# Heavy quark production in high energy electron positron collisions

Adrián Irles*†, R. Pöschl*, F. Richard*
on behalf of the **ILD Collaboration**

* **IJCLab** CNRS/IN2P3

† **IFIC** (UV / CSIC)

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# Outline of the talk

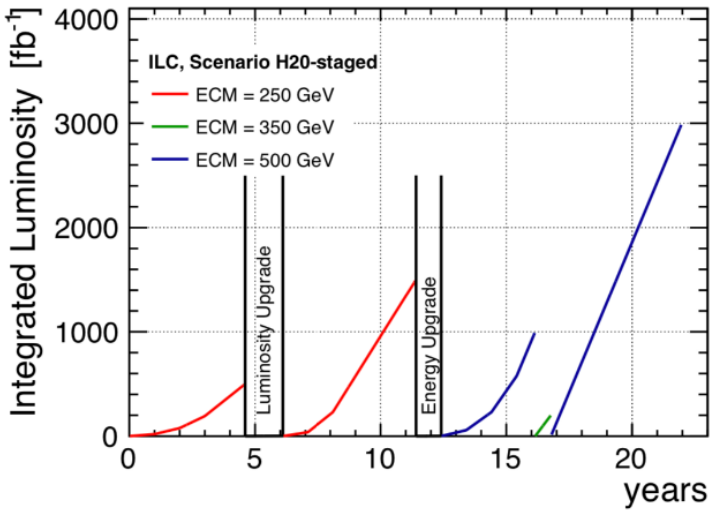
- What do we want to measure and why?
- Where? International Linear Collider, **ILC250**, and the International Large Detector **ILD**
- **top/b/c-quark electroweak couplings** extracted from **differential cross section** measurements
  - Experimental prospects based on full simulation including a comprehensive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

This talk

# ILC physics program

- ILC is a Linear Collider Project, to be hosted in Japan.
  - **Matured technollogy: TDR 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)

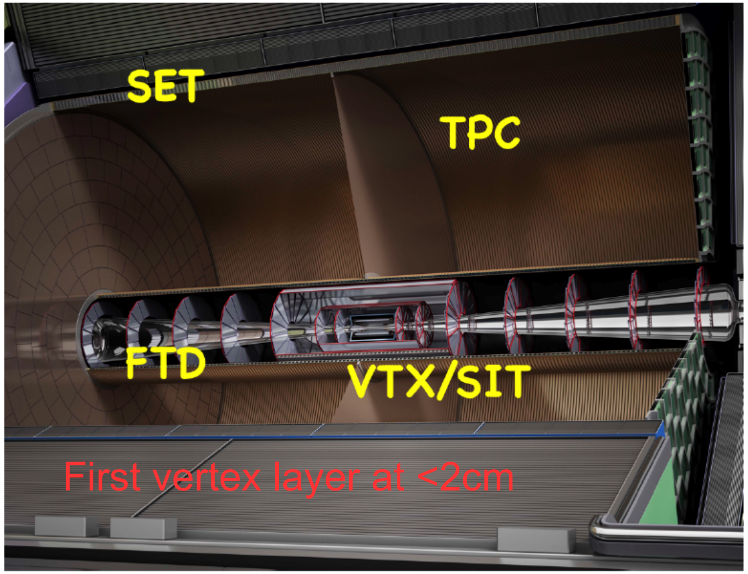
L upgrade: 5 Hz → 10 Hz; E upgrade: extend the linac

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

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

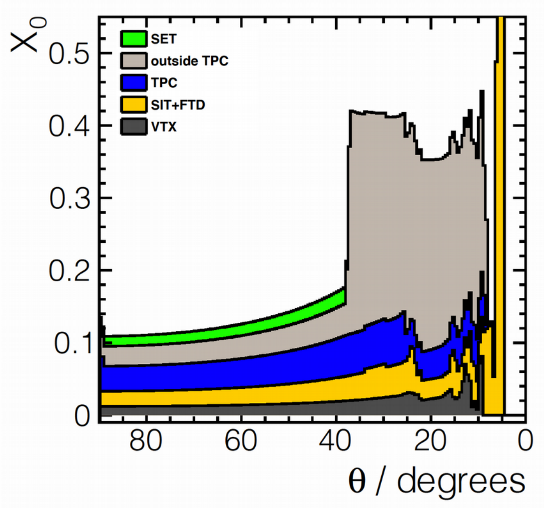
# ILD highlights

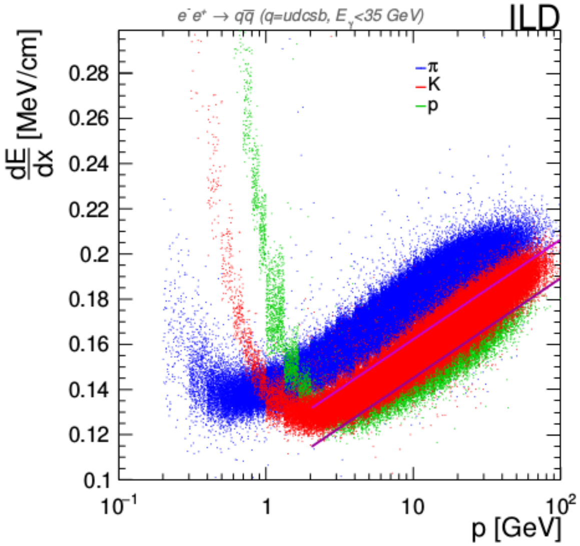
- **ILD snapshot**




- 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!)**



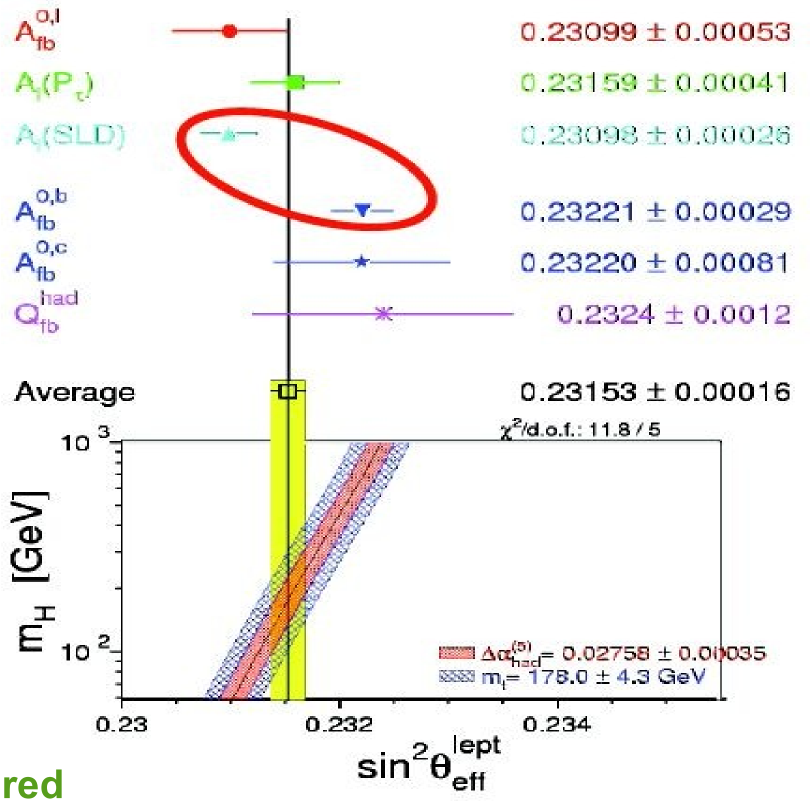

See T. Tanabe's talk on ILD

# 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

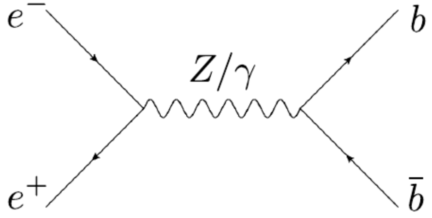
    → Hosotani et al arxiv:1705.05282 arxiv:2006.02157

  - 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




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

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

- The helicity amplitudes $\Sigma_{IJ}$, 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**

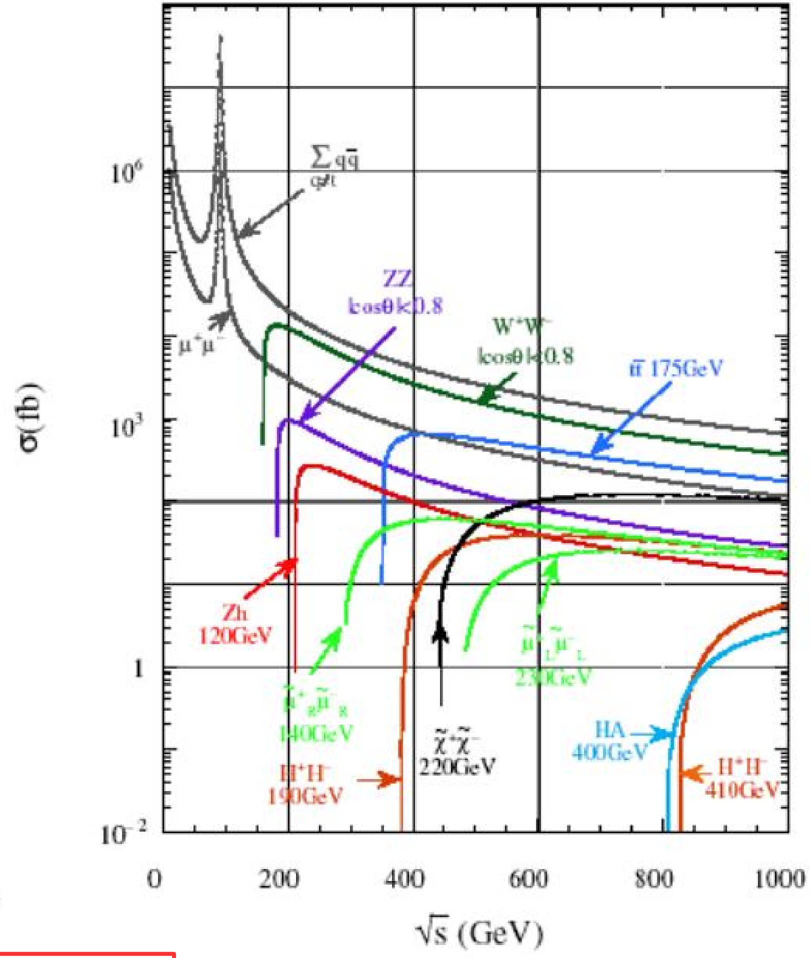
- no access to the γ or Z/γ interferences
- Moderated quark tagging or charge measurements capabilities.
- Also moderated angular acceptance of the detectors

# Cross sections

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

| | Channel | $\sigma_{unpol}$ [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**



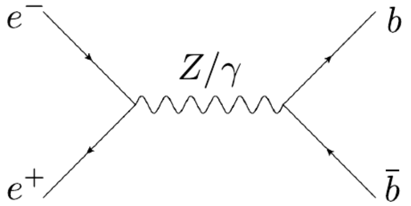

**In this talk I concentrate on b-quark pair production at 250 GeV**

# 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.




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

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

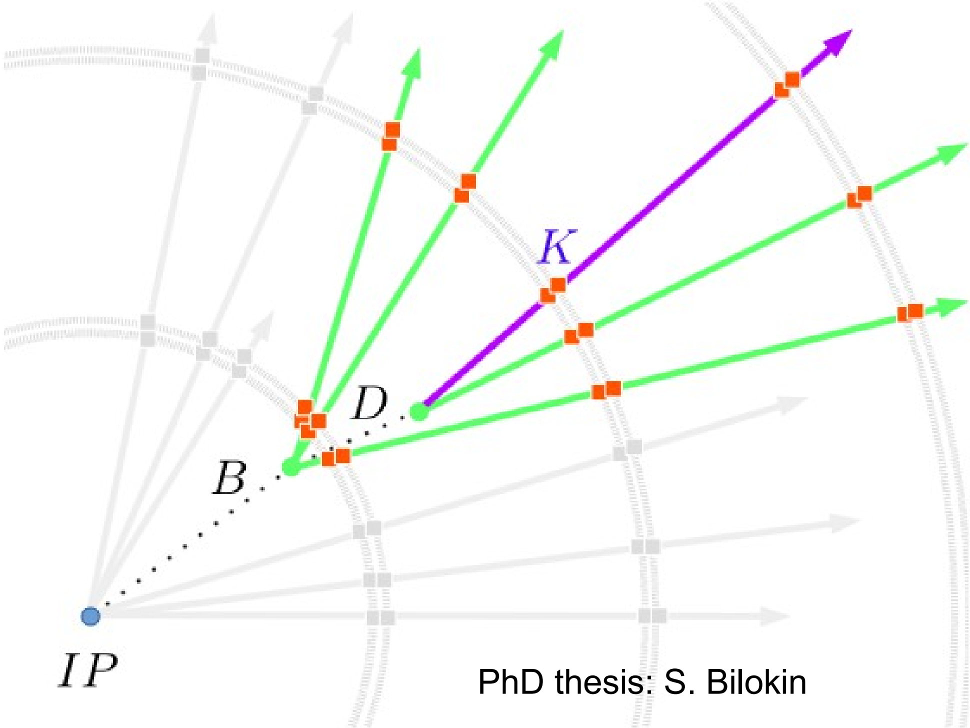
→ Angular Distribution.

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

IFIC INSTITUT DE FÍSICA CORPUSCULAR

**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

IJCLab Irène Joliot-Curie

# 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 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 $\varepsilon_b$ are measured simultaneously.

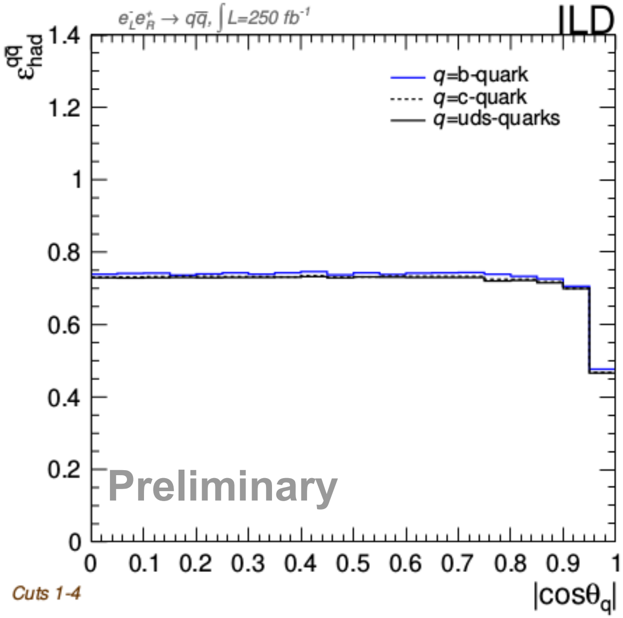
- **$\varepsilon_b$ = b-tagging efficiency**
- $\rho_b$ = b-tagging correlation factor
- $\varepsilon_c$ = probability of tagging a c-quark jet as b-jet
- $\varepsilon_{uds}$ = probability of tagging an uds-quark jet as b-jet

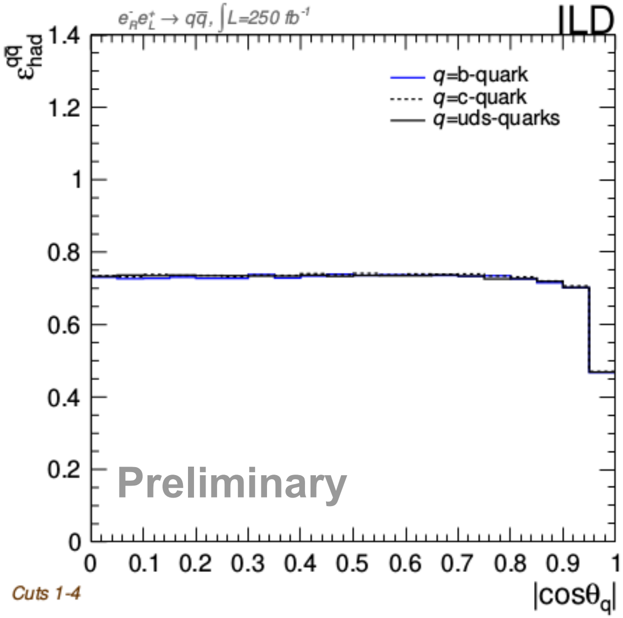
These values must be as small as possible and with small uncertainties

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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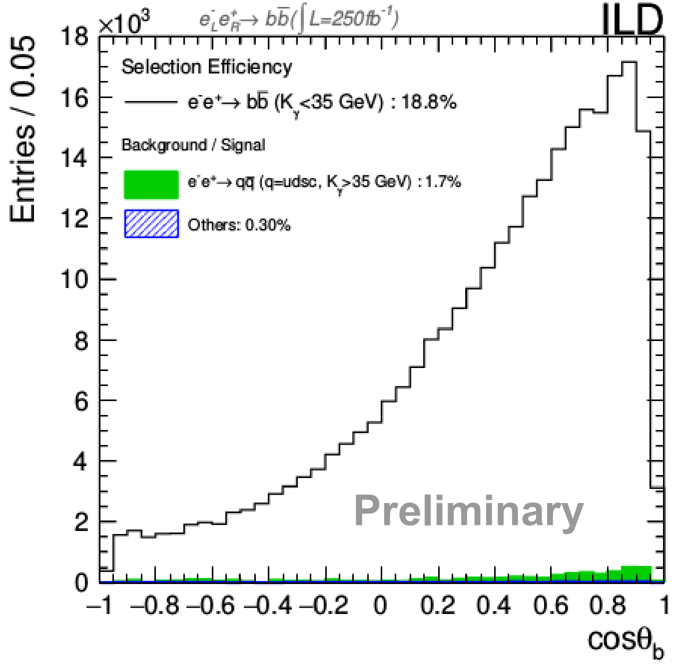


- Main bkg ee→ Zγ(ISR)
  - ~x10 larger than signal
  - For **~90% of such ISR photons are lost in the beam pipe** → events filtered by energy (angular) conservation arguments
  - The **remaining ~10% are filtered by identifying photons** in the detector (efficiency of ~90%)
- Very small B/S ~2%

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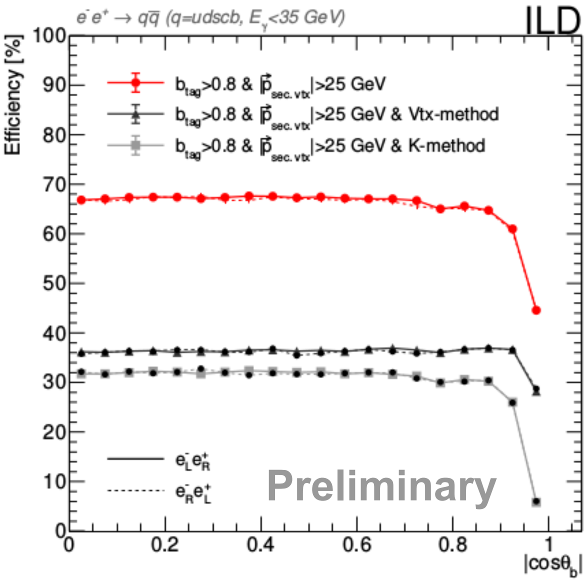
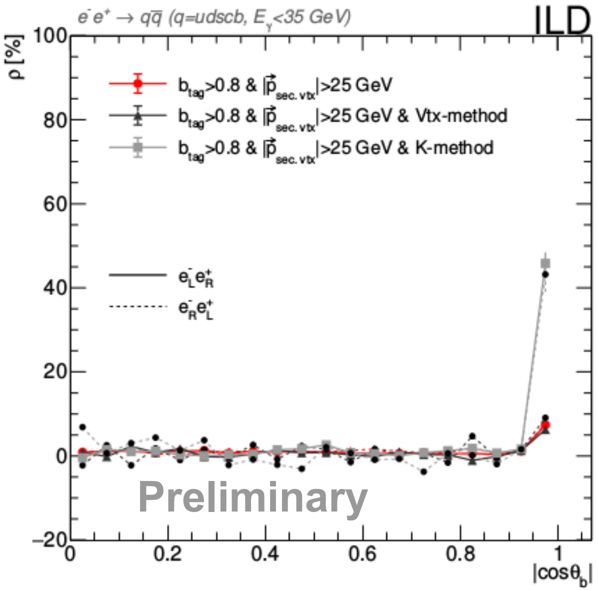


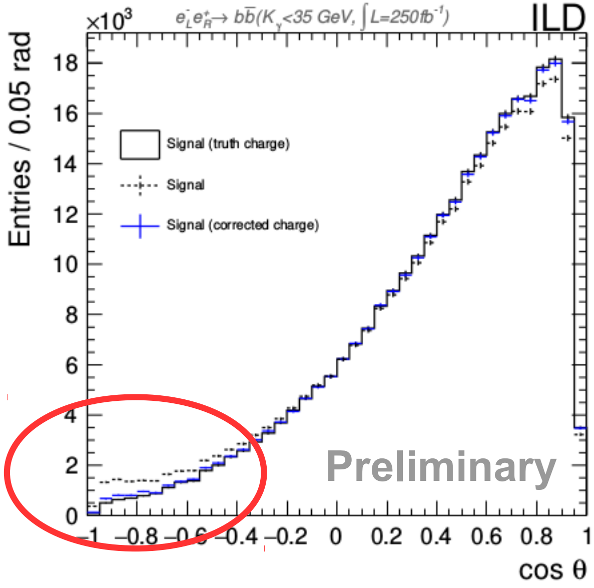

- **Excellent prospects for b-tagging** (or c-tagging) with very low correlation factor ~ 0 ( ~2% at LEP)
- **Differential measurements!**
  - Constant values for most of the angles
  - Drop of acceptance the very forward region → optimizations are under consideration
- **Miss-efficiencies very small**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

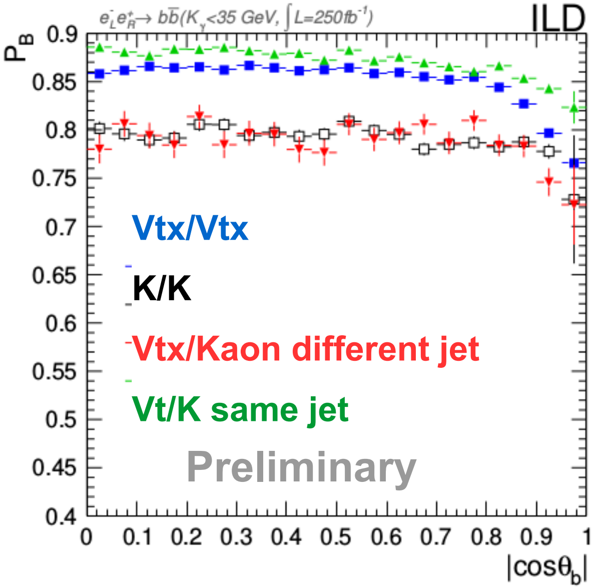
**Arxiv:1709.04289, PoS(EPS-HEP2019)624**
**ILD Note in progress**

# 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?**

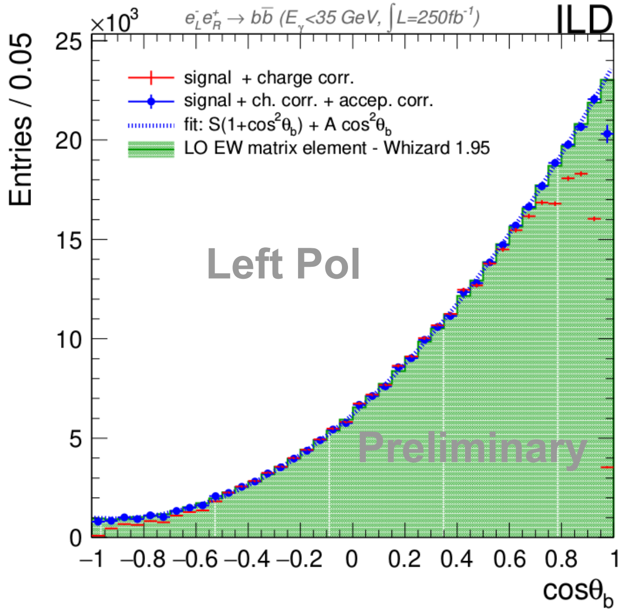


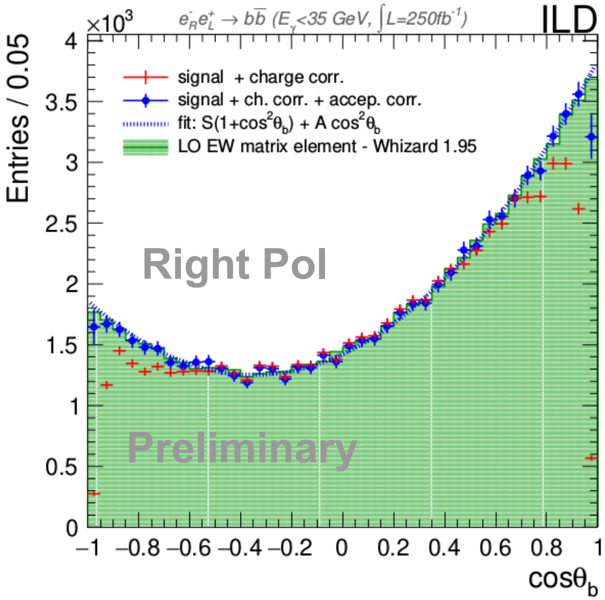




- **$P_B$ limited by vertex reconstruction efficiency, Particle ID efficiency and B0 oscillations.**

**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.) % |

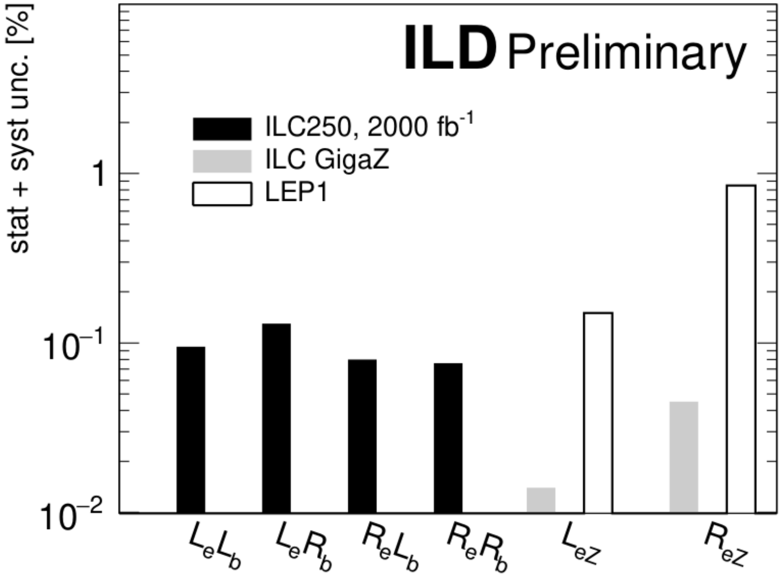
**Stat unc (2000 fb-1 )**

**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)**

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

ILC250 → LeLb; SM → QeQb; GigaZ → $\frac{LeZLbZ}{s^2wc^2w}$; New resonances → BWZ′

GigaZ ↓

*Sensitive to Z-Z' mixing effects*

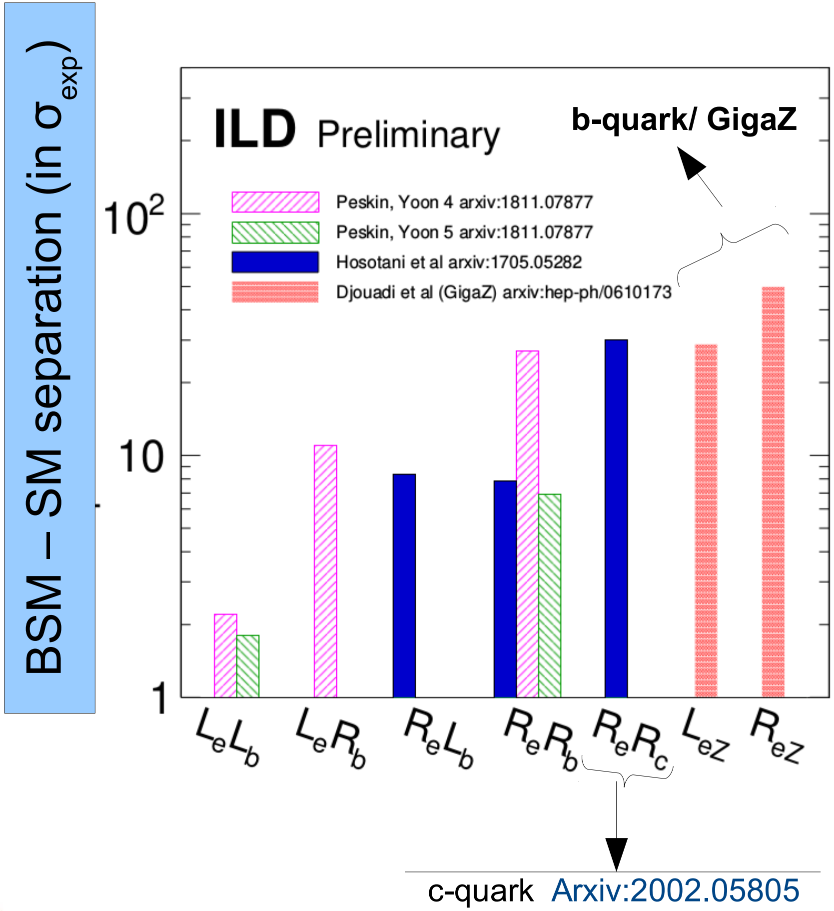
*(that could explain AFBb measurement of LEP?)*

**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




- 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).

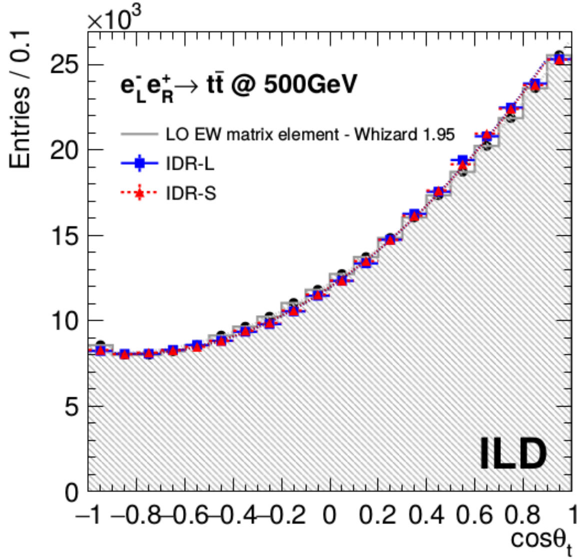
- Models that predict multi-TeV Z' resonances
- With or without mixing at Z-pole
- See backup for more details on the models

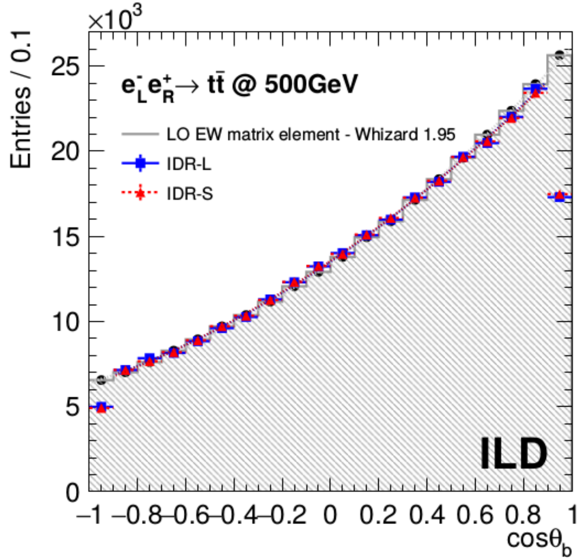
**Potential for discovery of new resonances mZ' ~ O(20-30) TeV at ILC250**

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

# Top quark: results (1)

ILD-PHYS-PUB-2019-007




- 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**

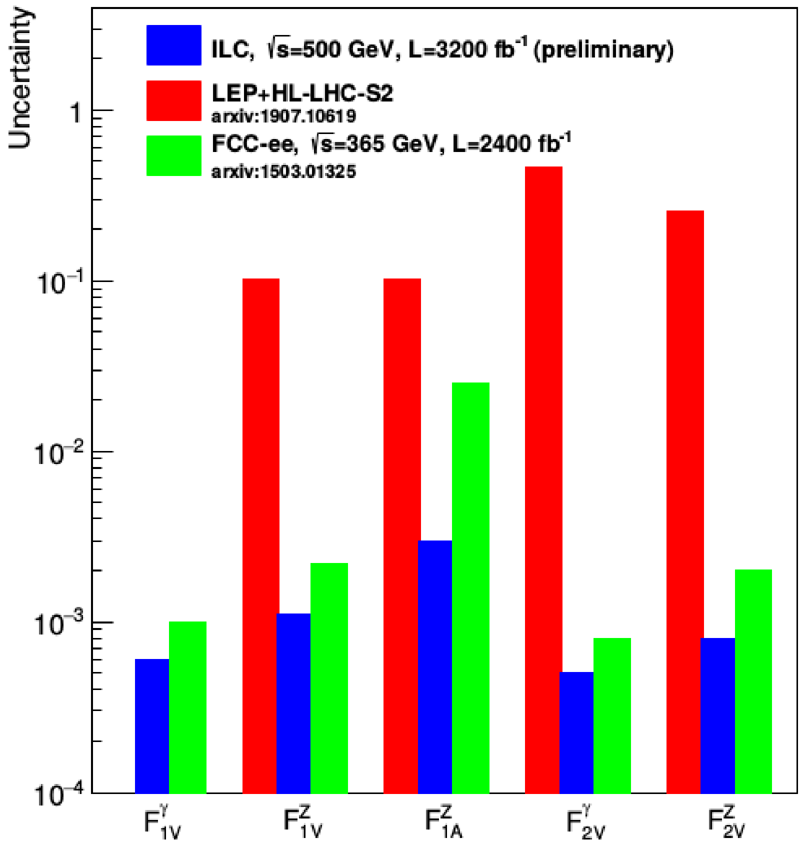
- Integrated Luminosity 4 $fb^{-1}$
- Thanks to the jet charge calculations capabilities, we could use all decay channels.
- Efficiencies of 75% (cross section) and 30% (differential cross section)
- Exact reproduction of generated spectra
  - Statistical precision on cross section: ~0.1%  Statistical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

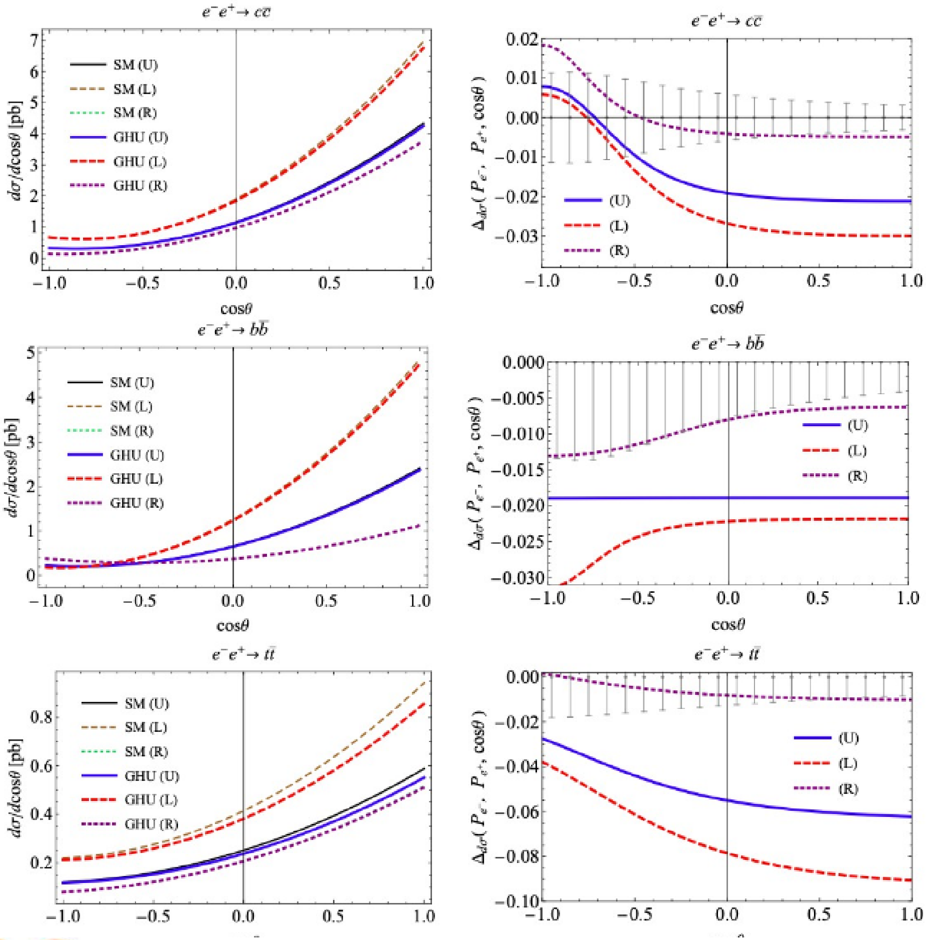
# Summary / conclusions

- 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** (studies at 500 GeV at preliminary stage)
  - **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.

# a BSM example: GUT Inspired Grand Higgs Unificaton Model



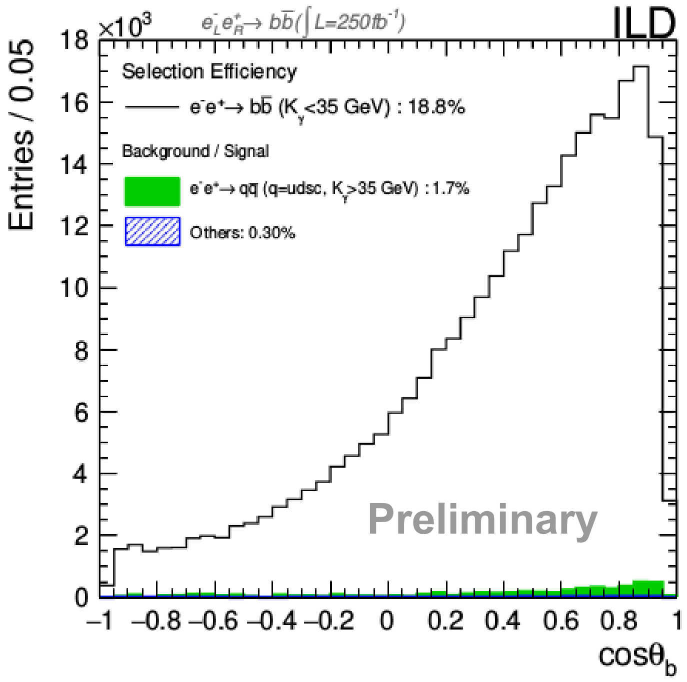

arxiv:2006.02157

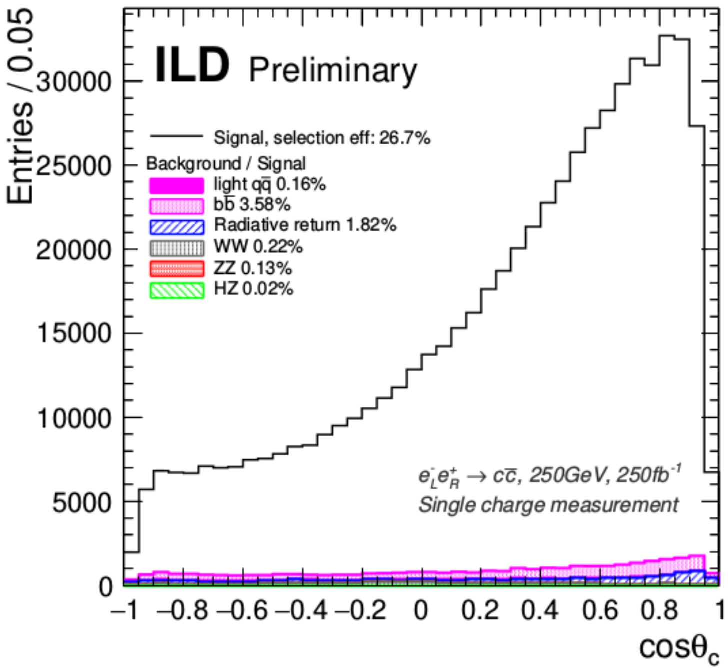
- Model parameter is Hosotani angle $\theta_H$ yielding the Higgs-Potential as consequence of Aharanov-Bohm Phase in 5$^{th}$ dimension
- Model defined in Randall-Sundrum warped extra dimensions
  - KK excitations of gauge bosons and new bosons modify fermion couplings
- Predictions for ILC
  - $m_{KK}$ = 13 TeV and $\theta_H$ = 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

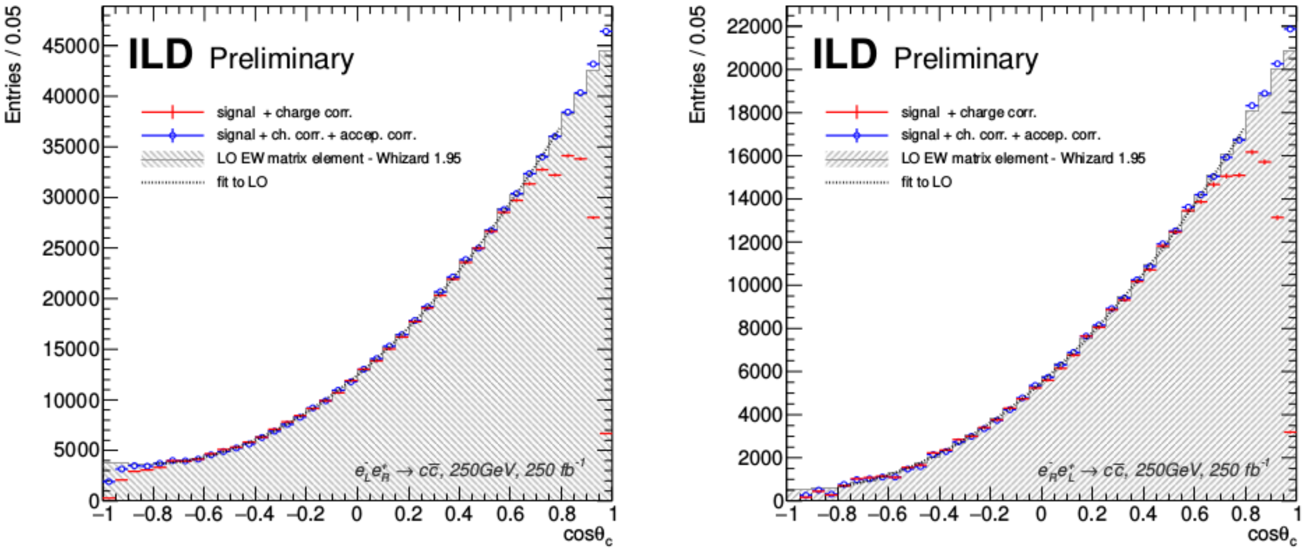



- Background ~free analysis!

Arxiv:2002.05805

# 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

$e_L^- e_R^+ \rightarrow t\bar{t}$ 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 | | |

$e_R^- e_L^+ \rightarrow t\bar{t}$ 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

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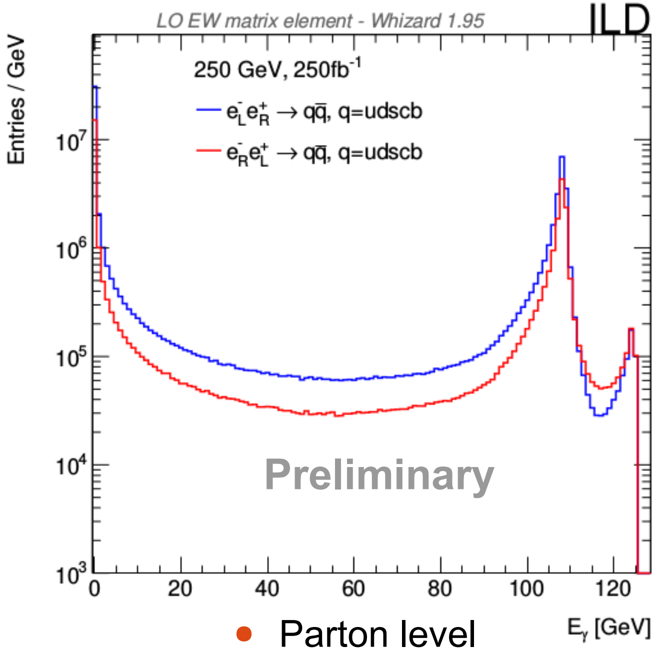
Irène Joliot-Curie

# Predictions (as a function of the ISR)

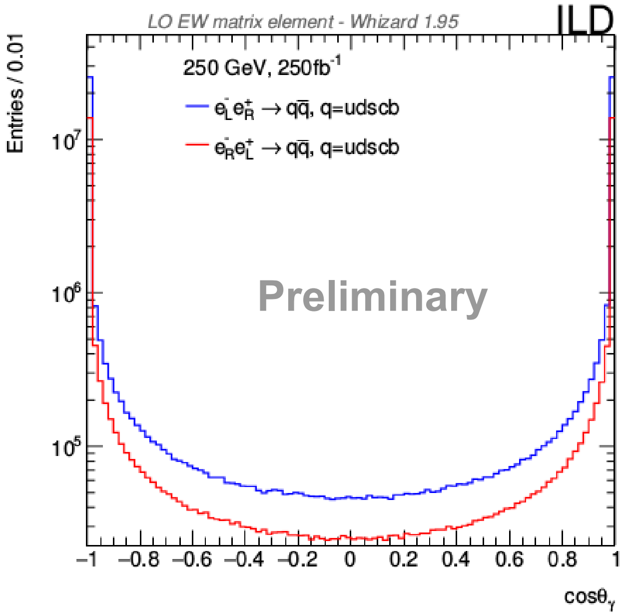
- The cross section depends on the "effective" center of mass energy
  - At which the Z/y couple to the quark-antiquark pair

$$\frac{d\sigma^{cont.}_{e^-e^+\to q\bar{q}}}{d\cos\theta_q}(s) \to$$

$$\to \frac{d\sigma^{cont.\bar{q}}_{q}}{d\cos\theta_q}(\hat{s} > s_{cut}) = \frac{d\sigma^{cont.}_{e^-e^+\to q\bar{q}}}{d\cos\theta_q}(E_\gamma < K_{cut})$$



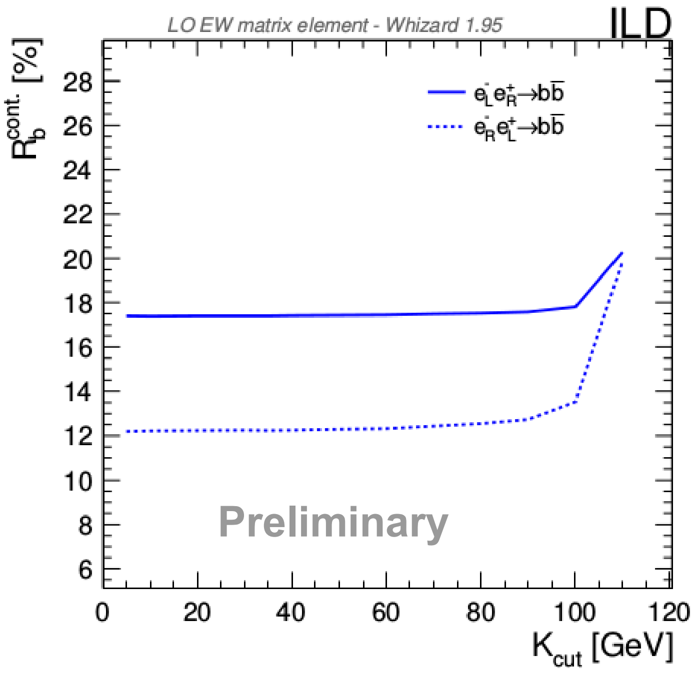

- Parton level

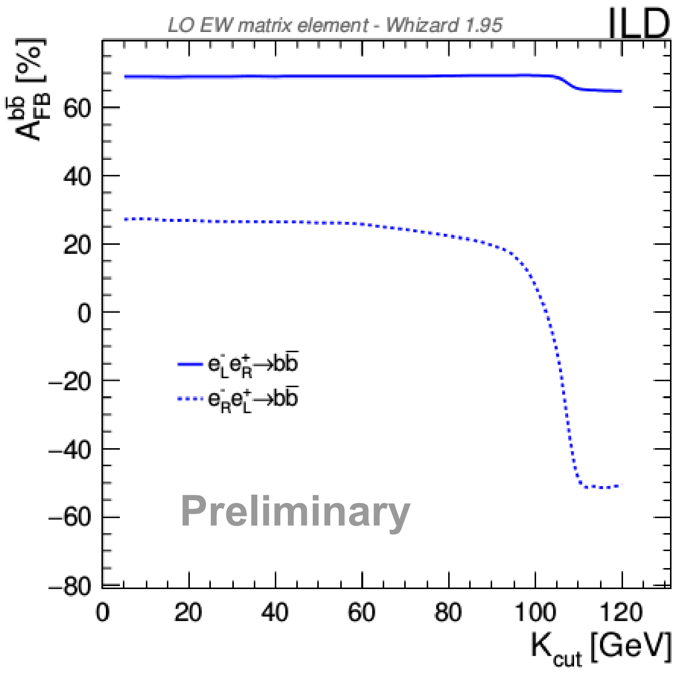



- Parton level

# Predictions (as a function of the ISR)

$$\frac{d\sigma^{cont.}_{e^-e^+\to q\bar{q}}}{d\cos\theta_q}(E_\gamma < K_{cut})$$




- The observables remain basically flat for a large range of the Kcut
- Drastic change when the photn ISR is large enough to produce a return to the Z-pole
  - We need to avoid that region of the phase space.

# Preselection

- Alternatives to m(2jets) ?
- Estimator of the energy of the photon ISR using only the two reconstructed jets.
  - From momentum conservation (if the photon/s are emitted parallel to the beam pipe):

$$|\vec{k}| \approx K_{reco} = \frac{250\,\mathrm{GeV}}{\sin\Psi_{acol} + sin\theta_1 + sin\theta_2}.$$

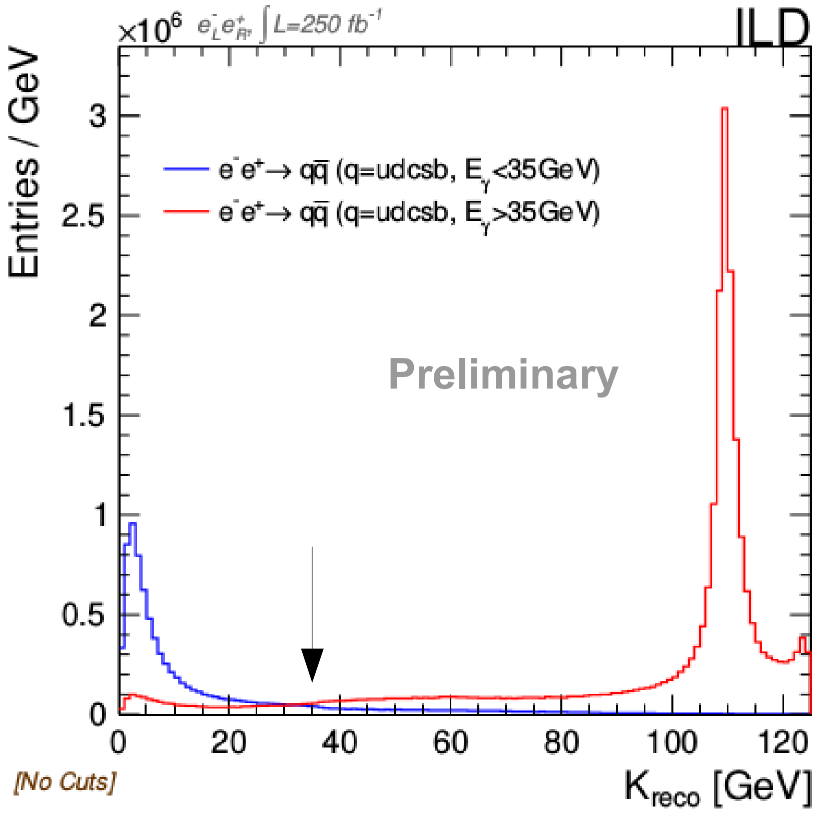
Two jet acolinearity

$$\sin\Psi_{acol} = \frac{\vec{p_{j_1}} \times \vec{p_{j_2}}}{|\vec{p_{j_1}}| \cdot |\vec{p_{j_1}}|}$$

Jet angular variables (w.r.t. detector frame)

# Preselection : Kreco

- Estimator of the energy of the photon ISR
- We apply a cut of Kreco<35 GeV
- Some signal events have larger Kreco (~15%)
  - Because of detector resolution and double photon ISR
- Some radiative return events have Kreco<35GeV (~7%)
  - Because the photon(s) has not escaped through the beam pipe
- Can we identify the photon clustered in one or both jets and veto these events?

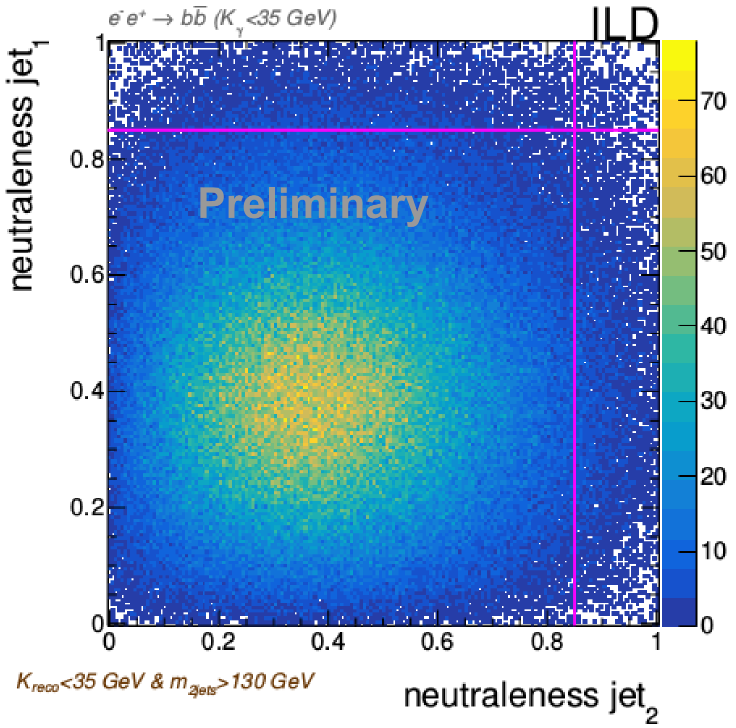


# Preselection : Photon Veto

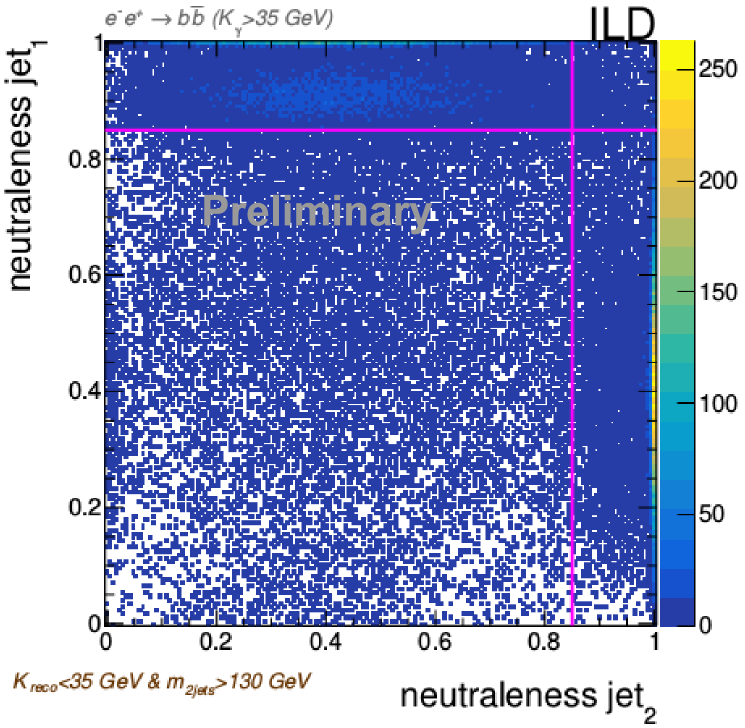
- We look at the neutraleness of the jets

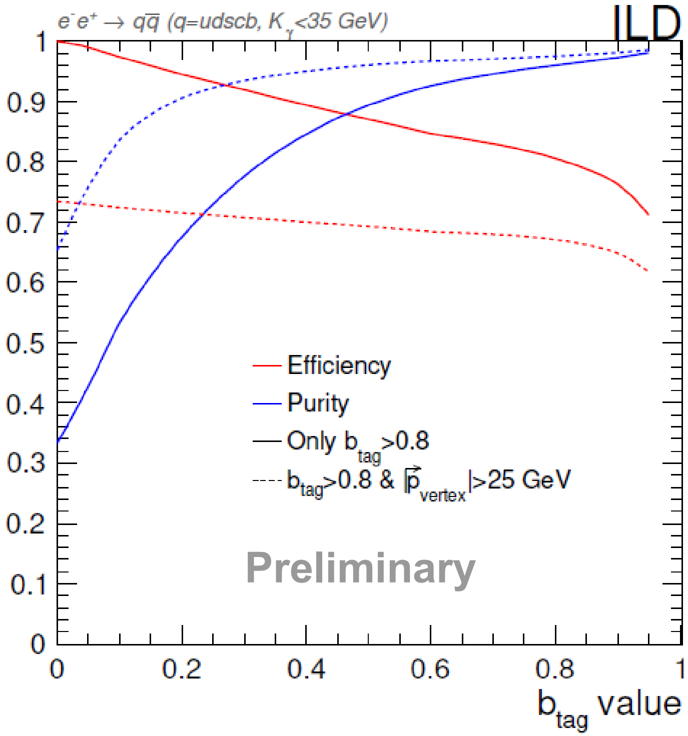
$$\text{neutraleness}_j = \frac{\sum_{i=nPFO} E_i}{E_j}.$$

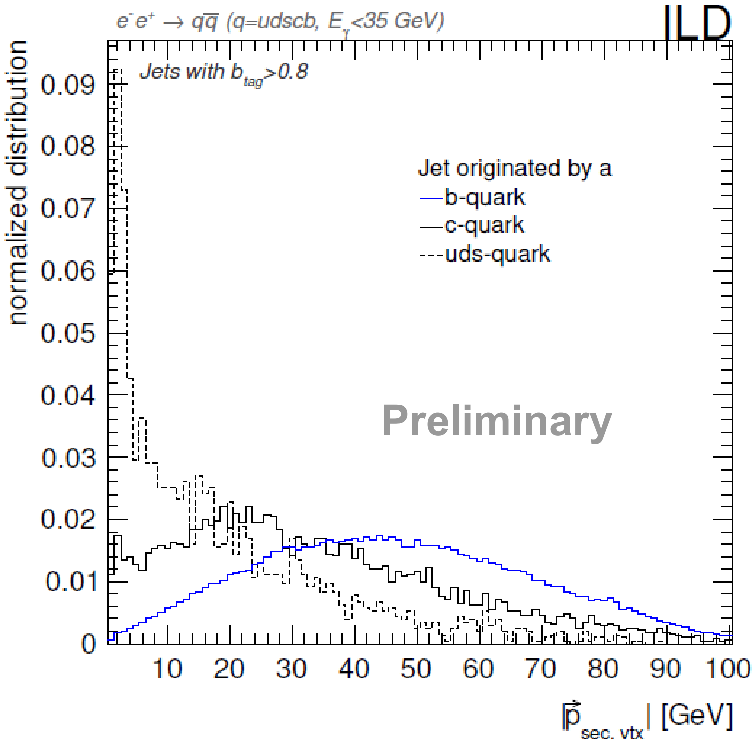
signal

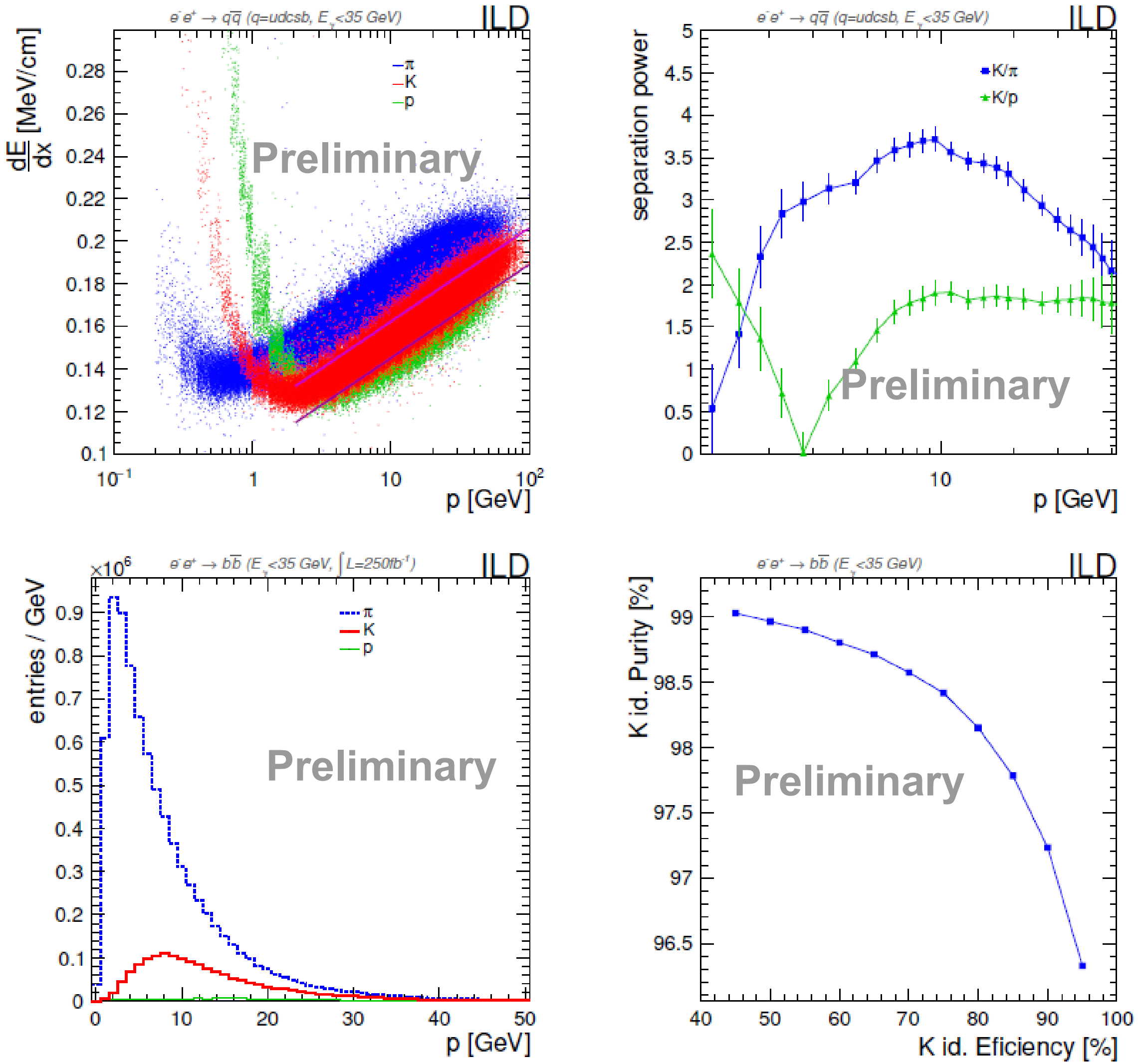



radiative return




$e^-e^+ \to q\bar{q}$ (q=udscb, $K_\gamma$<35 GeV)
ILD
Efficiency
Purity
Only $b_{tag}$>0.8
$b_{tag}$>0.8 & $|\vec{p}_{vertex}|$>25 GeV
Preliminary
$b_{tag}$ value

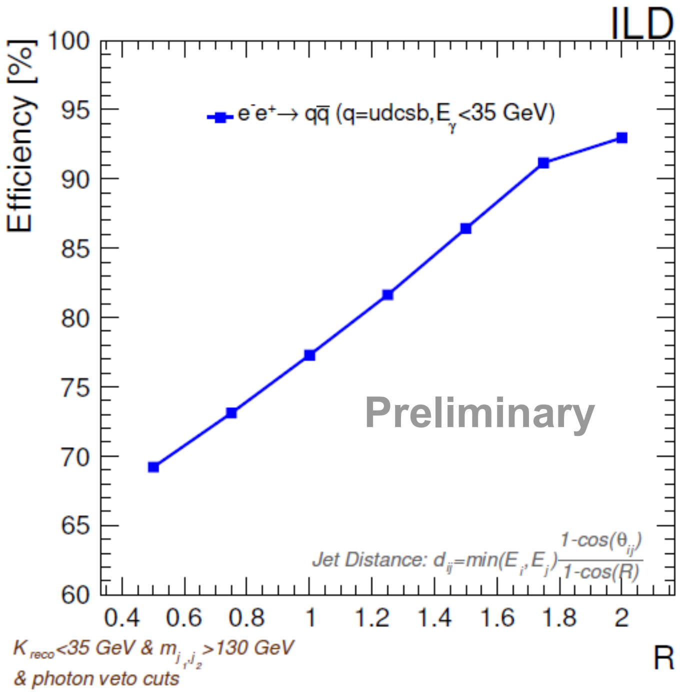

$e^-e^+ \to q\bar{q}$ (q=udscb, $E_\gamma$<35 GeV)
ILD
Jets with $b_{tag}$>0.8
Jet originated by a
b-quark
c-quark
uds-quark
Preliminary
normalized distribution
$|\vec{p}_{sec.\ vtx}|$ [GeV]

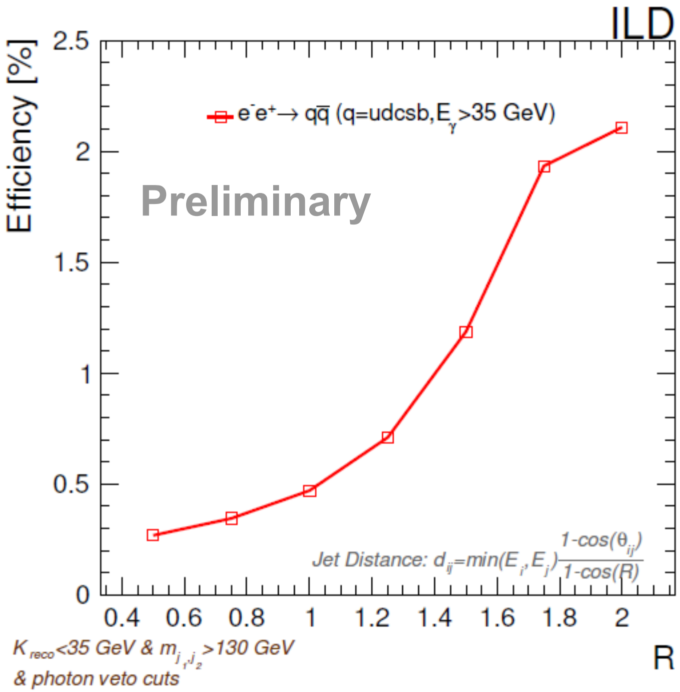


e⁻e⁺ → qq̄ (q=udcsb, E_γ<35 GeV)
ILD
dE/dx [MeV/cm]
p [GeV]
π
K
p
Preliminary
separation power
K/π
K/p
e⁻e⁺ → bb̄ (E_γ<35 GeV, ∫L=250fb⁻¹)
entries / GeV
×10⁶
e⁻e⁺ → bb̄ (E_γ<35 GeV)
K id. Purity [%]
K id. Eficiency [%]

$$d_{ij} = min(E_i^{2p}, E_j^{2p}) \frac{1 - cos(\theta_{ij})}{1 - cos(R)}$$

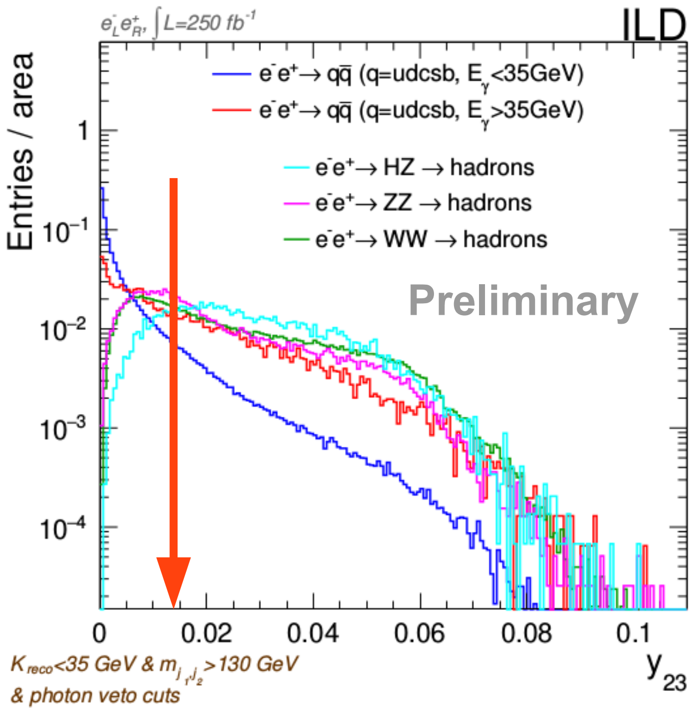
$$d_{iB} = E_i^{2p}$$

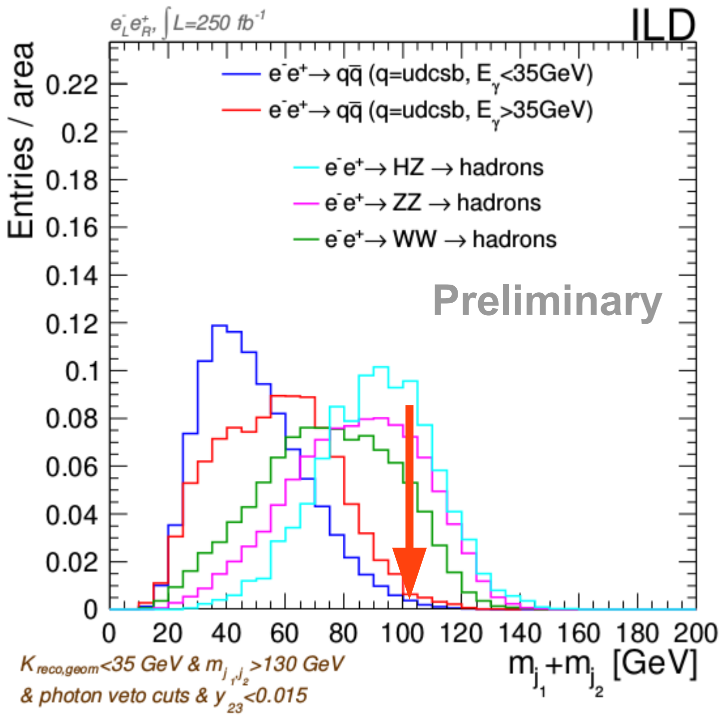


# Final steps of the preselection

- Cut on y23<0.015 (jet distance at which the 2 jet event would be clustered in 3 jets)
- Cut on mj1+mj2<100 GeV

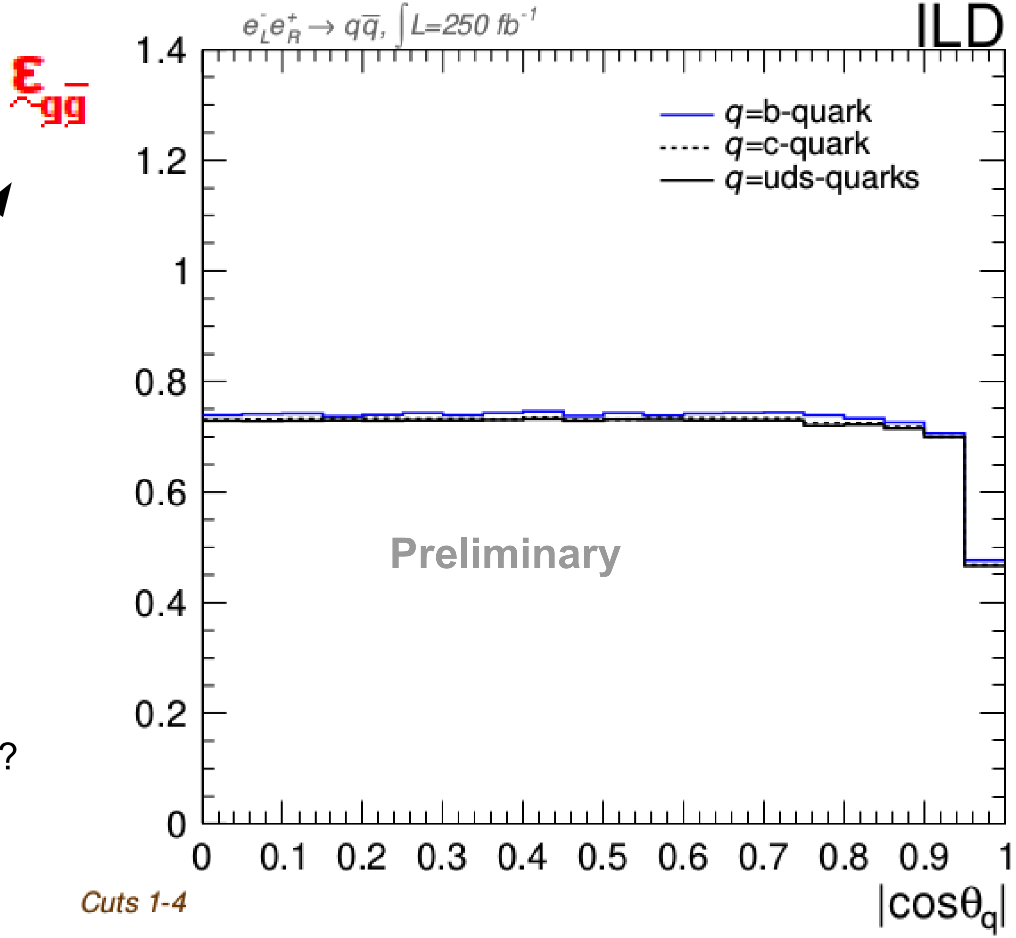


# Preselection summary

- Cut 1:
  - Kreco<GeV & m(2jets)>130 GeV
- Cut 2:
  - Photon veto cuts
- Cut 3:
  - y23<0.015
- Cut 4:
  - mj1+mj2<100 GeV

- What is the preselection efficiency $\varepsilon_{q\bar{q}}$ for each flavour?
  - It is flat in almost all the detector
  - Almost equal for all flavours




Cuts 1-4