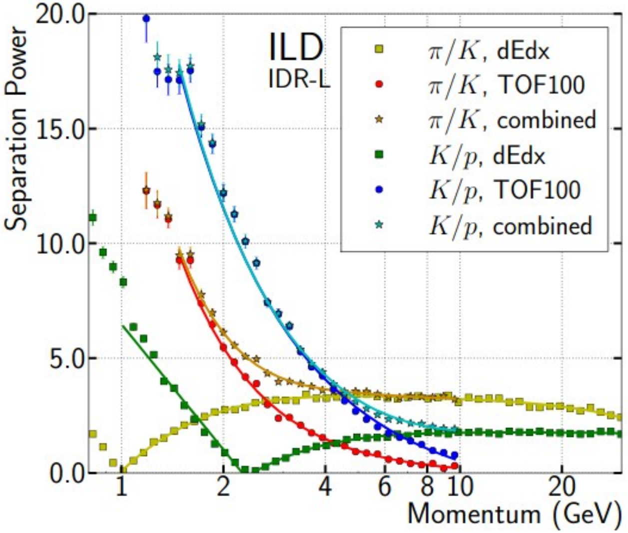
Charge measurement

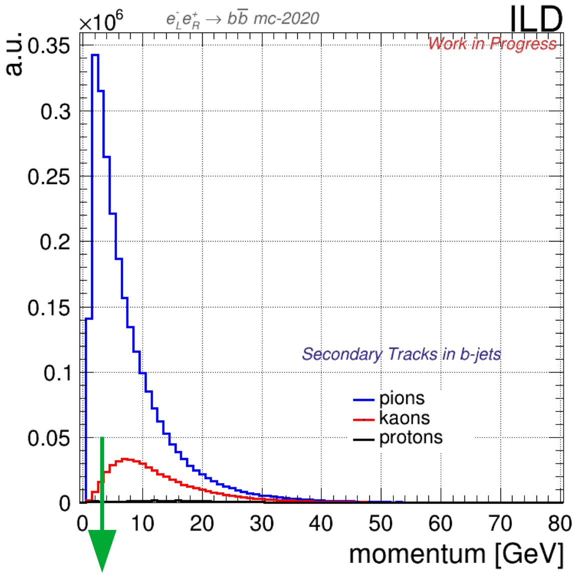
- **Quark charge measurements**
  - Important for top-quark studies but Indispensable for ee→ bb/cc/ss…
- **Methods**
  - Vtx charge and **Kaon Identification**
  - High efficiency **(double tagging)**
  - High purity → control of the migrations
- **Future detectors can base their entire measurements on double Tagging and vertex charge**
  - LEP/SLC had to include single tags and semi-leptonic events
  - **Critical for minimization of the systematics**

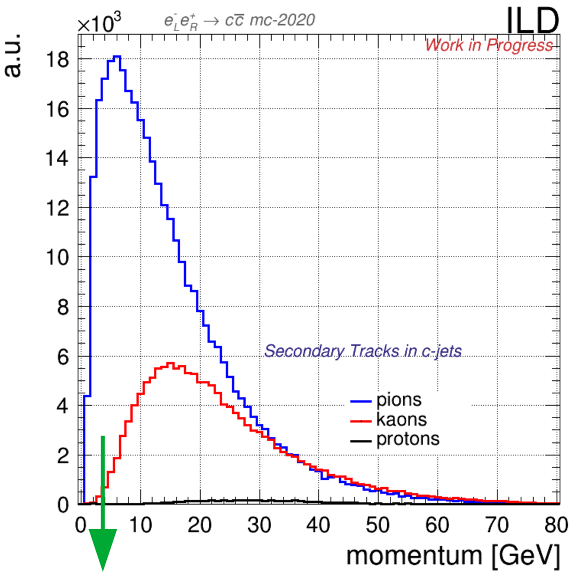


PhD thesis: S. Bilokin

High Level Reco Challenges: Particle ID





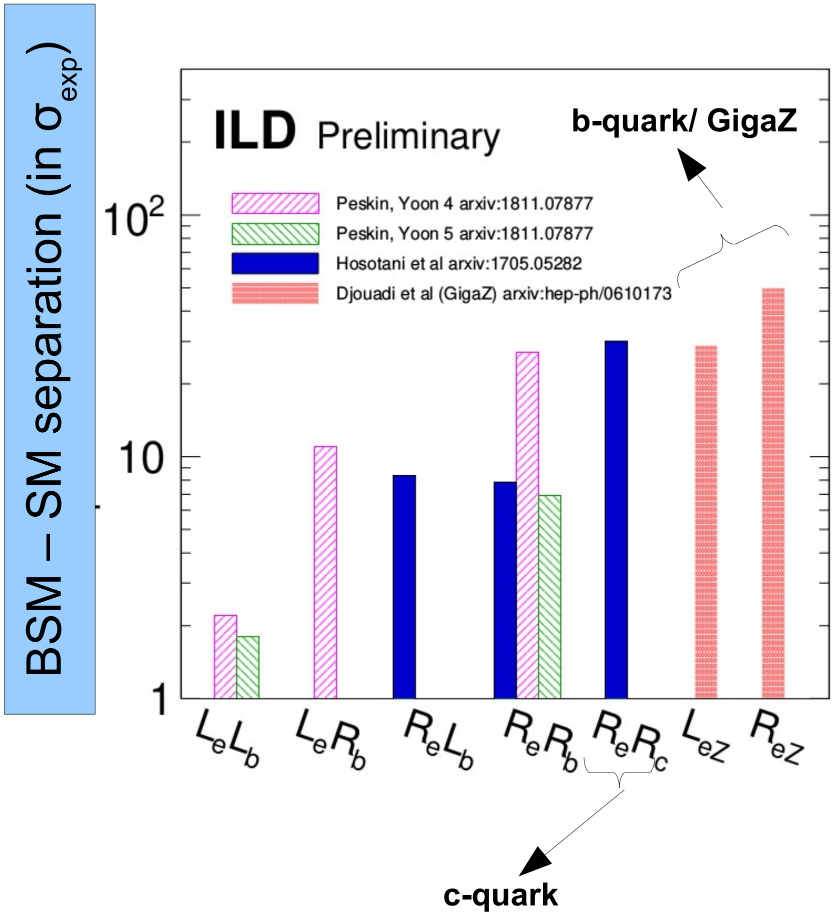


TOF or dE/dx
(left) (right)

TOF or dE/dx
(left) (right)

- For AFB measurements we are required to measure the jet-charge
- Therefore we are interested in a high power of K/pion separation
- Possible solutions: using dE/dx and/or TOF
  - Yellow points

BSM benchmarks



▶ Many BSM predict deviations only for the right couplings

BEAM POLARISATION is crucial

Per mil level experimental measurements required

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

Potential for discovery of new resonances mZ' ~ O(10-20) TeV at ILC250

Arxiv:1709.04289, PoS(EPS-HEP2019)624
+GigaZ-ILC250 complementary arxiv:1905.00220

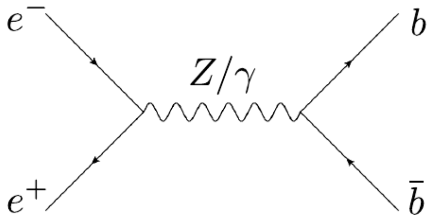
Summary

- ILC250 is a Higgs factory and much more: EW/Top/BSM(?) factory
  - Updgradability in energy
  - Polarised beams allowing detailed scrutiny of the quiral structure of the matter
- ILD is designed for precision physics with high capabilities in:
  - Particle Flow (not discussed here)
  - Flavour tagging
  - Particle Identification with dE/dx (for a broad range of energies)
- ILC/ILD have the potential to discover BSM physics with precision physics
  - qqbar final states asymmetries.

Back-up slides

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)
- Left≠right (characteristic for each fermion)

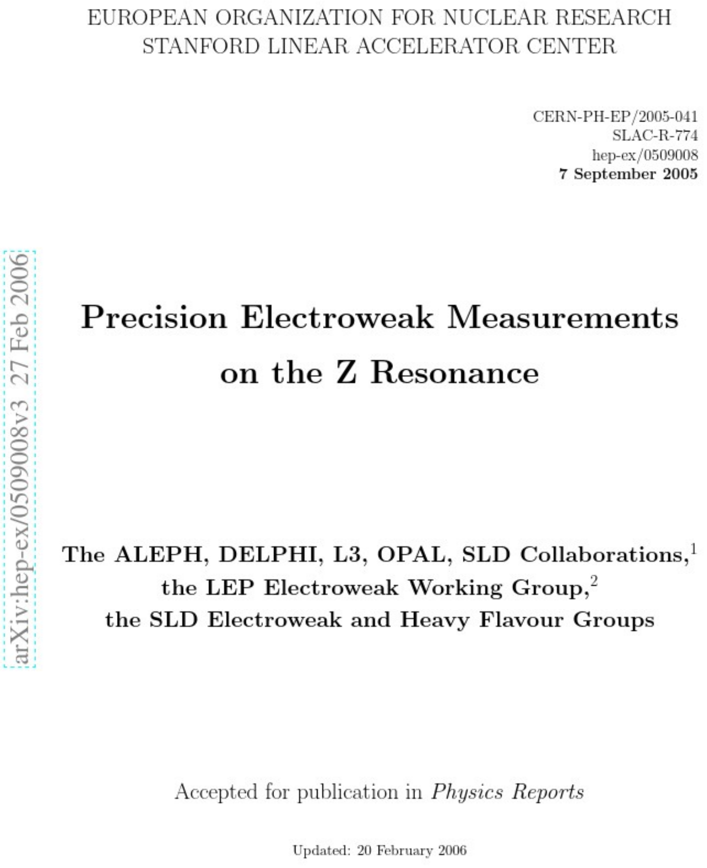
▶ **Only beam polarisation allows inspection of the 4 helicity amplitudes for all fermions**

- Beam polarisation also enhances the cross section values

Two fermion processes

▶ **These processes have been deeply studied at LEP/SLC at the Z-pole**

- Very comprehensive physics program at Z-Pole
- no access to the γ or Z/γ interference's ("cleaner" access to Z-couplings)
- Moderated quark tagging and/or charge measurements capabilities (or moderated statistics)
- Also moderated angular acceptance of the detectors


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
STANFORD LINEAR ACCELERATOR CENTER

CERN-PH-EP/2005-041
SLAC-R-774
hep-ex/0509008
7 September 2005

arXiv:hep-ex/0509008v3 27 Feb 2006

Precision Electroweak Measurements on the Z Resonance

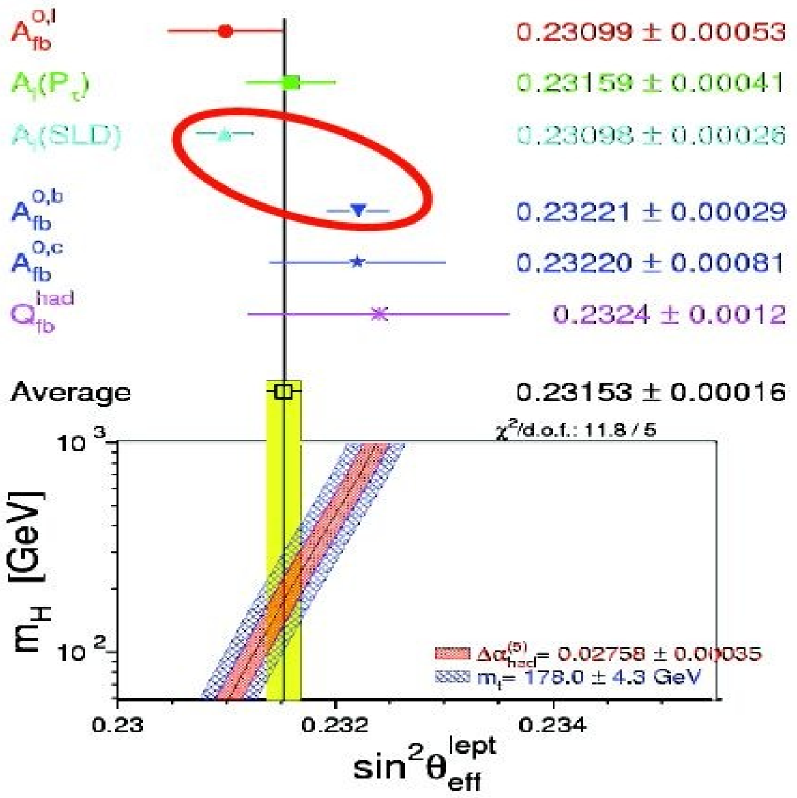
The ALEPH, DELPHI, L3, OPAL, SLD Collaborations,[1] the LEP Electroweak Working Group,[2] the SLD Electroweak and Heavy Flavour Groups

Accepted for publication in *Physics Reports*

Updated: 20 February 2006

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

ILD, a Detector for the ILC [T. Tanabe's (30/07)](#) ICEHP/2020

Detector Technologies

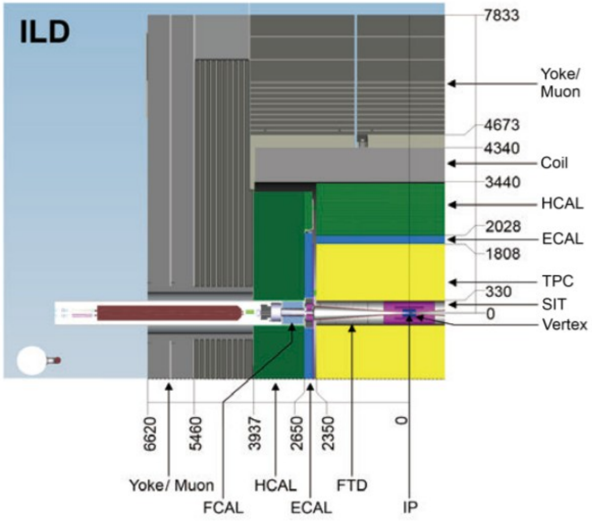
Vertex: CMOS, DEPFET, FPCCD, …

Tracker:
TPC (GEM, micromegas, pixel)
+ silicon pixels/strips

ECAL:
Silicon ($5x5mm^2$) or
Scintillator ($5x45mm^2$)
with Tungsten absorber

HCAL:
Scintillator tile ($3x3\ cm^2$)
or Gas RPC ($1x1\ cm^2$)
with Steel absorber

All inside solenoidal coil of 3-4 T



Detector R&D collaborations: CALICE, LC-TPC, FCAL

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ILD Design Goals

Features of ILC:
low backgrounds, low radiation, low collision rate (5-10 Hz)

These allow us to pursue aggressive detector design:

Detector Requirements ←	Physics
• Impact parameter resolution $\sigma(d_0) < 5 \oplus 10 / (p[GeV] \sin^{3/2}\theta)\ \mu m$	$H \rightarrow bb, cc, gg, \tau\tau$
• Transverse momentum resolution $\sigma(1/p_T) = 2 \times 10^{-5}\ GeV^{-1} \oplus 1 \times 10^{-3} / (p_T \sin^{1/2}\theta)$	Total e+e-→ZH cross section
• Jet energy resolution 3-4% (around $E_{jet} \sim 100$ GeV)	H→invisible
• Hermeticity $\theta_{min} = 5$ mrad	H→invisible; BSM

R. Ete: "The ILD Software Tools and Detector Performance"

9

Why this luxury?

Beam spot size

	FCCee	ILC	SLC	LEP
σ_x[nm]	13700	516	1500	200000
σ_y[nm]	36	7.7	500	2500

Source SLC, LEP, PDG

©R. Poeschl

LEP >> **SLC** >> **ILC**

Cross sections

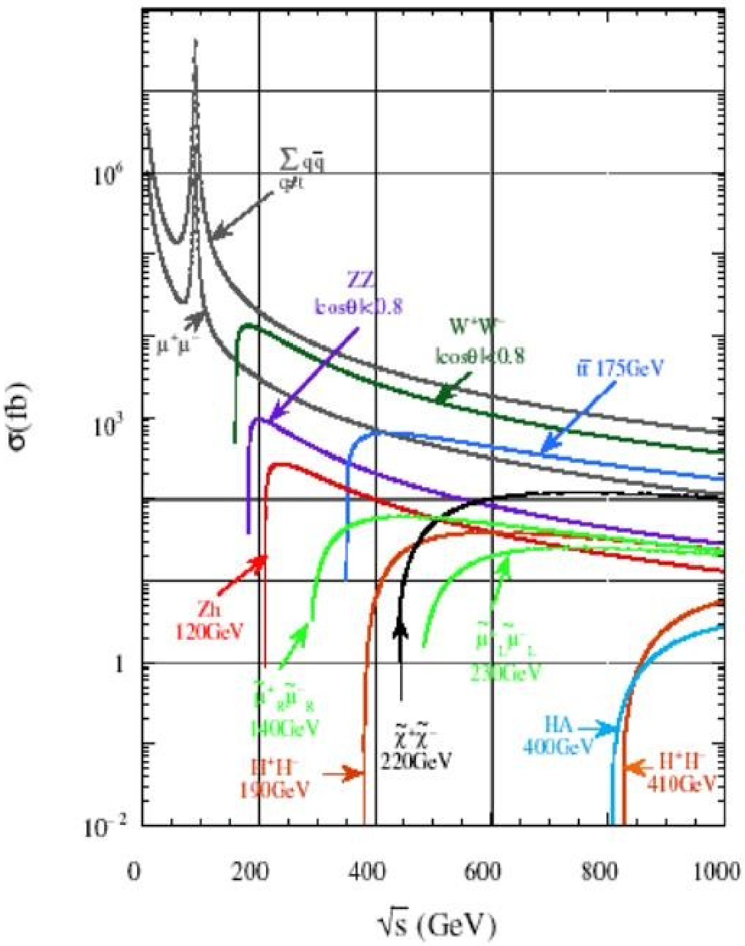
$$\sigma_{e^- e^+ \to q\bar{q}}$$

	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

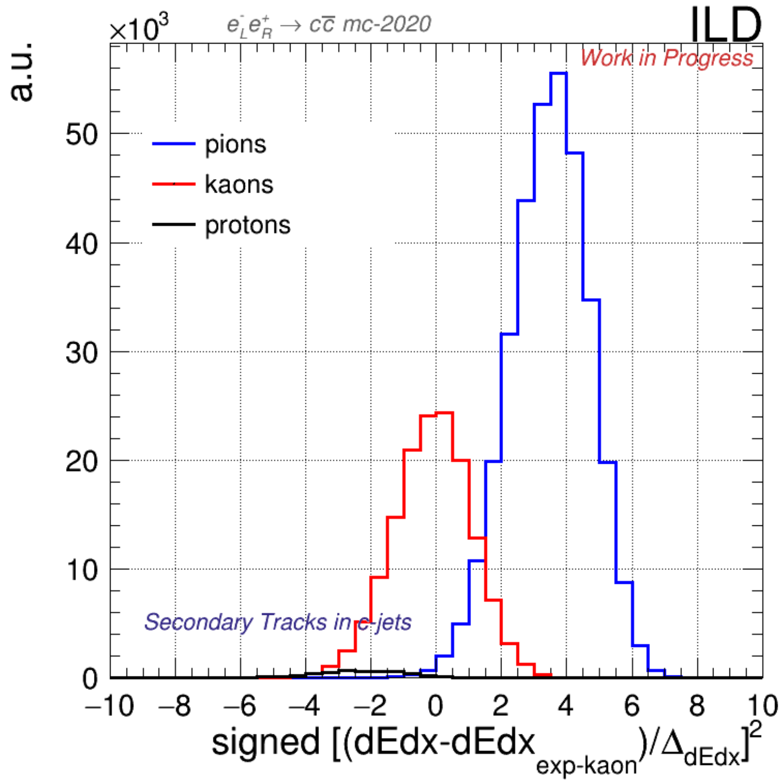
▶ **Beam polarisation also enhances the cross section values**

nts

pb



Kaon identification for the ccbar case



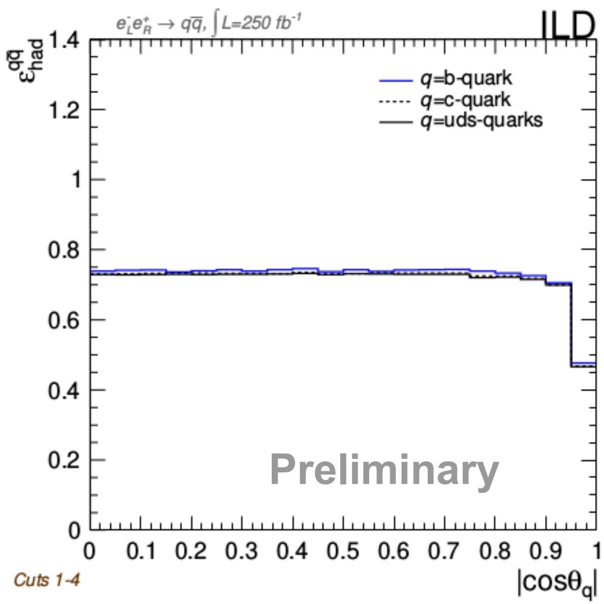
▶ Using **dEdx separation power:**

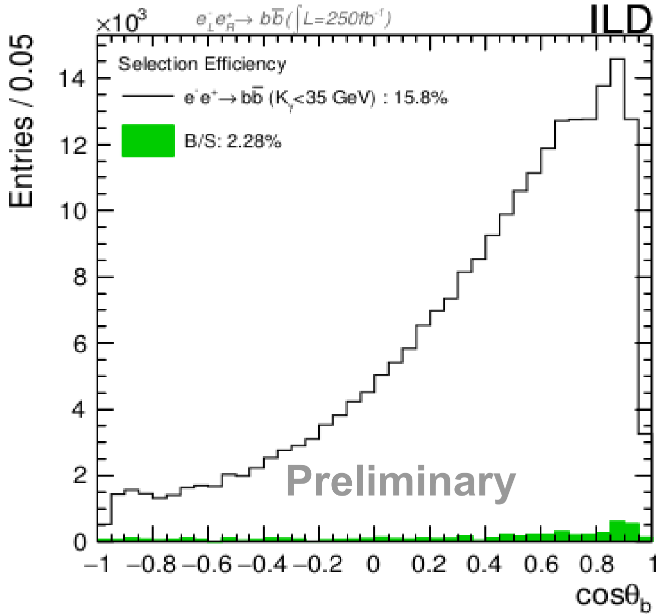
$$\text{signed } [(\text{dEdx}-\text{dEdx}_{\text{exp-kaon}})/\Delta_{\text{dEdx}}]^2$$

- $\text{dEdx}_{\text{exp-kaon}}$ = theoretical curve (B.Bloch)
- Delta dEdX = experimental uncertainty

Analysis chain: preselection

- **Preselection aiming for high background rejection and high efficiency.**
- Main bkg ee→ Zγ(ISR)
  - ~x10 larger than signal
  - **~90% of such ISR photons are lost in the beam pipe** → events filtered by energy & angular mom. conservation arguments
  - The r**emaining ~10% are filtered by identifying photons** in the detector (efficiency of >90%)

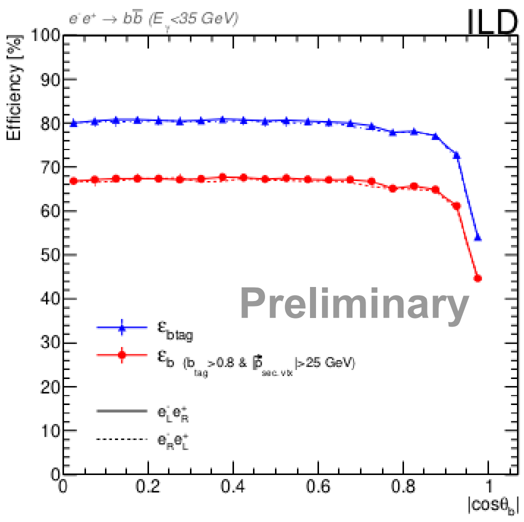


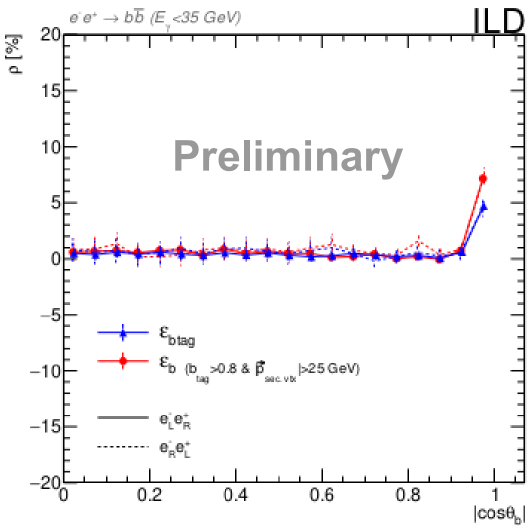


Arxiv:1709.04289, PoS(EPS-HEP2019)624

Analysis chain: Double Tag Method

- The method is based on the comparison of single vs double tagged samples
- It is required to minimize the modeling dependence on the efficiency of b-tagging → aiming to the per mil precision





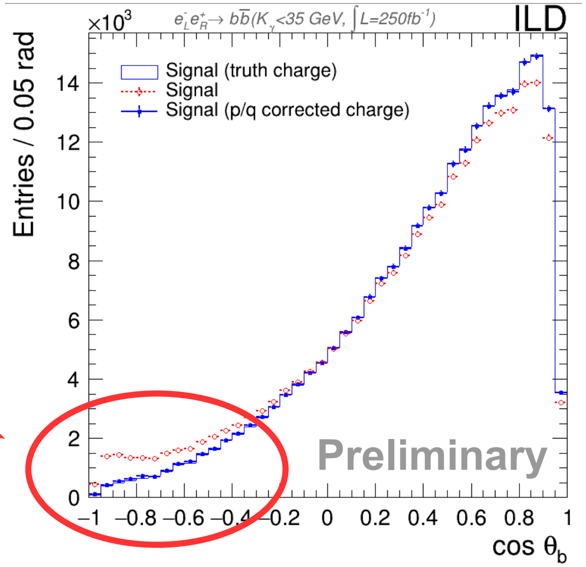
- **Excellent prospects for b-tagging** (or c-tagging) with very low correlation factor ~ 0% (~2% at LEP)
- **Differential measurements!**
  - Constant values for most of the angles
  - Drop of acceptance the very forward region → optimizations are under consideration
- **Miss-efficiencies very small**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

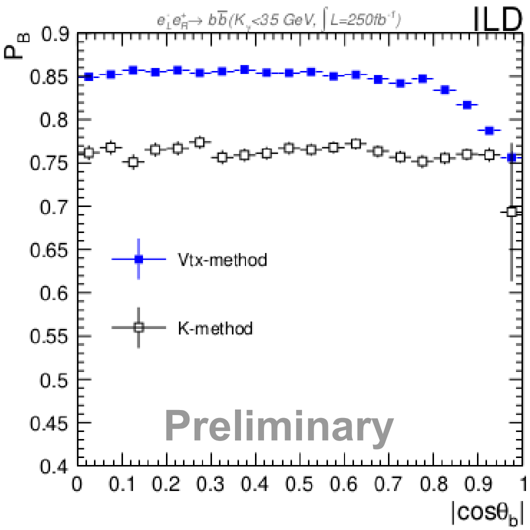
Arxiv:1709.04289, PoS(EPS-HEP2019)624

Analysis chain: jet charge

- 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.**

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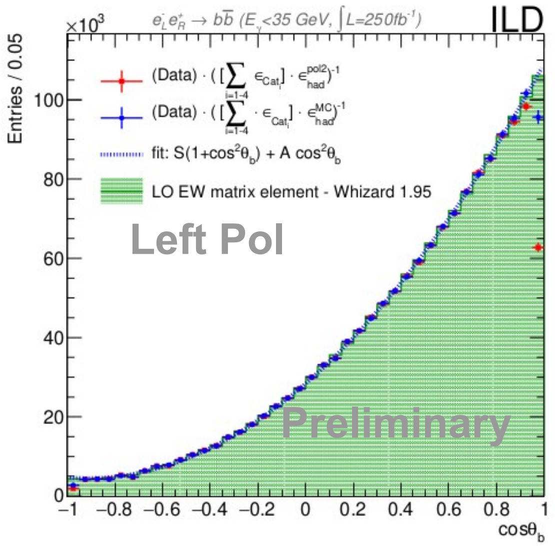
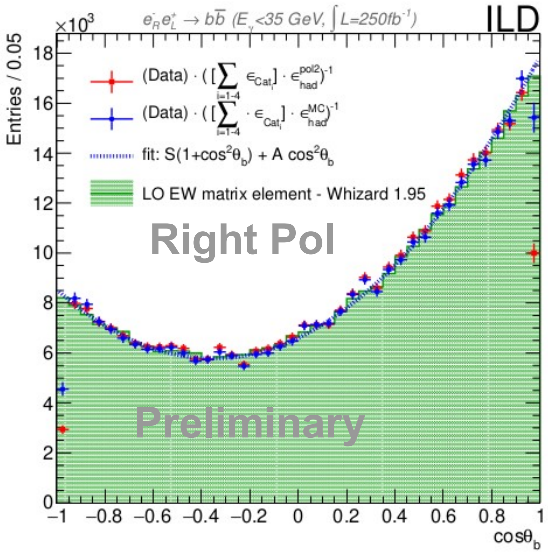
Results (1)





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*

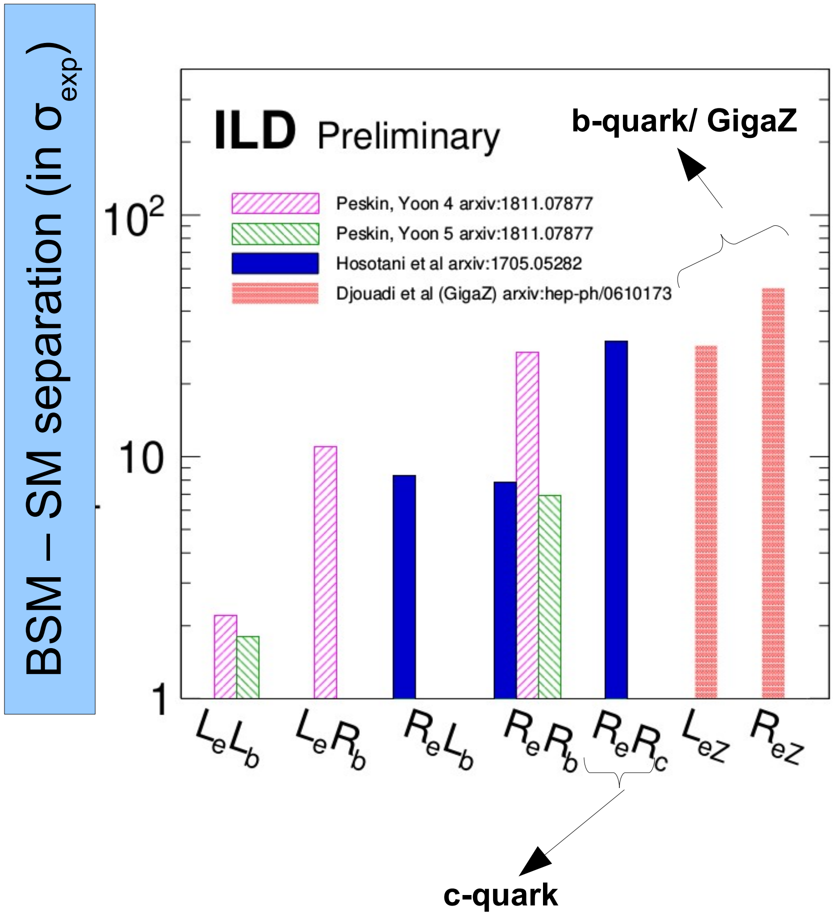
	Beam Polarisation	
	$(-+)$	$(+-)$
$R_b^{cont.}$	$0.173 \pm 0.12\%$ (stat.) $\pm 0.14\%$ (syst.)	$0.130 \pm 0.15\%$ (stat.) $\pm 0.13\%$ (syst.)
$A_{FB}^{b\bar{b}}$	$0.6823 \pm 0.15\%$ (stat.) $\pm 0.06\%$ (syst.)	$0.3487 \pm 0.75\%$ (stat.) $\pm 0.29\%$ (syst.)

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

Results (2) BSM benchmarks



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