Heavy Quark cross section and forward backward asymmetries at ILC250 (and beyond)

Adrián Irles* on behalf of the Orsay/Tohoku/Valencia HQ-ILC team

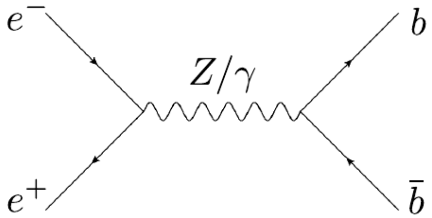
**AITANA group at IFIC - CSIC/UV*

Introduction

- Orsay/Tohoku/Valencia Heavy Quark ILC research team
  - From top to strange (so far...)

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 (characteristic for each fermion)

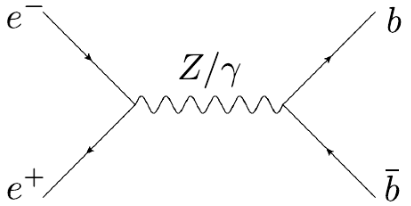
- **Only beam polarisation allows inspection of the 4 helicity amplitudes for all fermions**
  - Beam polarisation also enhances the cross section values

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**

Measuring Rq

Preselection

▶ Event selection → backgrounds from radiative return (x10 signal) events and WW/ZZ/HZ

Signal | Rad return bkg

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

Diboson bkg

Channel	$\sigma_{e^-_L e^+_R\to X}$ [fb]	$\sigma_{e^-_R e^+_L\to X}$ [fb]
$X = WW \to q_1\bar{q}_2 q_3\bar{q}_4$	14874.4	136.4
$X = ZZ \to q_1\bar{q}_1 q_2\bar{q}_2$	1402.1	605.0
$X = HZ \to q_1q_2H$	346.0	222.0

Preselection

- **Event selection → backgrounds from radiative return (x10 signal) events and WW/ZZ/HZ**
- Cuts (see J. Márquez talk https://agenda.linearcollider.org/event/9285/)
  - **C1-2:** Energy_photon < 35 GeV & 2jet inv_mass > 140GeV

    (Cuts for events with ISR escaping the reconstruction)
  - **C3-5:** photon removal cuts

    (veto events with reconstructed ISR photons)
  - **C6:** y23 <0.015

    (cut against dibosons)

eLpR

	Signal Efficiency (%)			B/S (%)			
	bb	cc	qq (uds)	RadRet	WW	ZZ	qqH
	100.0	100.0	100.0	287.0	44.9	4.3	1.0
CUT 1	81.1	80.9	81.0	20.3	6.2	0.6	0.2
CUT 2	80.8	80.9	81.0	18.6	5.8	0.6	0.2
CUT 3	80.8	80.5	80.0	10.4	5.8	0.6	0.2
CUT 4	80.8	80.5	79.9	10.3	5.8	0.6	0.2
CUT 5	77.7	77.2	75.9	4.8	6.0	0.6	0.2
CUT 6	64.0	64.1	63.3	3.8	1.5	0.2	0.1

eRpL

	Signal Efficiency (%)			B/S (%)			
	bb	cc	qq (uds)	RadRet	WW	ZZ	qqH
	100.0	100.0	100.0	562.0	1.3	5.7	2.1
CUT 1	81.0	81.0	81.2	41.4	0.2	0.9	0.3
CUT 2	80.8	80.9	81.2	38.0	0.2	0.8	0.3
CUT 3	80.7	80.6	80.2	17.6	0.2	0.8	0.3
CUT 4	80.7	80.6	80.1	17.4	0.2	0.8	0.3
CUT 5	77.5	77.2	76.2	6.9	0.2	0.8	0.3
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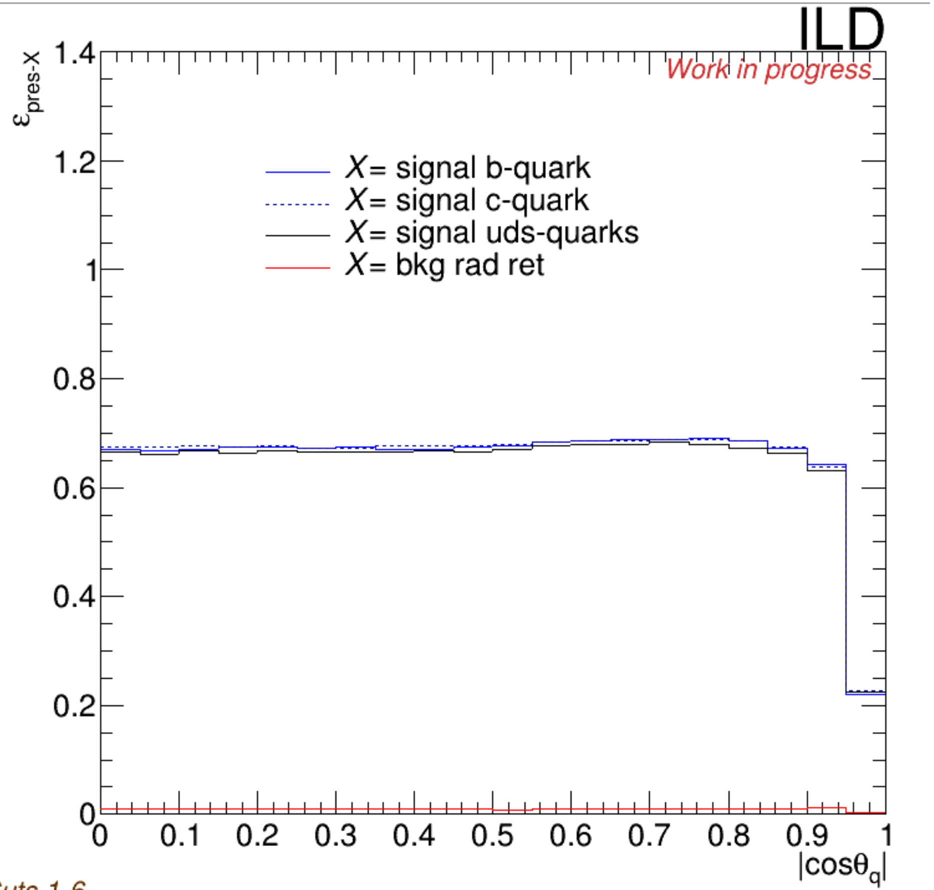

Cuts 1-6

Double Tag Method

- **Method used to remove modeling dependence on the efficiency of b-tagging → aiming to 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**

$$N_0 = N_{presel} = [\varepsilon_{pres-signal}\,\sigma_{q\bar{q}} + \varepsilon_{pres-bkg}\,\sigma_{bkg}] \cdot Lum$$

$$N_{1tag,c} = [\varepsilon_{pres-signal}(\varepsilon_c\,\sigma_{c\bar{c}} + \varepsilon_b\,\sigma_{b\bar{b}} + \varepsilon_q\,\sigma_{q\bar{q}}) + \varepsilon_c\,\varepsilon_{bkg}\,\sigma_{bkg}] \cdot Lum$$

$$N_{2tag,c} = [\varepsilon_{pres-signal}(\varepsilon_c^2(1+\rho_c)\,\sigma_{c\bar{c}} + \varepsilon_b^2\,\sigma_{b\bar{b}} + \varepsilon_q^2\,\sigma_{q\bar{q}}) + \varepsilon_c^2\,\varepsilon_{bkg}\,\sigma_{bkg}] \cdot Lum$$

Double Tag Method

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▶ The sample consisted on events made of two hadronic jets (qqbar)

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$$N_{1tag,c}^{signal} = [\varepsilon_{pres-signal}(\varepsilon_c\,\sigma_{c\bar{c}} + \varepsilon_b\,\sigma_{b\bar{b}} + \varepsilon_q\,\sigma_{q\bar{q}})]\cdot Lum$$

$$N_{2tag,c}^{signal} = [\varepsilon_{pres-signal}(\varepsilon_c^2(1+\rho_c)\,\sigma_{c\bar{c}} + \varepsilon_b^2\,\sigma_{b\bar{b}} + \varepsilon_q^2\,\sigma_{q\bar{q}})]\cdot Lum$$

▶ For the moment, let’s assume that **we know the bkg contribution with perfect accuracy**

- We remove the bkg contribution from the equations

Double Tag Method

▶ **Assuming that:**

- Minimal contribution from the brackgrounds
- the preselection efficiency is the same for all flavours

$$f_{1tag} = \varepsilon_c R_c + \varepsilon_b R_b + \varepsilon_{uds} (1 - R_b - R_c)$$
$$f_{2tag} = \varepsilon_c^2 (1 + \rho^2) R_c + \varepsilon_b^2 R_b + \varepsilon_{uds}^2 (1 - R_b - R_c)$$

▶ **We are interested in Rc / epsilon_c**

- f1, f2 are our observables (dependent on N0, N1, N2)
- Rho, Rb and the mistagging efficiencies are assumptions (MC, measurement,...)

ideally →

$$f_{1\,tag} \simeq \varepsilon_c R_c$$
$$f_{2\,tag} \simeq \varepsilon_c^2 R_c$$
$$with$$
$$BKG \simeq 0$$
$$\varepsilon_b^{pres} \simeq \varepsilon_c^{pres} \simeq \varepsilon_{uds}^{pres}$$

Double Tag Method

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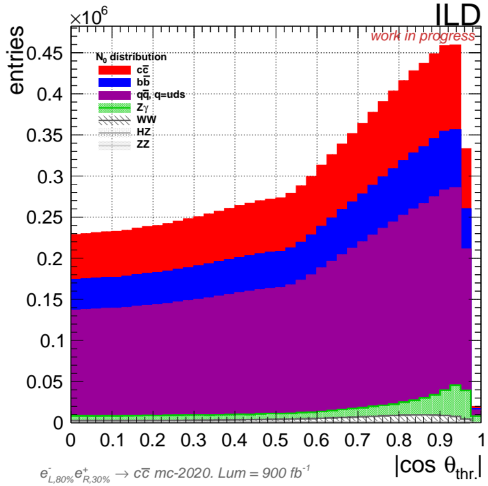
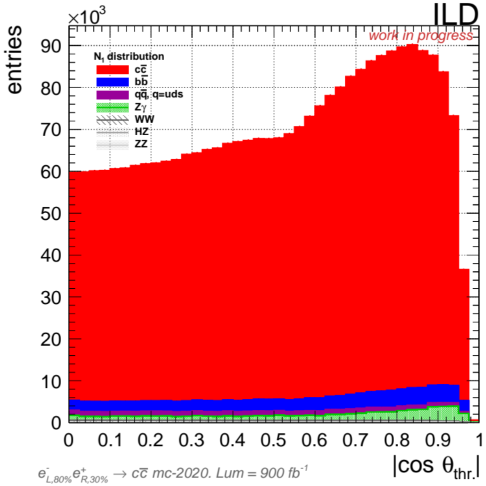
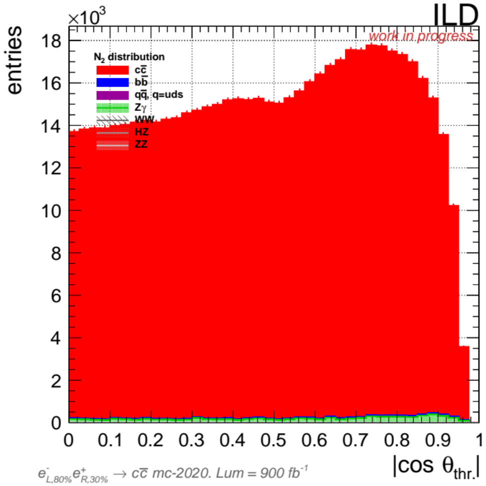
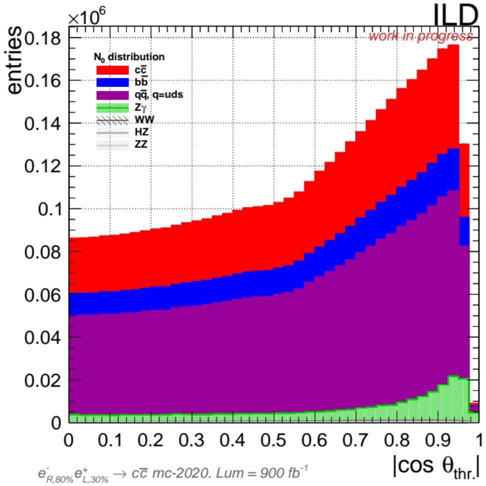
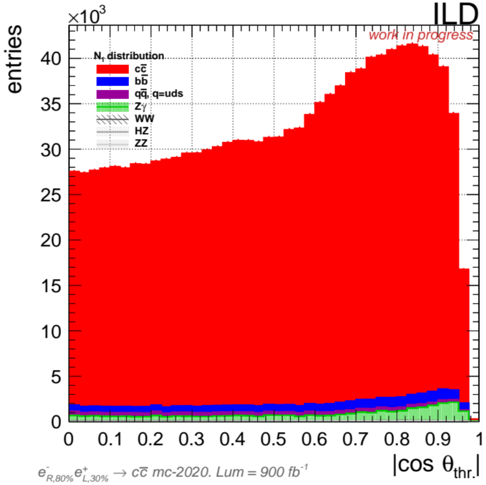
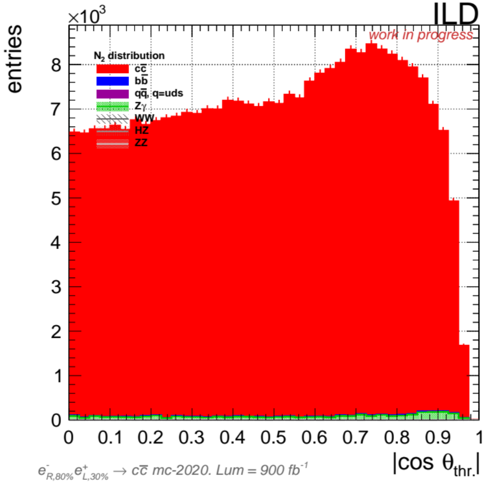
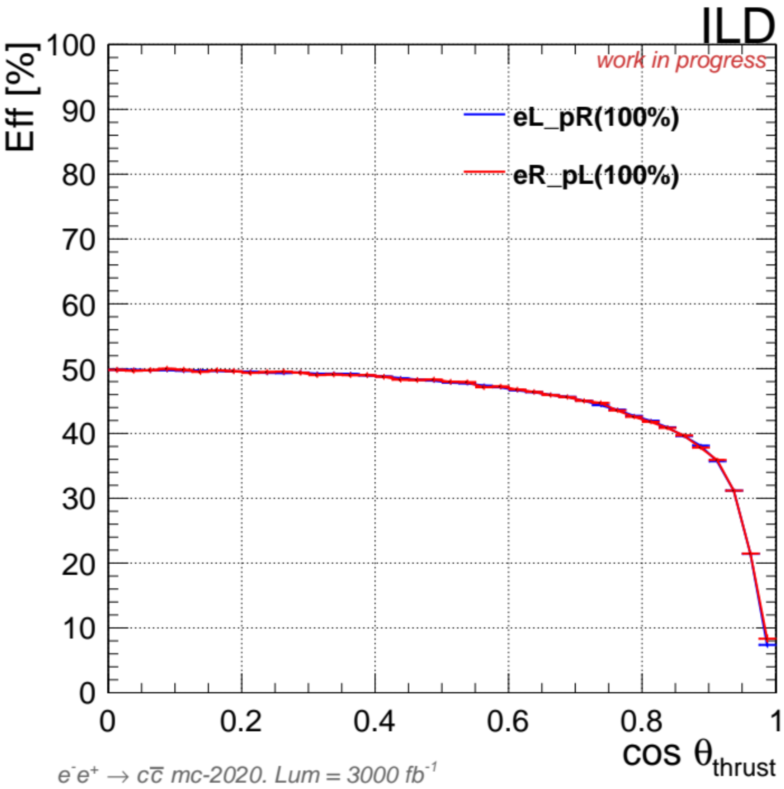
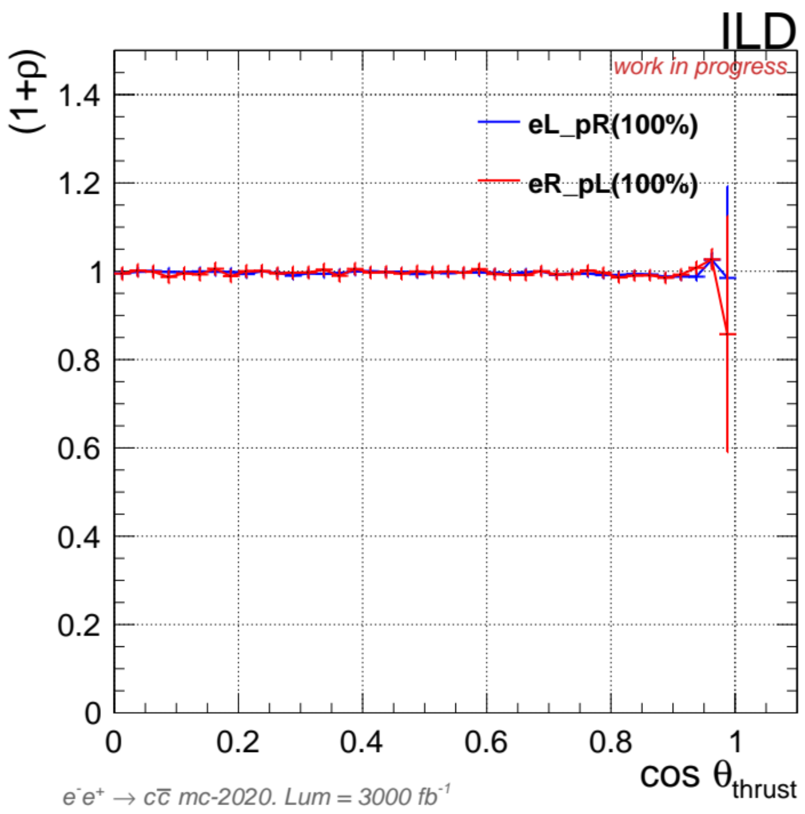
	N0	N1	N2
eLpR (80,30)			
eRpL (80,30)			

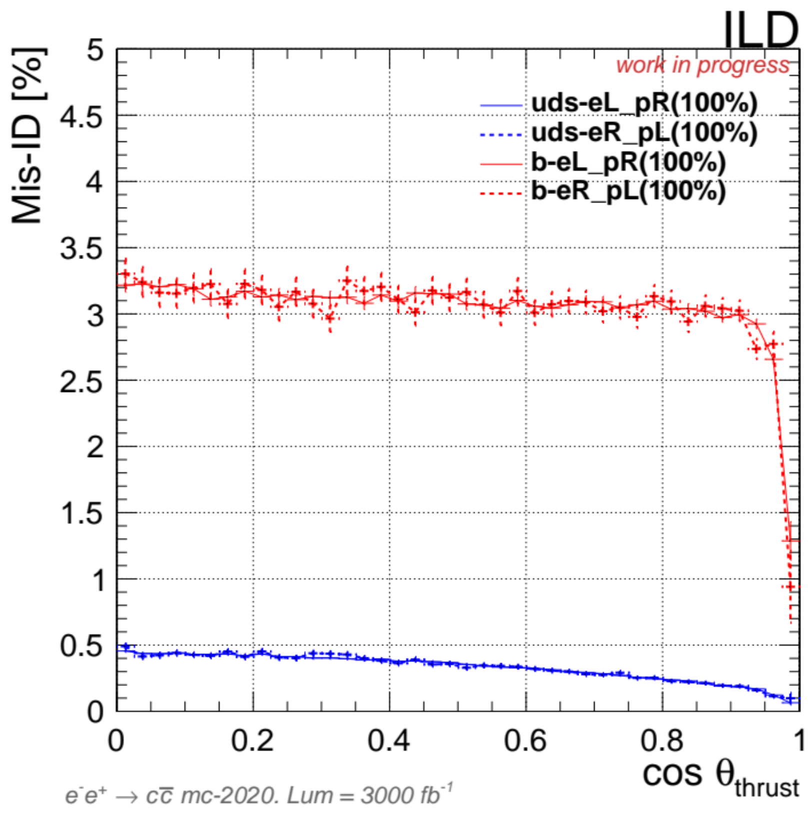
Double Tag Method



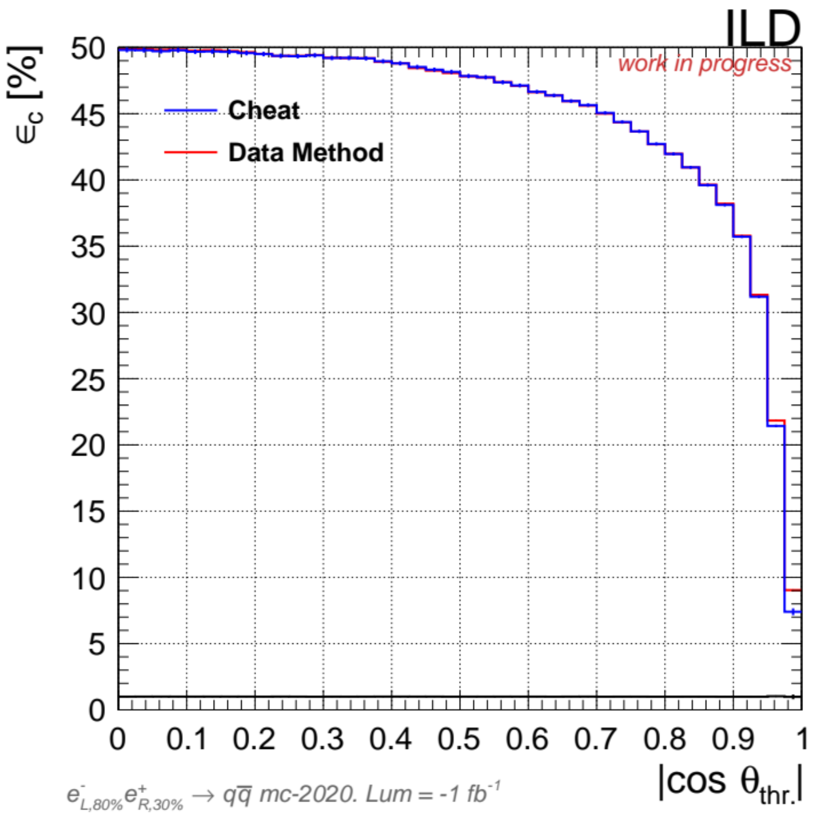
- **The efficiency of quark tagging can be measured with the single vs double tagging, with some assumptions**
  - We perfectly know the bkgs
  - We perfectly know the miss-tagging efficiencies (measurement? MC?)
  - We perfectly know the correlation factor (only via MC)
  - We have measured Rb
- Fortunately, we expect that all these quantities are small at ILC and well understood
  - Minimal impact either case.
  - Controlled systematic uncertainties

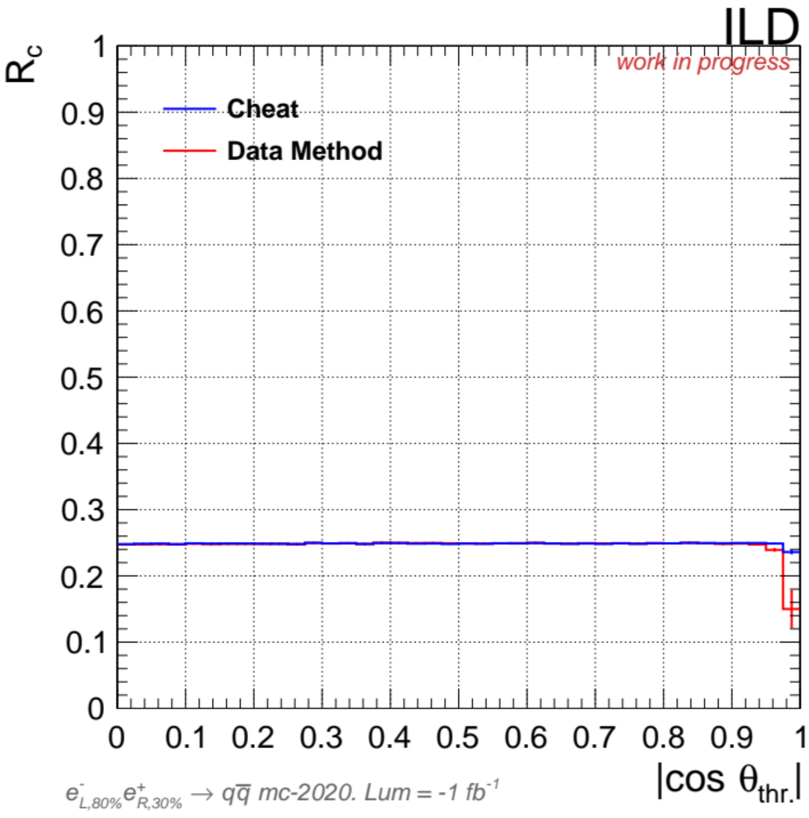
Double Tag Method





Results (eLpR 80,30)





Results (eLpR 80,30)

- **Rc=0.248915.** **I quote all the estimated relative uncertainties.**
- Statistical uncertainties (2000 fb-1 of shared luminosity)
  - Only **stats**: **Delta → 0.13%**
- Preselection uncertainties
  - The preselection is MC dependent…. Assume 10% level accuracy
  - The flavour selection gives differences of ~1% between flavours. We take this as a total uncertainty .
  - **Delta → 0.1%**
- Can we know the mistagging efficiencies at the 10% level
  - LEP estimated with at similar accuracy hep-ex/0503005
  - If yes → **Delta ~ 0.05%**
  - Using or not the MC prediction of **rho** gives us: **Delta → 0.06%**
- Can we know the **backgrounds** at the 10% accuracy ?
  - If yes → **Delta ~ 0.08%**
- What about **polarization**?
  - Using the estimates from 10.3204/PUBDB-2019-03013 we estimate: **Delta → 0.003%**
- Assuming 1% **precision in Rb: Delta → 0.04%**

Results (c & b)

$$R_c(e_L p_R, 80{,}30) = 0.2489\,(SM-LO) \pm 0.14\,\%\,(stat) \pm 0.16\,\%\,(syst.)$$
$$R_c(e_R p_L, 80{,}30) = 0.3144\,(SM-LO) \pm 0.20\,\%\,(stat) \pm 0.17\,\%\,(syst.)$$

C-quark case: systematics are dominated by the flavour selection estimations

$$R_b(e_L p_R, 80{,}30) = 0.1694\,(SM-LO) \pm 0.12\,\%\,(stat) \pm 0.15\,\%\,(syst.)$$
$$R_b(e_R p_L, 80{,}30) = 0.1251\,(SM-LO) \pm 0.22\,\%\,(stat) \pm 0.17\,\%\,(syst.)$$

B-quark case: systematics are dominated by the background estimation (assumed to be know only at 10% level)

Conservative estimation of the systematic unc. in both cases

Results (c & b)

Key Message: we reduce the usage of MC Tools for systematic control to the minimum

We want to measure observables at 0.1% level accuracy

An unfair(?) ILC-LHC comparison:
Get ~0.5 GeV precision in the mtpole requires ~2% precision on the R-distribution (sensitive bin)

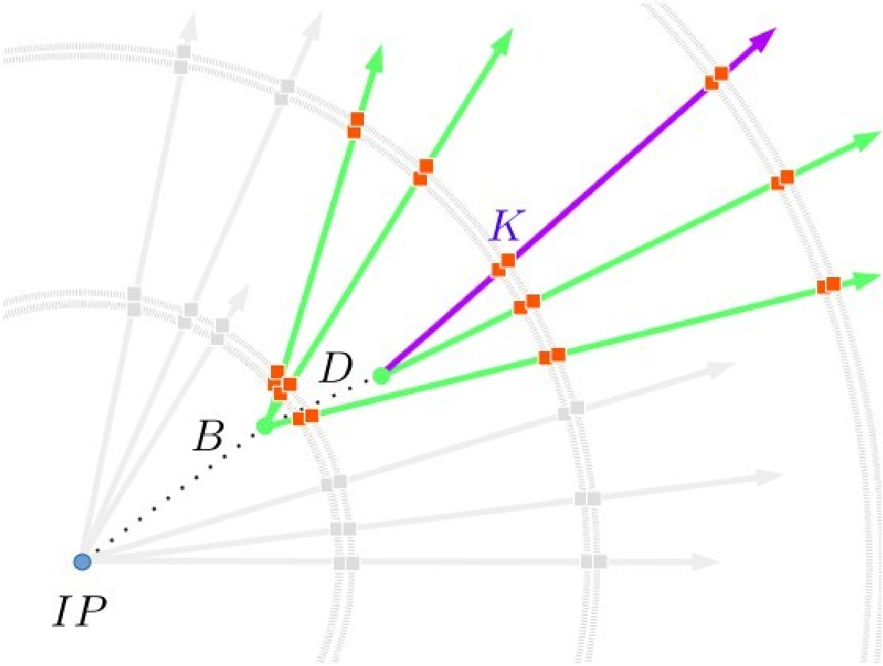
Measuring AFB

AFB measurement: basis

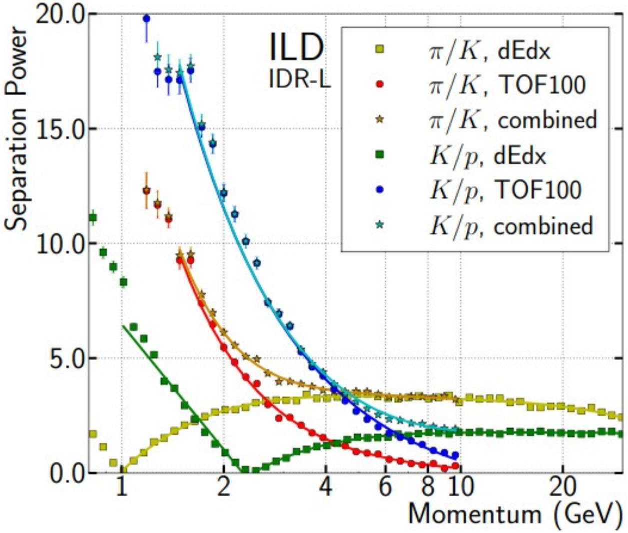
- We are required to **measure the jet charge**
  - Using K-ID and/or full Vtx charge measurement
  - K-ID is better suited for the C-quark (Vtx is better suited for b-quark)

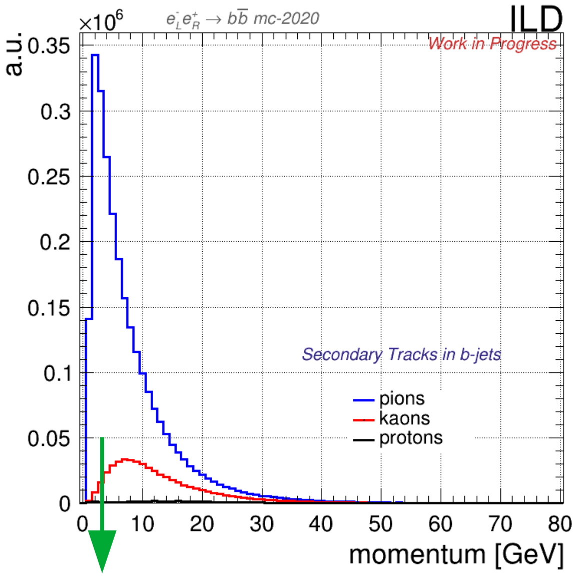
- Ideally we would use the **double charge** measurements
  - To control / reduce the systematic uncertainties

- **Today I focus only on the K-method**

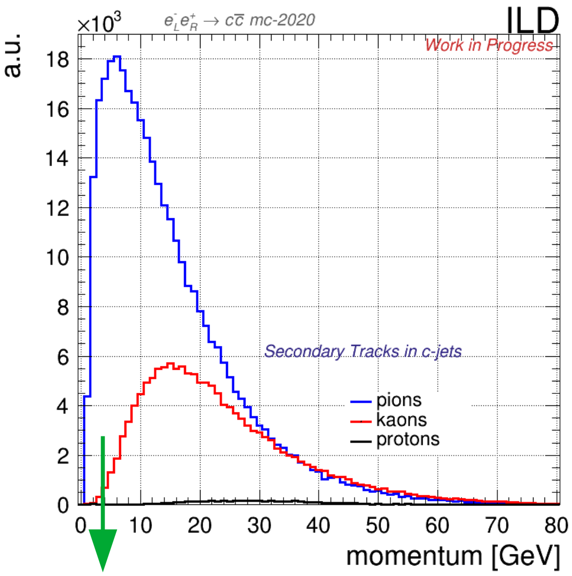


High Level Reco Challenges: Particle ID





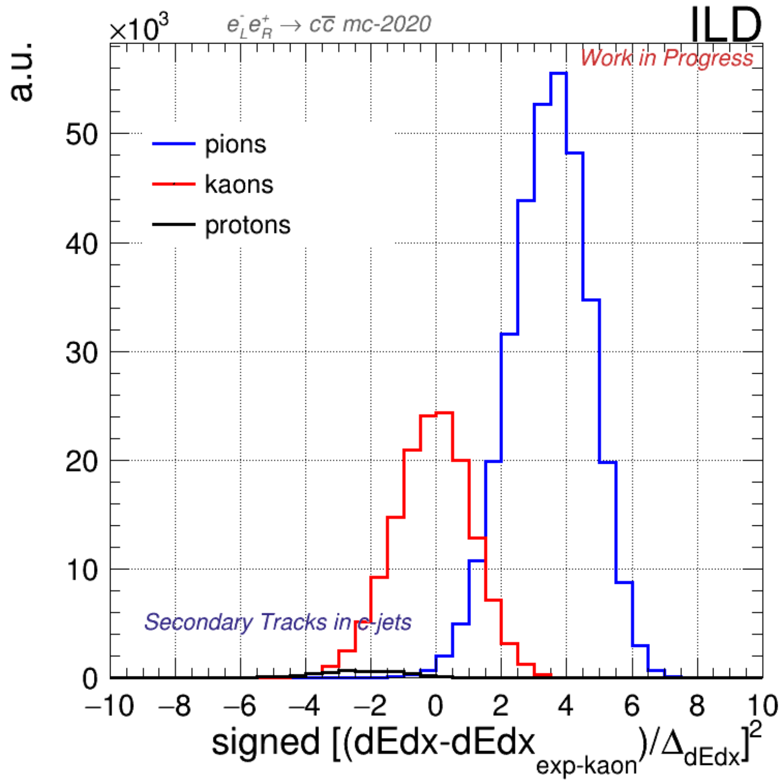
TOF or dEdx
(left) (right)



TOF or dEdx
(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 dEdx and/or TOF
  - Yellow points

Kaon identification for the ccbar case



▶ Using **dEdx separation power:**

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

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

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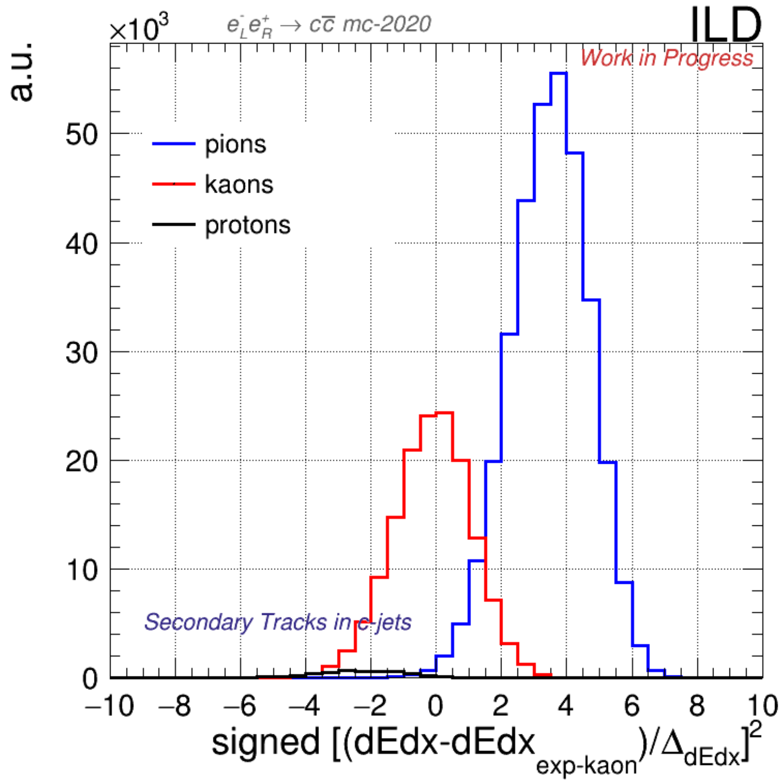

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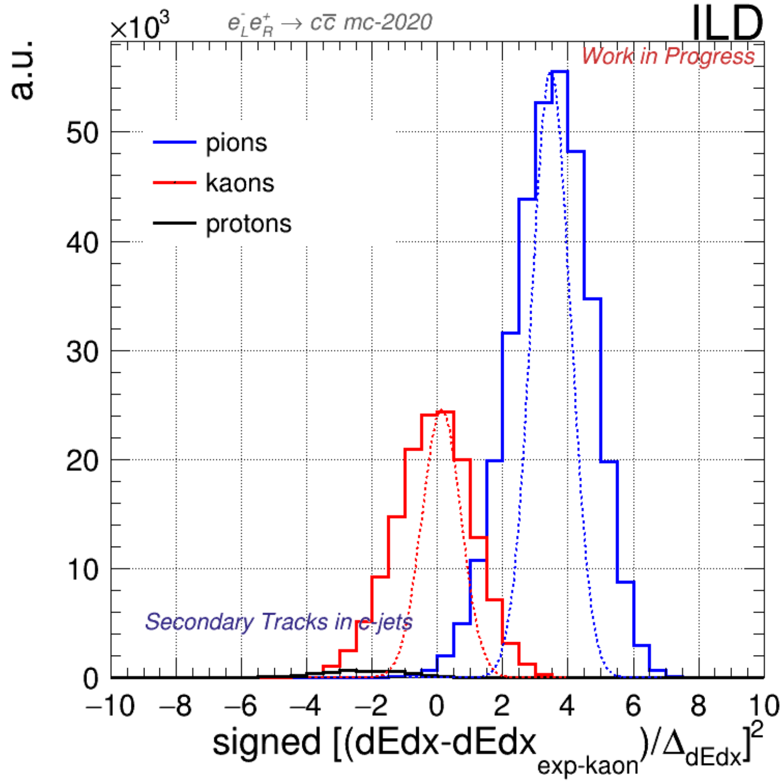
▶ Could we imagine a factor 2 improvement in the power separation ? (i.e. cluster counting)

Kaon identification for the ccbar case



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▶ Could we imagine a factor 2 improvement in the power separation ? (i.e. cluster counting)

- Then the kaon ID performance will be almost perfect

End of presentation

AFB measurement

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- For the K-method we study three variations
  - Default: we sum up the charge of all identified kaons
  - Weighted: we perform a weighted sum of all identified kaons (using the momentum)
  - Leading: we only use the leading K

AFB measurement

▶ **Final Selection Efficiency:**

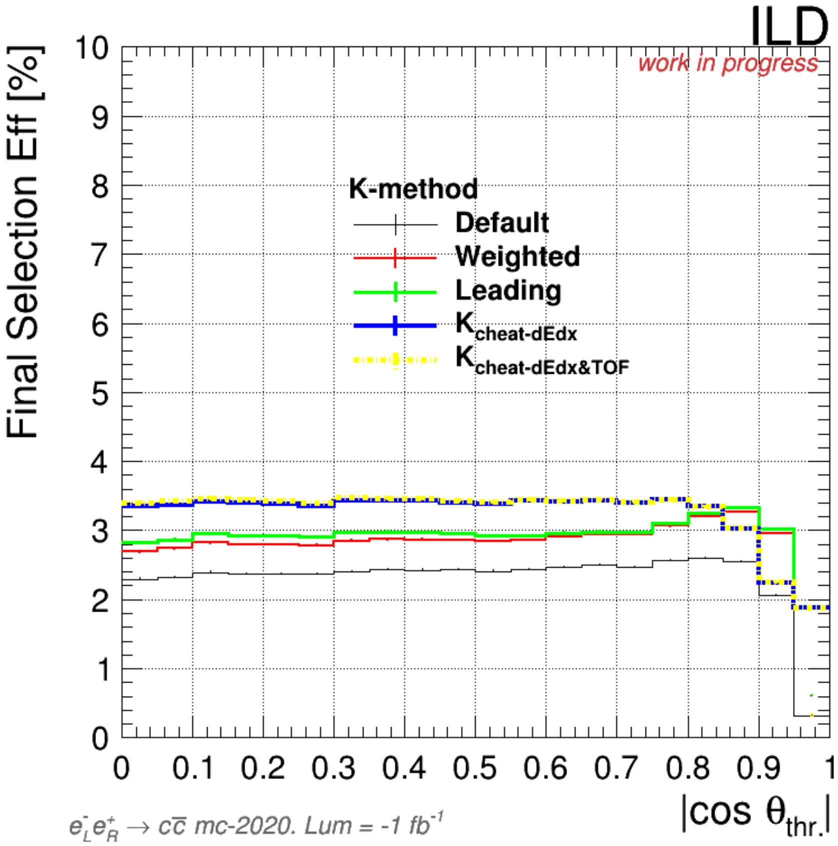
- Fraction of ccbar events after the full reconstruction including double charge measurement (only using K-method)

▶ To improve the selection efficiency we would require:

- a) use single charge measurements (larger migrations)
- b) improving the dEdx performance and the charge measurement (leading kaon method kaon)

▶ With ~3% efficiency we expect statistical uncertainties of

- eLpR (80%,30) → ~0.5%
- eRpL (80%,30) → ~0.8%
- 200fb-1 of shared luminosity
- only using Kaons...

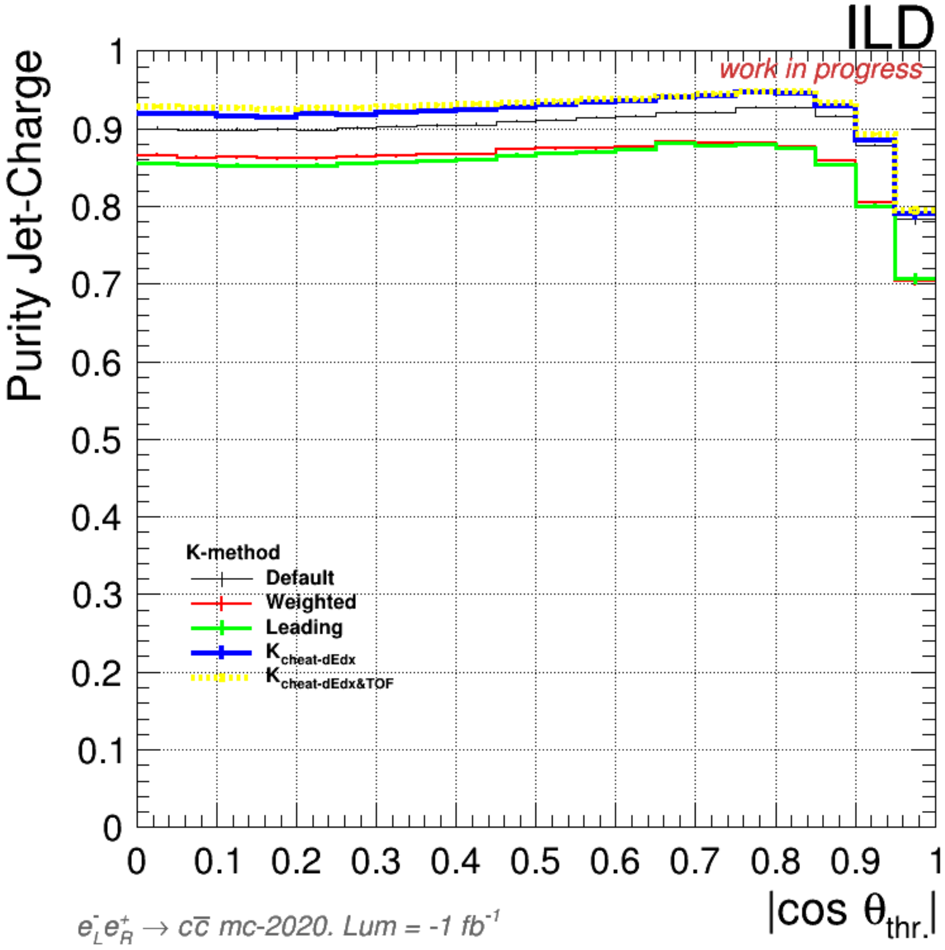


AFB measurement

- **Purity of charge measurement:**
  - Probability of measuring the charge correctly
  - estimated with data: using events with compatible or incompatible charge measurements

- Using the leading kaons shows a slight decrease in purity but still almost at 90%

- With "perfect" dEdx measurement we have purities larger than 90%

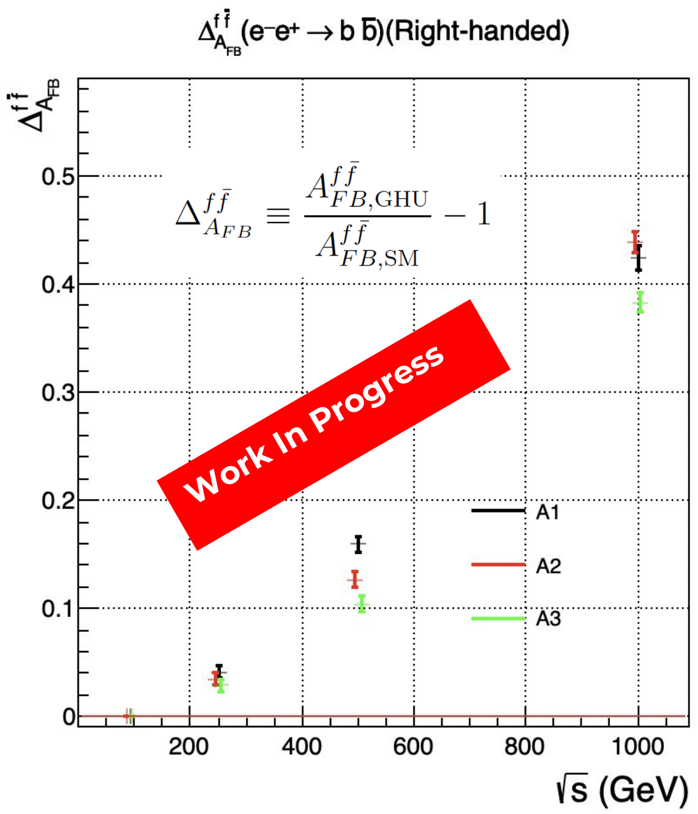


Next actions (short term)

- Estimate the AFB uncertainties using also the Vtx method
- And using the single charge measurements
  - In principle possible because the c-quark tagging is very efficient → almost background free
- Numbers ready for the ILCX2021 ?
  - Uff.. I still have saturday and sunday !!

Medium/long term actions

- ▶ The Orsay/Tohoku/Valencia HQ-ILC research team is running out of flavours!
- ▶ Strong motivations for looking at other energies
  - Many BSM predict large deviations that are enhanced at higher energies (GHU, …)
  - Improving the Z-pole couplings knowledge at the Z-pole is also crucial to separate between models
- ▶ Medium (short) term
  - J. Márquez will present the studies snapshoted in the right plot (several flavours and energies)
  - We will perform a 500 GeV sample request
- ▶ Medium (long) term
  - Explore the Giga-Z scenario (A.I)
  - ILC500 studies by J. Marquez



Poster presented at INFIERI2021 school by J. Márquez.
"realistic" statistical uncertainties (assuming ILC250 GeV performance at all the energies)

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

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

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

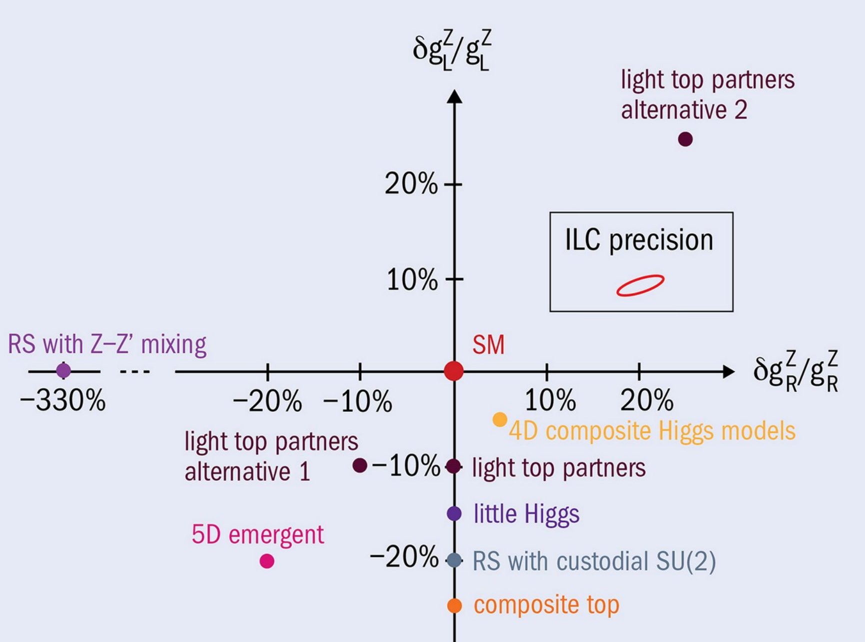


Figure from F. Richard

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Detector Technologies

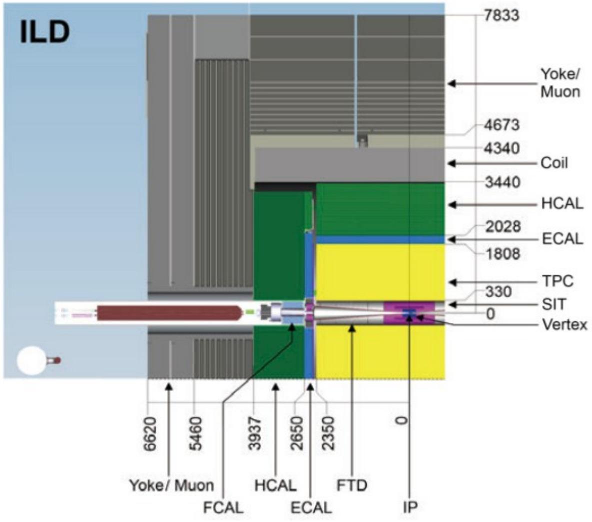
Vertex: CMOS, DEPFET, FPCCD, …

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 Calorimeter for ILC, LC TPC, FCAL Collaboration

10

ILD Design Goals

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

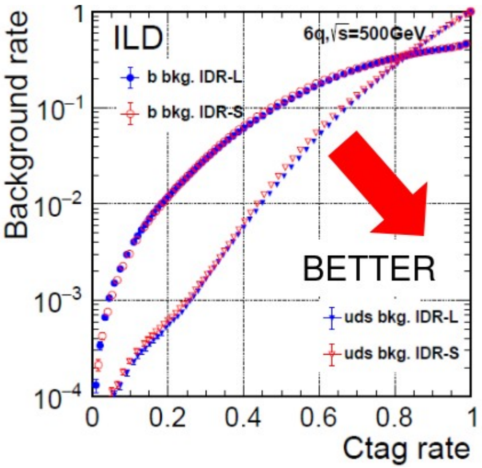
These allow us to pursue aggressive detector design:

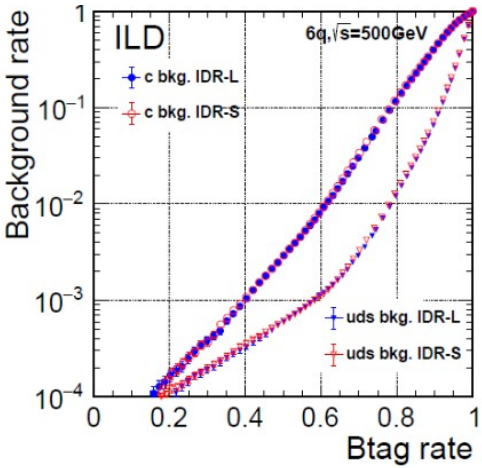
Detector Requirements ←	**Physics**
• Impact parameter resolution $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)$ μm	$H \to bb, cc, gg, \tau\tau$
• Transverse momentum resolution $\sigma(1/p_T) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_T \sin^{1/2}\theta)$	Total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

R. Ete: “The ILD Software Tools and Detector Performance”

9

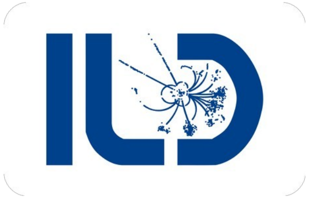
Flavour tagging





▶ **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 and c jet



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%

Double charge measurements (b-quark)

▶ Mistakes in the charge calculation due to loss tracks (acceptance issues, mis reconstruction etc) have to be corrected and estimated using data → Mistakes produce migrations (flip of the cos(θ))

▶ The **migrations are restored** by determining the purity of the charge calculation using double charge measurements

- Accepted events, N_{acc}, with (-,+) compatible charges
- Rejected events, N_{rej}, non compatible (–,++) charges

pq-equation
Incognitas: pq and N.

$$N_{acc} = Np^2 + Nq^2$$
$$N_{rej} = 2Npq$$
$$1 = p + q$$

The **pq-equation** allows for correcting for migrations (finding the correct N) and in particular for the last and ultimate migration (dilution) due to B0 oscillations

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

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

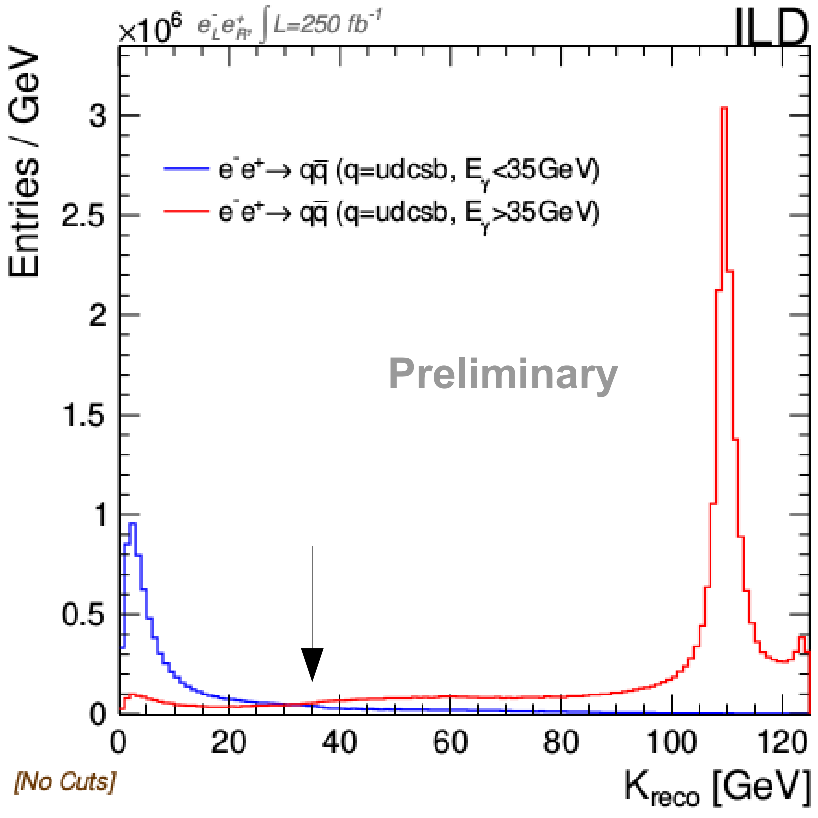
Jet angular variables (w.r.t. detector frame)

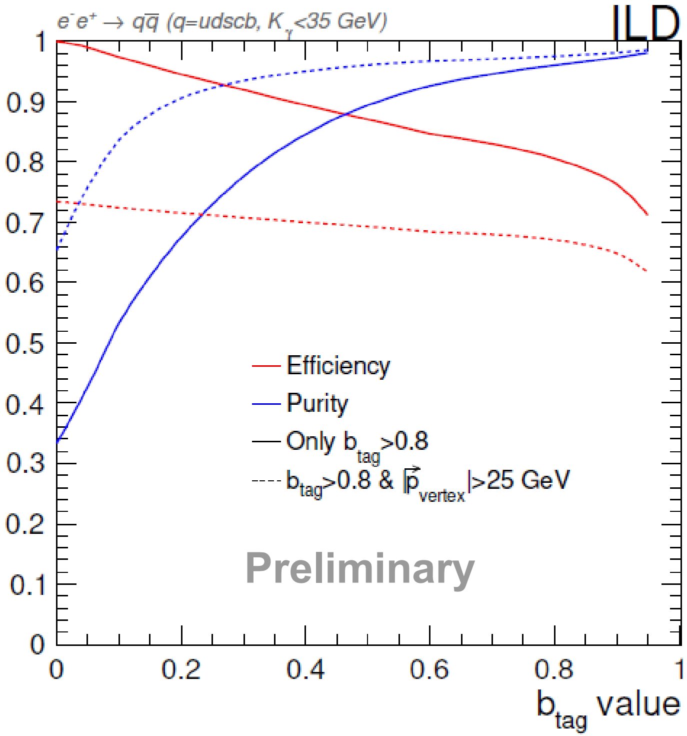
Preselection : Kreco

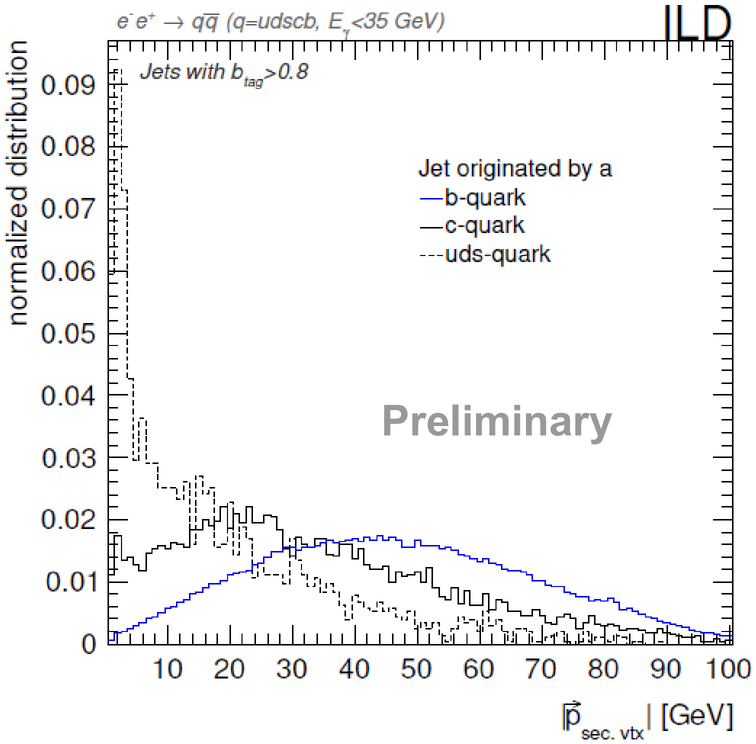
- Estimator of the energy of the photon ISR
- We apply a cut of Kreco<35 GeV

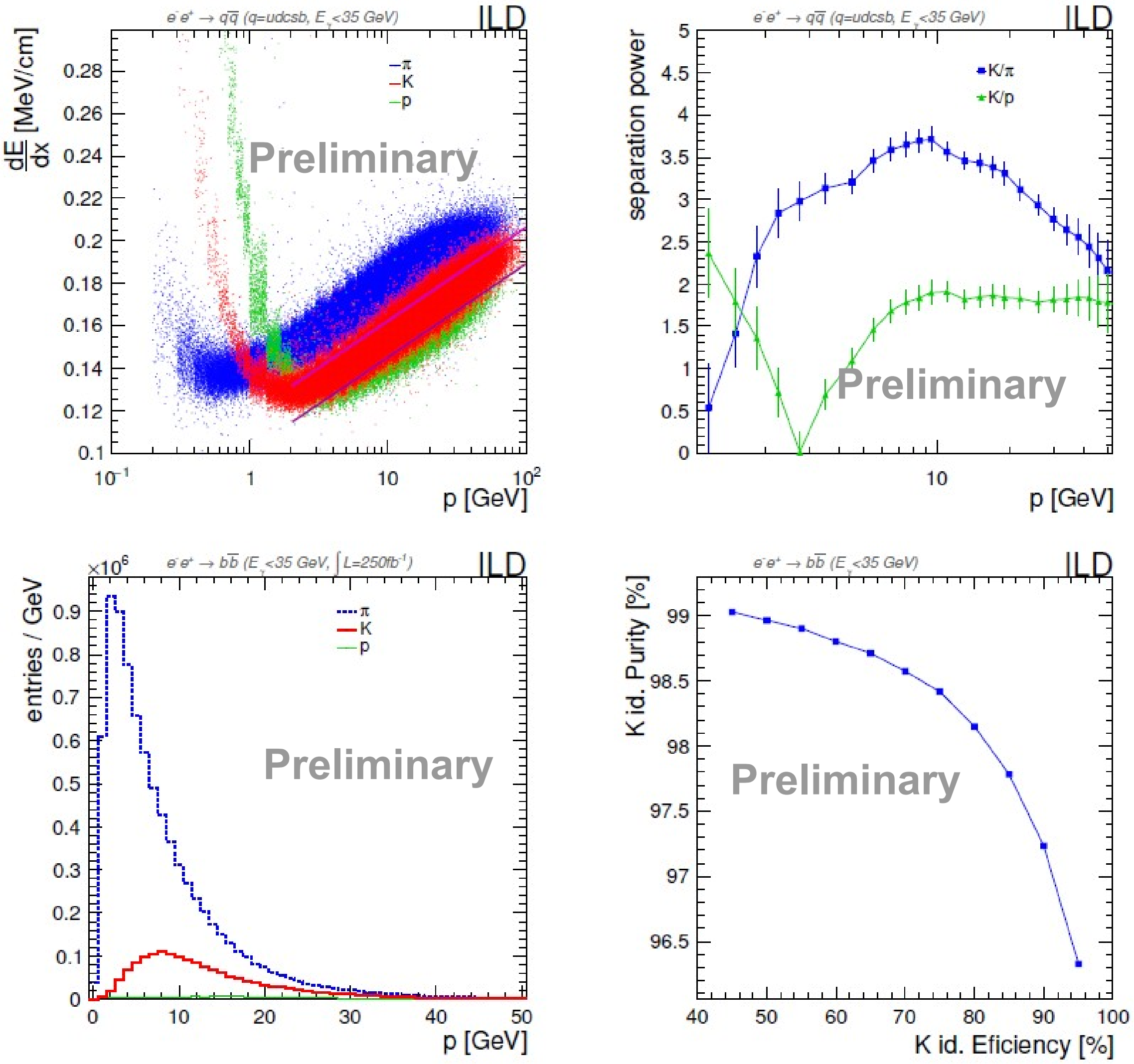
- Some signal events have larger Kreco (~15%)
  - Because of detector resolution and double photon ISR

- 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?




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

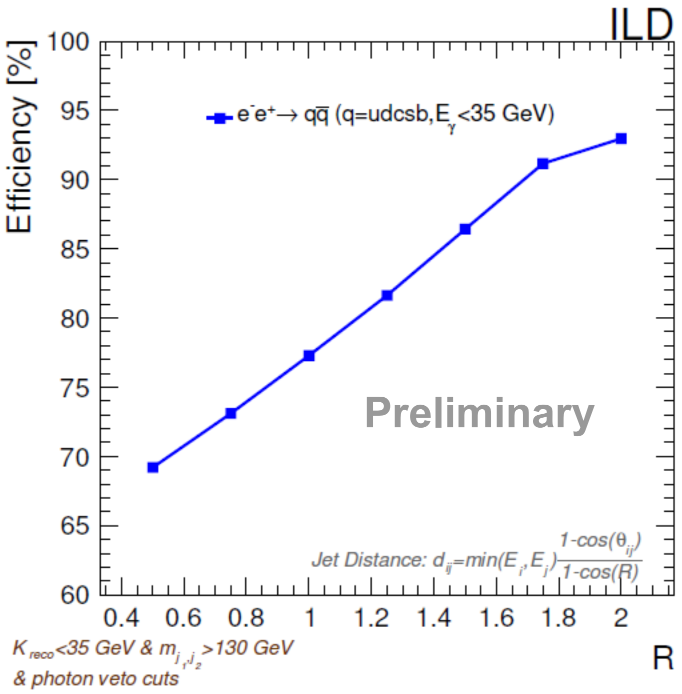

$e^-e^+ \rightarrow q\bar{q}$ (q=udscb, E_γ<35 GeV)
ILD
Jets with b_{tag}>0.8
Jet originated by a
b-quark
c-quark
uds-quark
Preliminary
normalized distribution
$|\vec{p}_{sec. vtx}|$ [GeV]

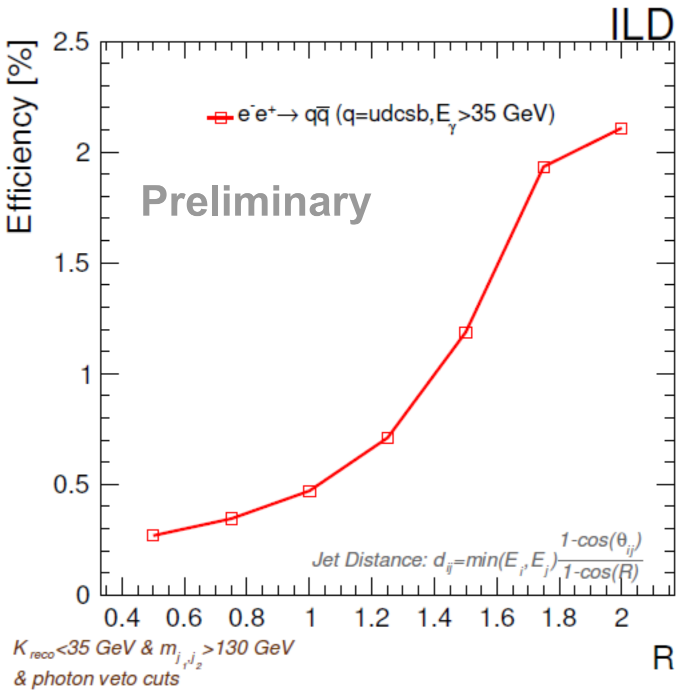


ILD
Preliminary
dE/dx [MeV/cm]
p [GeV]
π
K
p
separation power
K/π
K/p
entries / GeV
K id. Purity [%]
K id. Eficiency [%]

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

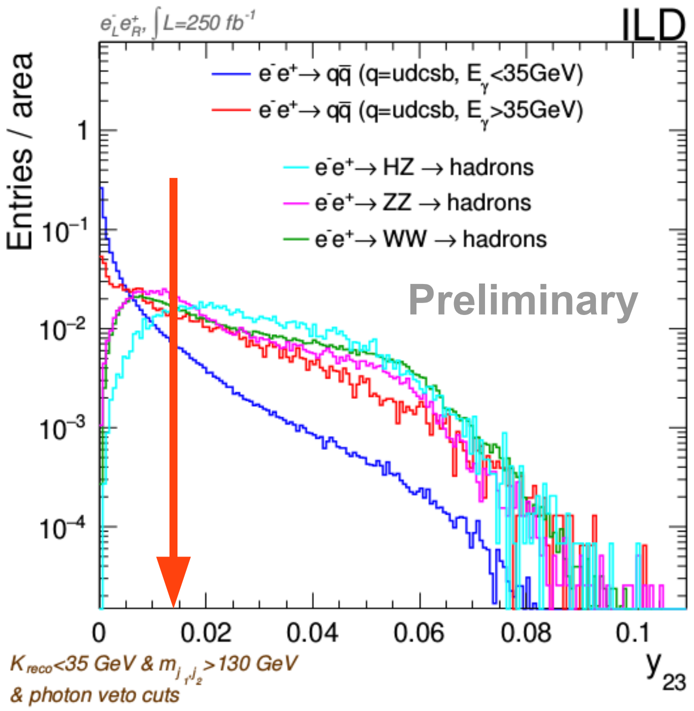
$$d_{iB} = E_i^{2p}$$

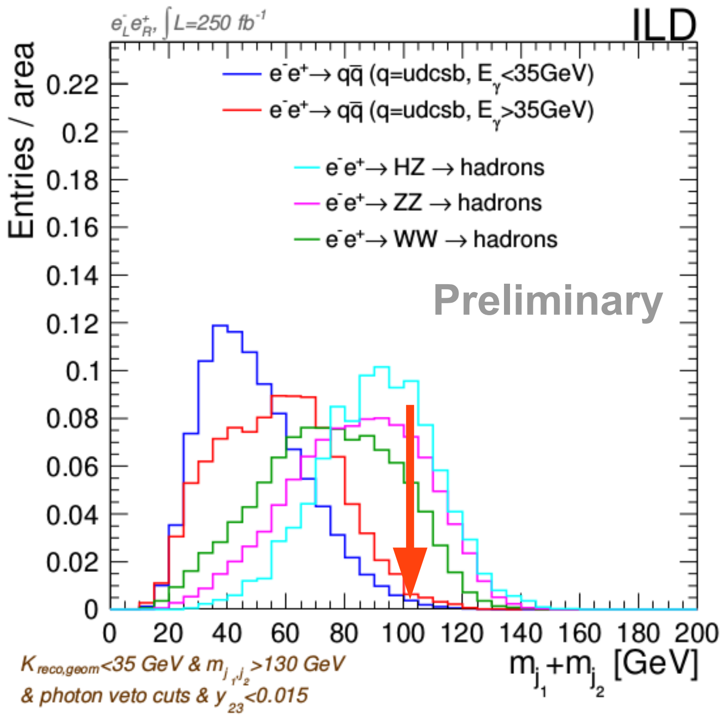




Final steps of the preselection

- 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





ILC250: Event Selection

- Cut 2: veto of events in which the ISR photon was reconstructed and identified inside the detector