

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

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

*\*AITANA group at IFIC - CSIC/UV*



► Orsay/Tohoku/Valencia Heavy Quark ILC research team

- From top to strange (so far...)

► Today:

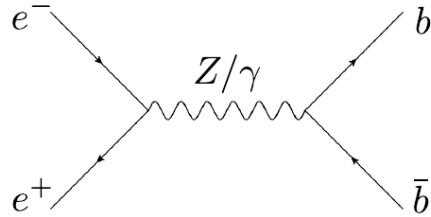
- Report on  $c\bar{c}$  at ILC250 (with some  $b\bar{b}$ ) – A.I.
- Report on  $s\bar{s}$  at ILC250 – Yuichi Okugawa
- Both reports are based on mc2020 samples





# Motivation

- ▶ 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 $\neq$ right (characteristic for each fermion)

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

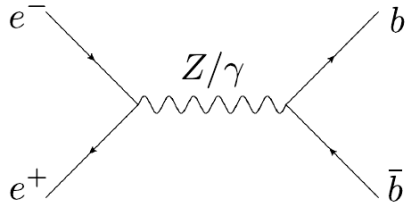
- Beam polarisation also enhances the cross section values

- ▶ Quark (fermion) **electroweak couplings** can be **inferred from cross section,  $R_q$**  and forward backward asymmetry  **$A_{FB}$**  observables.

$$R_q^0 = \Gamma_{q\bar{q}} / \Gamma_{had} (Z\text{-pole})$$

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

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

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

Polarization	Signal			Rad return bkg		
	$\sigma_{e^-e^+ \rightarrow q\bar{q}}(E_\gamma < 35 \text{ GeV})[\text{fb}]$			$\sigma_{e^-e^+ \rightarrow q\bar{q}}(E_\gamma > 35 \text{ GeV})[\text{fb}]$		
	$b\bar{b}$	$c\bar{c}$	$q\bar{q} (q = uds)$	$b\bar{b}$	$c\bar{c}$	$q\bar{q} (q = uds)$
$e_L^-e_R^+$	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	$\sigma_{e_L^-e_R^+ \rightarrow X} [\text{fb}]$	$\sigma_{e_R^-e_L^+ \rightarrow X} [\text{fb}]$
$X = WW \rightarrow q_1\bar{q}_2q_3\bar{q}_4$	14874.4	136.4
$X = ZZ \rightarrow a_1\bar{a}_1a_2\bar{a}_2$	1402.1	605.0
$X = HZ \rightarrow q_1q_2H$	346.0	222.0

► **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  
CUT 1  
CUT 2  
CUT 3  
CUT 4  
CUT 5  
CUT 6

**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
81.1	80.9	81.0	20.3	6.2	0.6	0.2
80.8	80.9	81.0	18.6	5.8	0.6	0.2
80.8	80.5	80.0	10.4	5.8	0.6	0.2
80.8	80.5	79.9	10.3	5.8	0.6	0.2
77.7	77.2	75.9	4.8	6.0	0.6	0.2
64.0	64.1	63.3	3.8	1.5	0.2	0.1

eRpL  
CUT 1  
CUT 2  
CUT 3  
CUT 4  
CUT 5  
CUT 6

**Signal Efficiency (%)**

**B/S (%)**

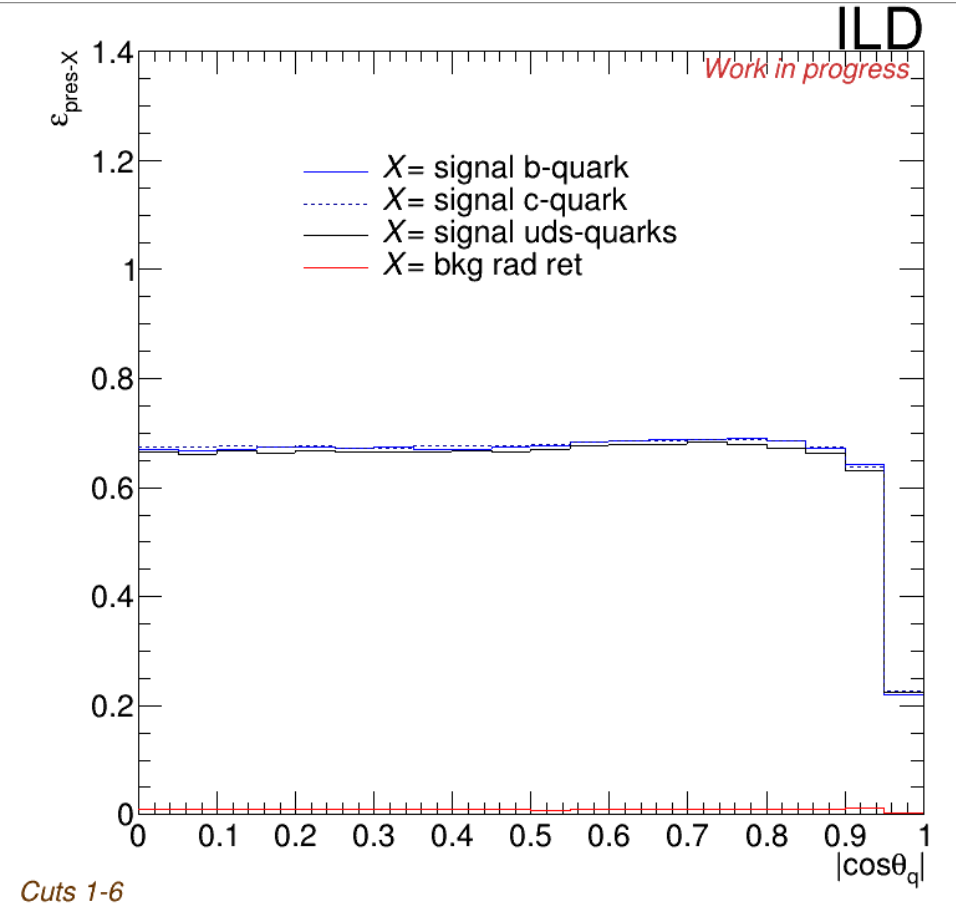
bb	cc	qq (uds)	RadRet	WW	ZZ	qqH
100.0	100.0	100.0	562.0	1.3	5.7	2.1
81.0	81.0	81.2	41.4	0.2	0.9	0.3
80.8	80.9	81.2	38.0	0.2	0.8	0.3
80.7	80.6	80.2	17.6	0.2	0.8	0.3
80.7	80.6	80.1	17.4	0.2	0.8	0.3
77.5	77.2	76.2	6.9	0.2	0.8	0.3
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(cut against dibosons)



- ▶ **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  $Z \rightarrow$  leptons events
- ▶ The method is based on the comparison of **single vs double tagged samples**

$$N_0 = N_{\text{presel}} = [\varepsilon_{\text{pres-signal}} \sigma_{q\bar{q}} + \varepsilon_{\text{pres-bkg}} \sigma_{\text{bkg}}] \cdot Lum$$
$$N_{1\text{tag},c} = [\varepsilon_{\text{pres-signal}} (\varepsilon_c \sigma_{c\bar{c}} + \varepsilon_b \sigma_{b\bar{b}} + \varepsilon_q \sigma_{q\bar{q}}) + \varepsilon_c \varepsilon_{\text{bkg}} \sigma_{\text{bkg}}] \cdot Lum$$
$$N_{2\text{tag},c} = [\varepsilon_{\text{pres-signal}} (\varepsilon_c^2 (1 + \rho_c) \sigma_{c\bar{c}} + \varepsilon_b^2 \sigma_{b\bar{b}} + \varepsilon_q^2 \sigma_{q\bar{q}}) + \varepsilon_c^2 \varepsilon_{\text{bkg}} \sigma_{\text{bkg}}] \cdot Lum$$

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$$N_0^{signal} = N_{presel} = [\varepsilon_{pres-signal} \sigma_{q\bar{q}}] \cdot Lum$$
$$N_{1tag,c}^{signal} = [\varepsilon_{pres-signal} (\varepsilon_c \sigma_{c\bar{c}} + \varepsilon_b \sigma_{b\bar{b}} + \varepsilon_q \sigma_{q\bar{q}})] \cdot Lum$$
$$N_{2tag,c}^{signal} = [\varepsilon_{pres-signal} (\varepsilon_c^2 (1 + \rho_c) \sigma_{c\bar{c}} + \varepsilon_b^2 \sigma_{b\bar{b}} + \varepsilon_q^2 \sigma_{q\bar{q}})] \cdot Lum$$

- ▶ For the moment, let's assume that **we know the bkg contribution with perfect accuracy**
  - We remove the bkg contribution from the equations

► Assuming that:

- Minimal contribution from the backgrounds
- 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  $R_c$  /  $\varepsilon_{c}$

- $f_1, f_2$  are our observables (dependent on  $N_0, N_1, N_2$ )
- $\rho, R_b$  and the mistagging efficiencies are assumptions (MC, measurement,...)



$$f_{1tag} \simeq \varepsilon_c R_c$$
$$f_{2tag} \simeq \varepsilon_c^2 R_c$$

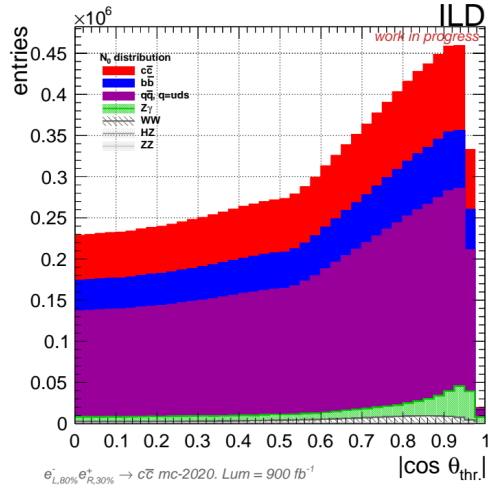
with

$$BKG \simeq 0$$
$$\varepsilon_b^{pres} \simeq \varepsilon_c^{pres} \simeq \varepsilon_{uds}^{pres}$$

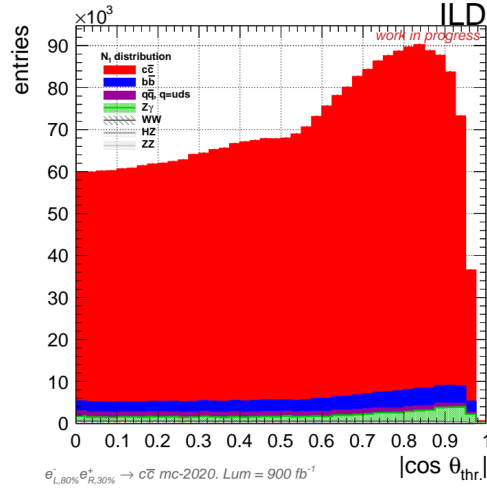
# Double Tag Method

eLpR (80,30)

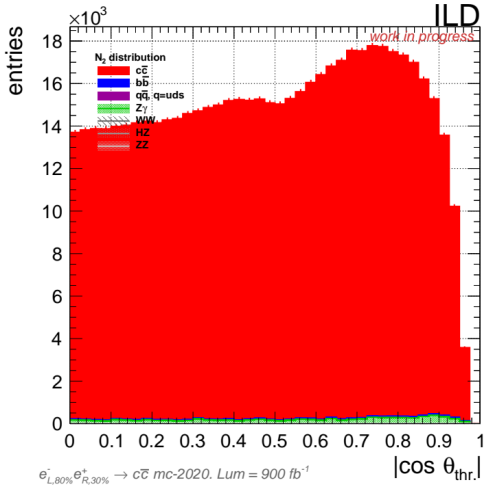
N0



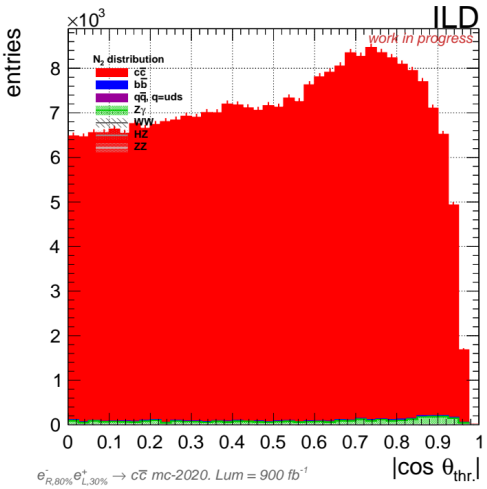
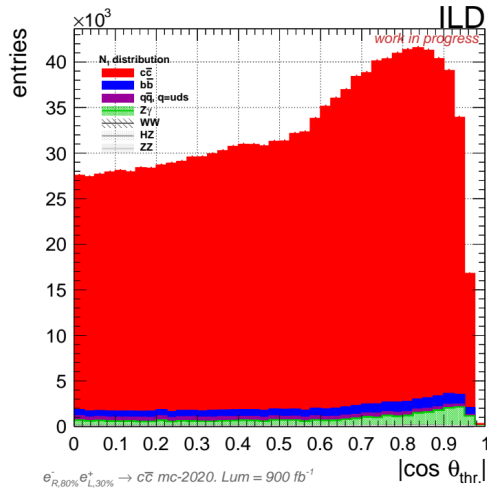
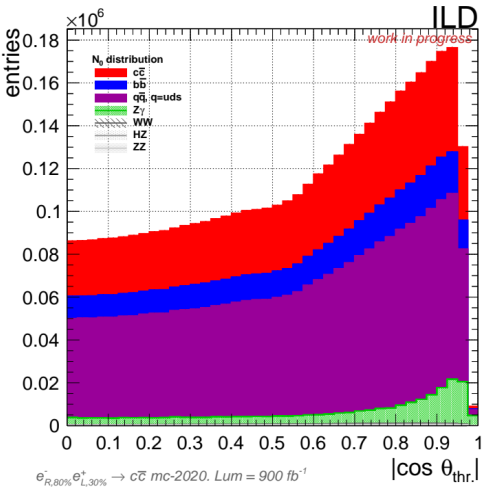
N1

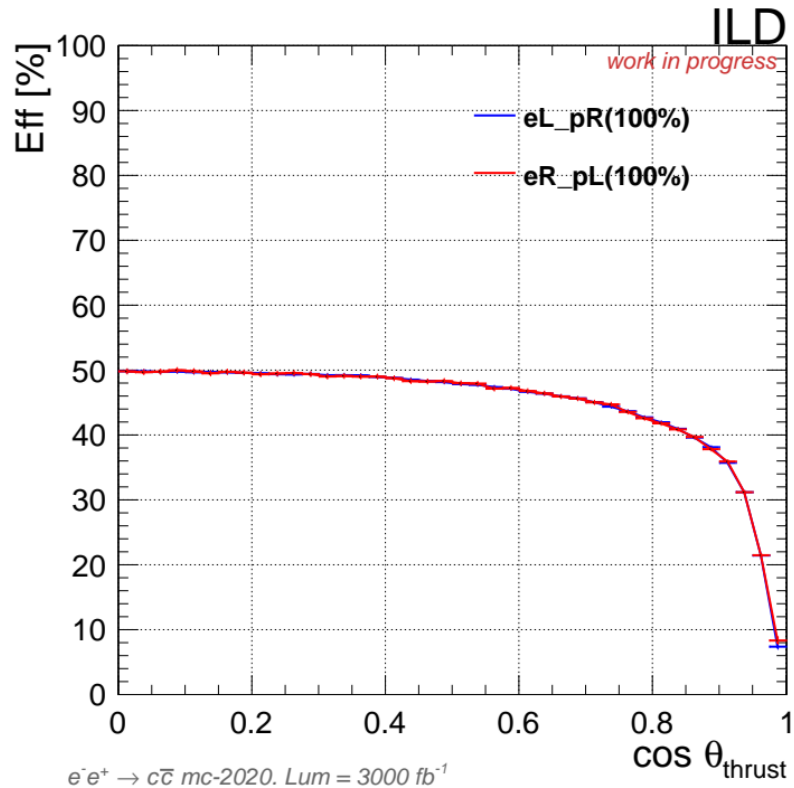


N2

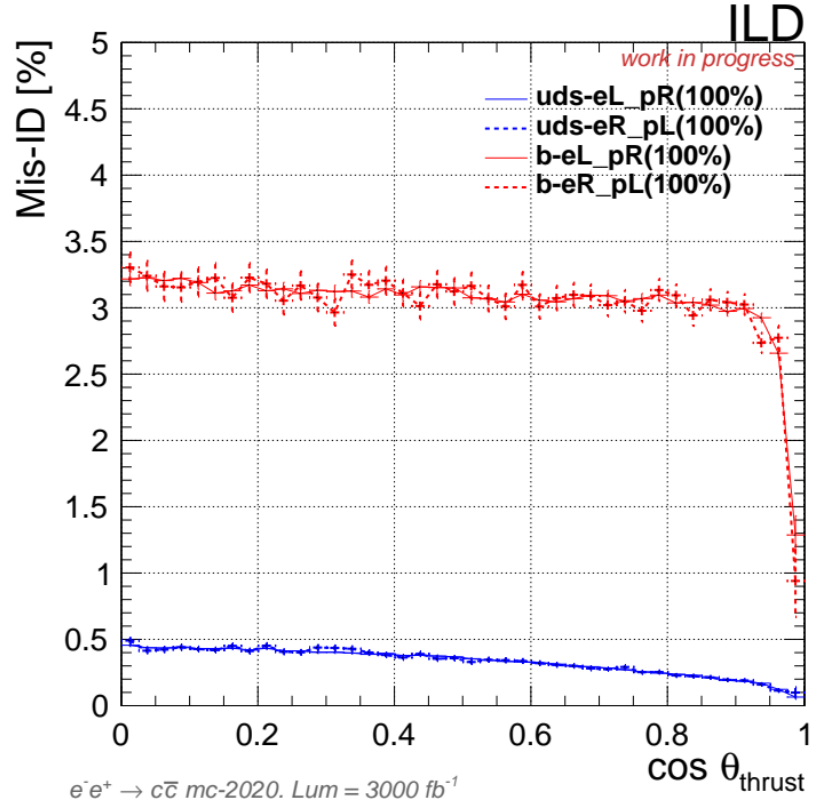
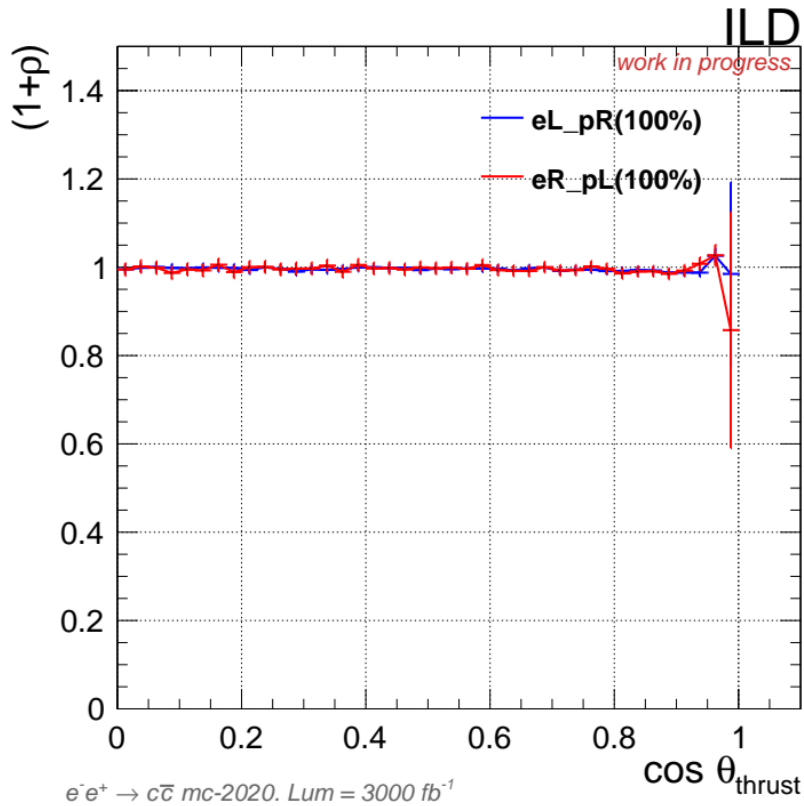


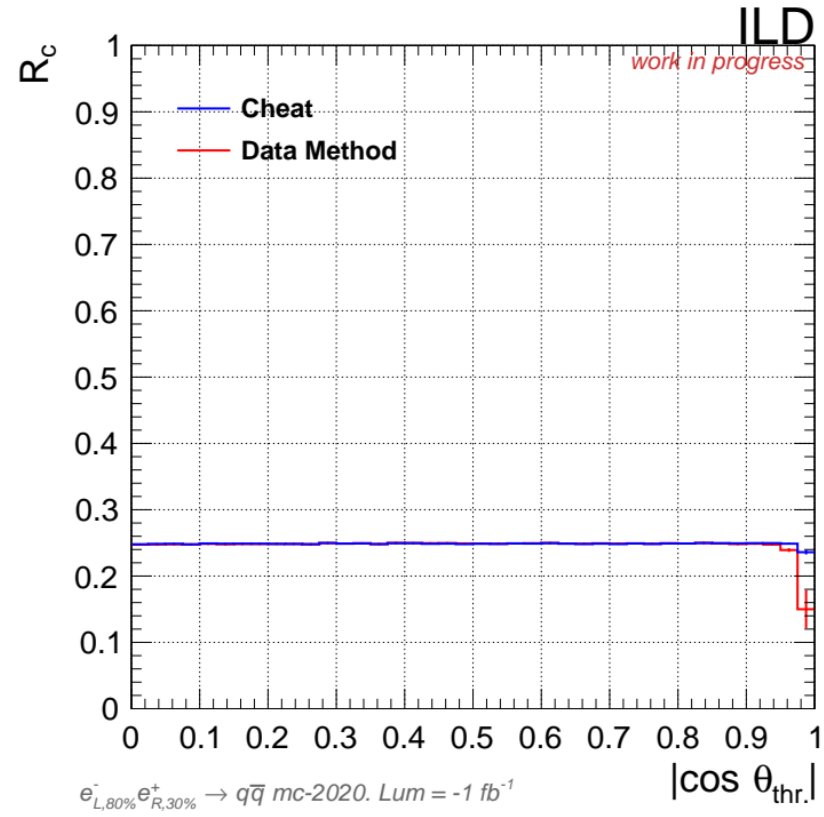
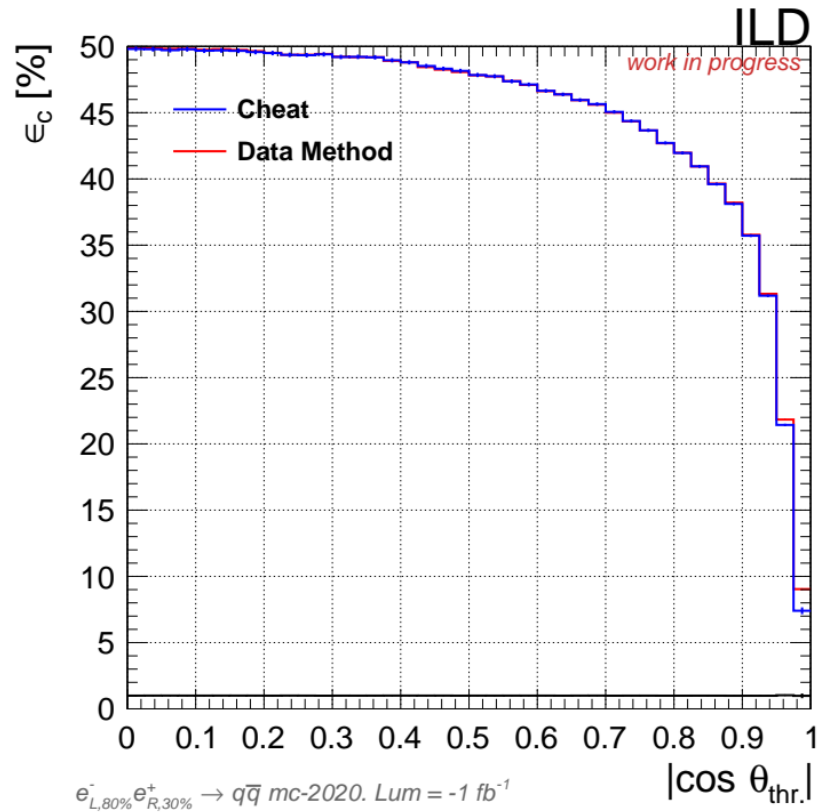
eRpL (80,30)





- ▶ The efficiency of quark tagging can be measured with the single vs double tagging, with some assumptions
  - We perfectly know the bkg
  - 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







- ▶ **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%**

$$R_c(e_L p_R, 80, 30) = 0.2489 (SM - LO) \pm 0.14\% (stat) \pm 0.16\% (syst.)$$

$$R_c(e_R p_L, 80, 30) = 0.3144 (SM - LO) \pm 0.20\% (stat) \pm 0.17\% (syst.)$$

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

$$R_b(e_L p_R, 80, 30) = 0.1694 (SM - LO) \pm 0.12\% (stat) \pm 0.15\% (syst.)$$

$$R_b(e_R p_L, 80, 30) = 0.1251 (SM - LO) \pm 0.22\% (stat) \pm 0.17\% (syst.)$$

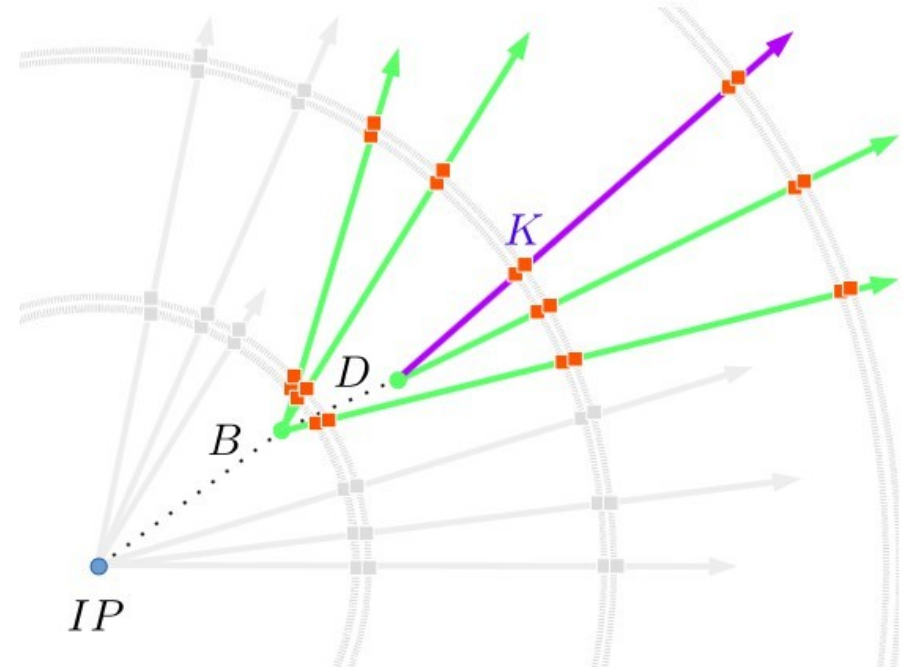
B-quark case: systematics are dominated by the background estimation (assumed to be known only at 10% level)

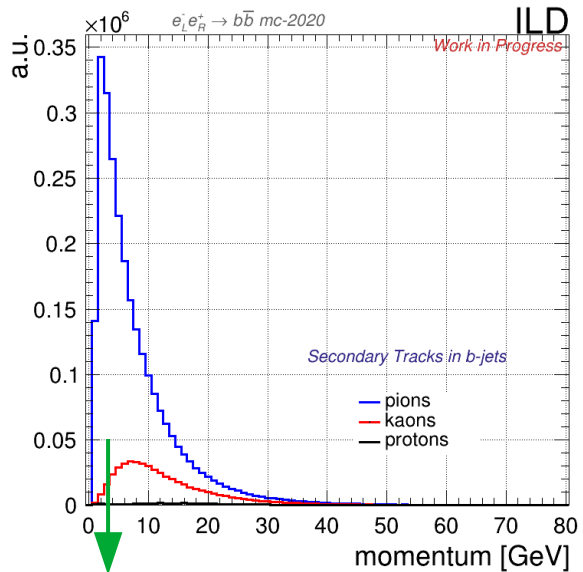
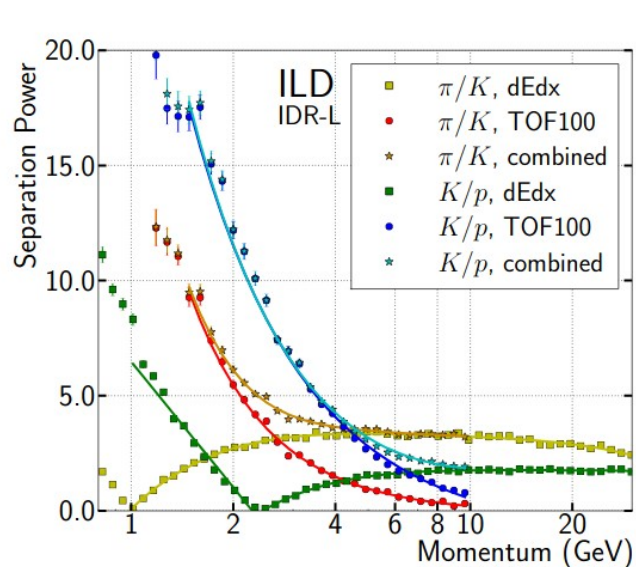
**Conservative estimation of the  
systematic unc. in both cases**



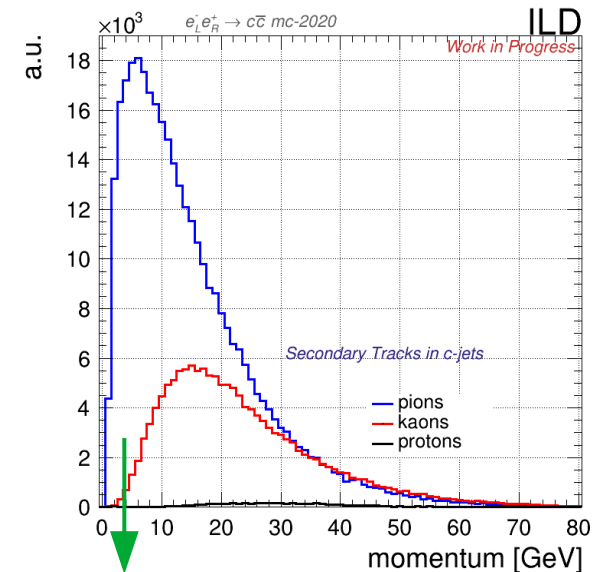
# Measuring AFB

- ▶ 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**





TOF or dEdx  
(left) (right)

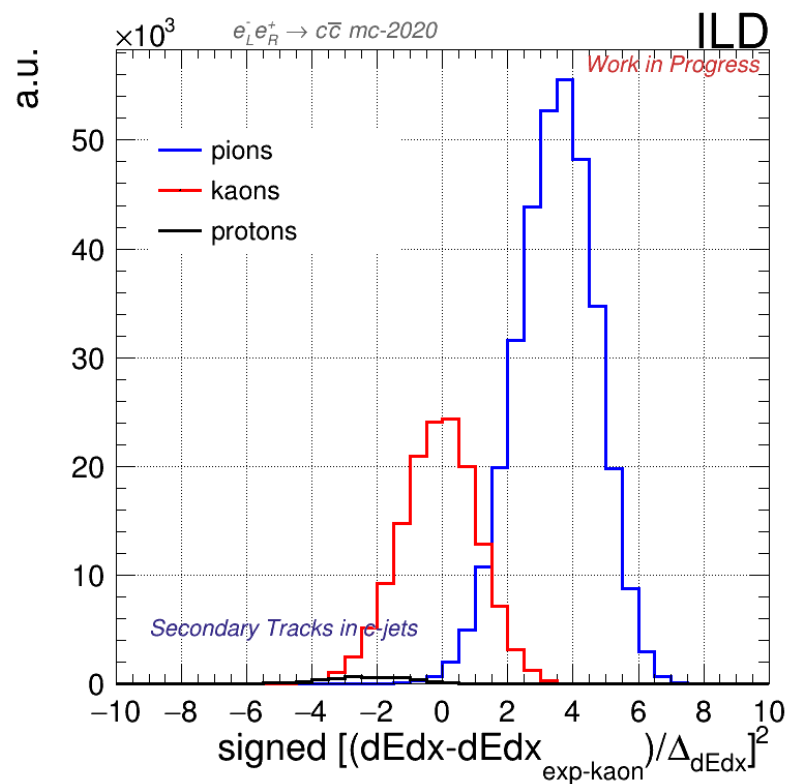


TOF or dEdx  
(left) (right)

- ▶ 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

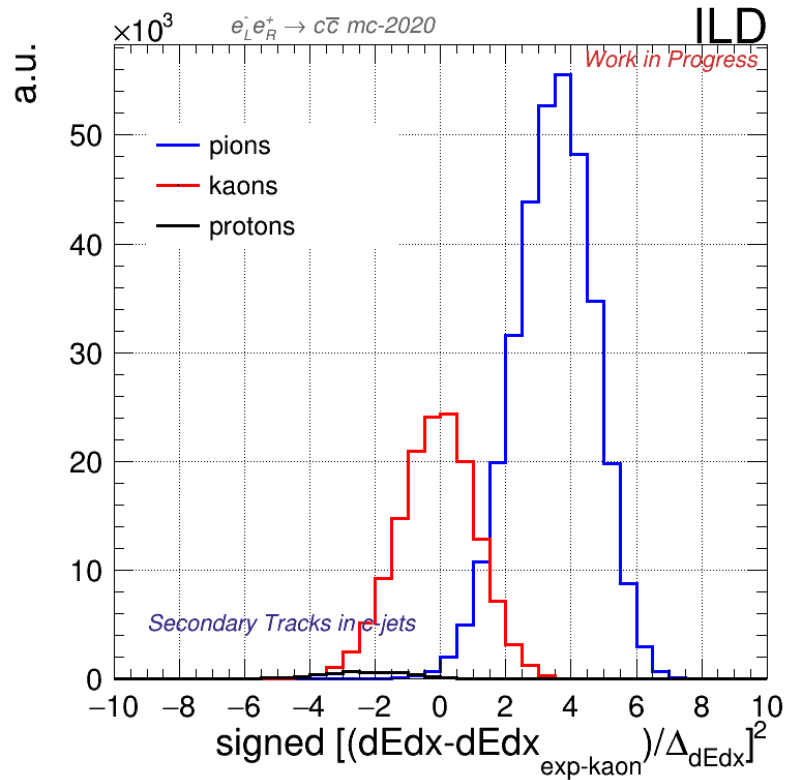




► Using **dEdx separation power:**

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

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

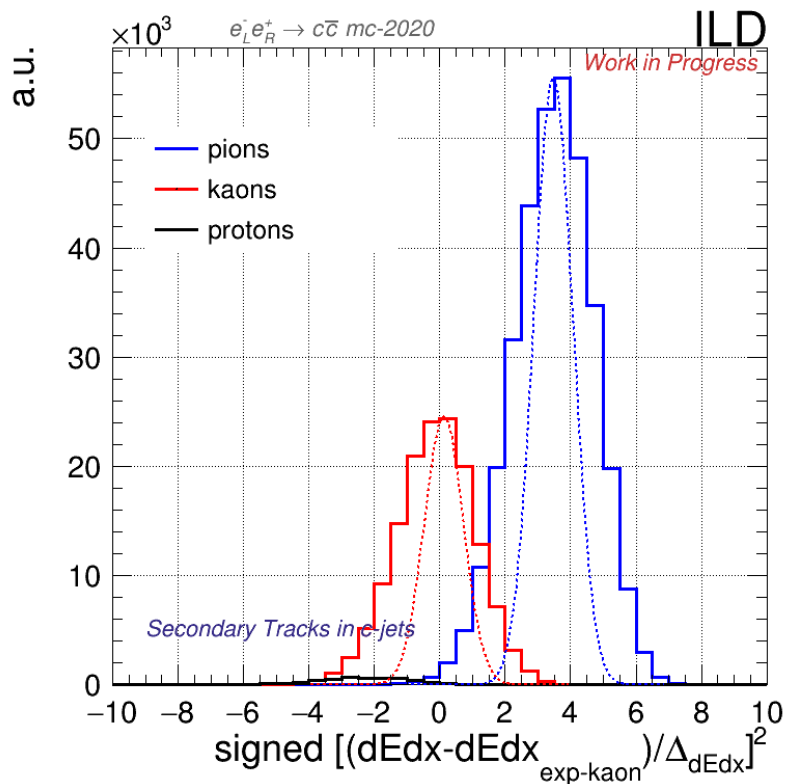


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► Could we imagine a factor 2 improvement in the power separation ? (i.e. cluster counting)



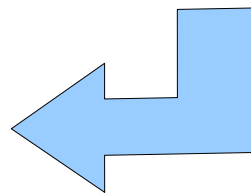
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► Could we imagine a factor 2 improvement in the power separation ? (i.e. cluster counting)

- Then the kaon ID performance will be almost perfect



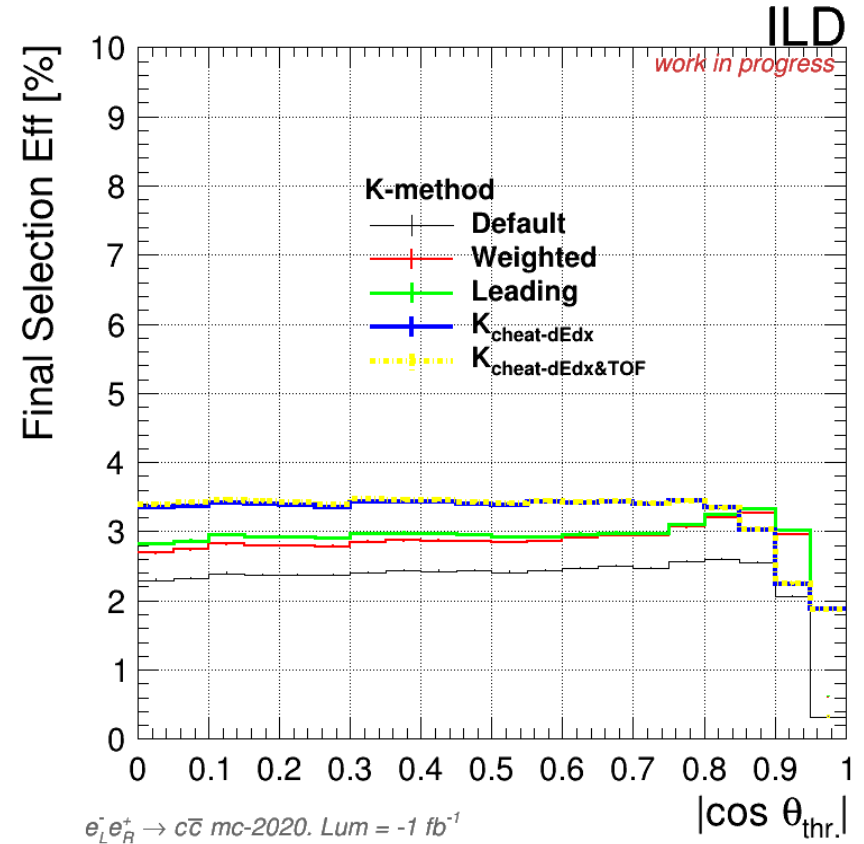


► For the K-method we study three variations

- 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

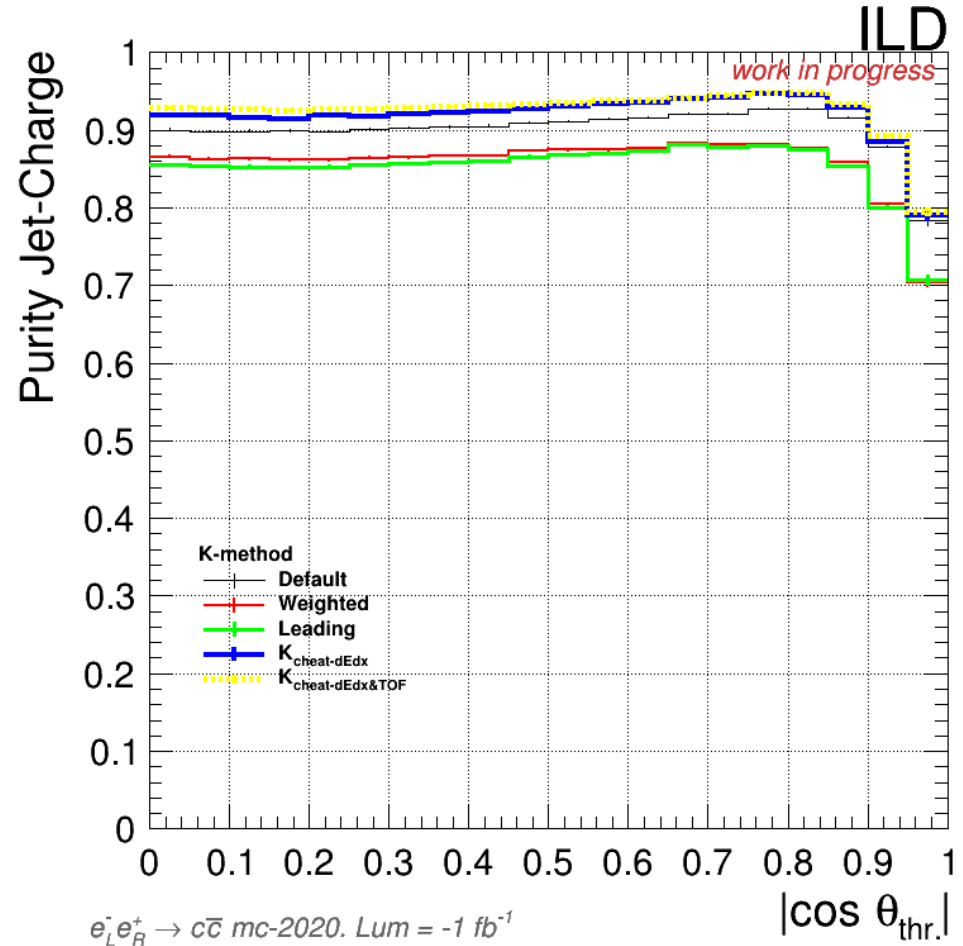
## ► Final Selection Efficiency:

- Fraction of  $c\bar{c}$  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)  $\rightarrow$  ~0.5%
  - eRpL (80%,30)  $\rightarrow$  ~0.8%
  - 200fb<sup>-1</sup> of shared luminosity
  - only using Kaons...



## ► 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%

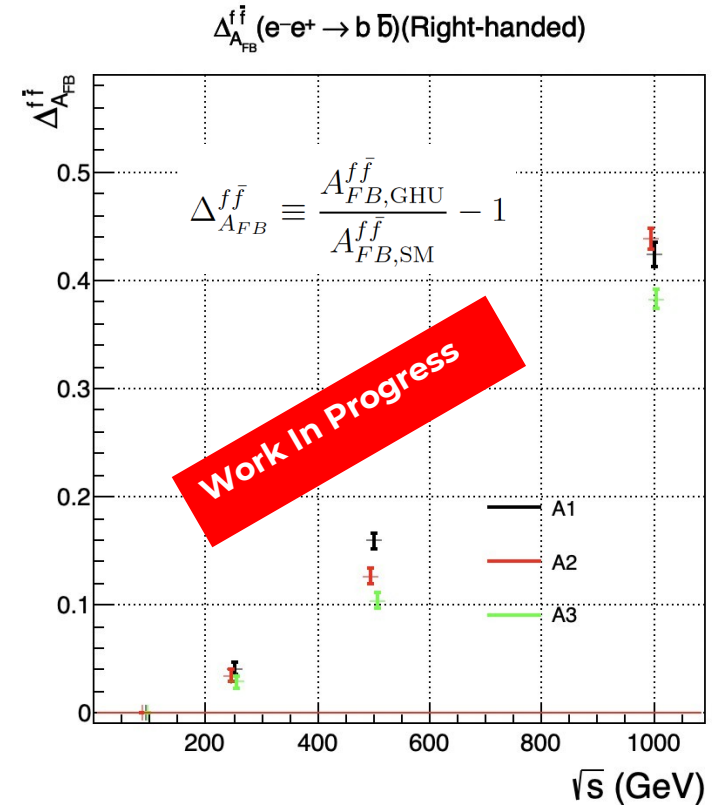


# Next actions (short term)

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- ▶ 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 ?

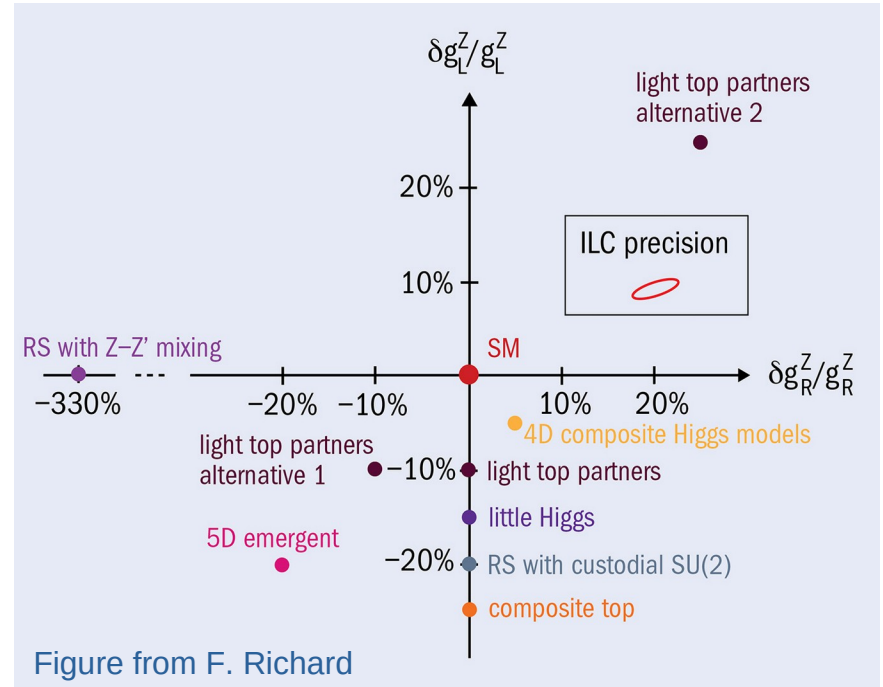
- ▶ The Orsay/Tohoku/Valencia HQ-ILC research team is running out of flavours!
- ▶ Strong motivations for looking at other energies
  - Many BSM predict large deviations that are enhanced at higher energies (GHU, ...)
  - Improving the Z-pole couplings knowledge at the Z-pole is also crucial to separate between models
- ▶ Medium (short) term
  - J. Márquez will present the studies snapshotted 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)



- ▶ 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



## Detector Technologies

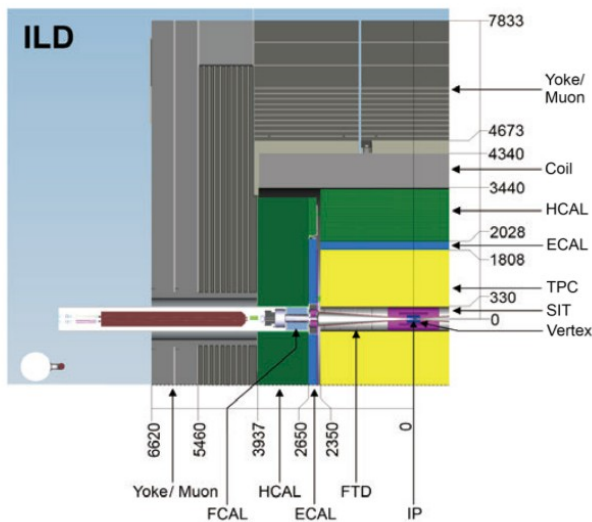
Vertex: CMOS, DEPFET, FPCCD, ...

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

ECAL:  
Silicon ( $5 \times 5 \text{ mm}^2$ ) or  
Scintillator ( $5 \times 45 \text{ mm}^2$ )  
with Tungsten absorber

HCAL:  
Scintillator tile ( $3 \times 3 \text{ cm}^2$ )  
or Gas RPC ( $1 \times 1 \text{ cm}^2$ )  
with Steel absorber

All inside solenoidal coil of 3-4 T



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

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

Detector R&D collaborations:



10



## Beam spot size



	FCCee	ILC	SLC	LEP
$\sigma_x$ [nm]	13700	516	1500	200000
$\sigma_y$ [nm]	36	7.7	500	2500

Source SLC, LEP, PDG

©R. Poeschl

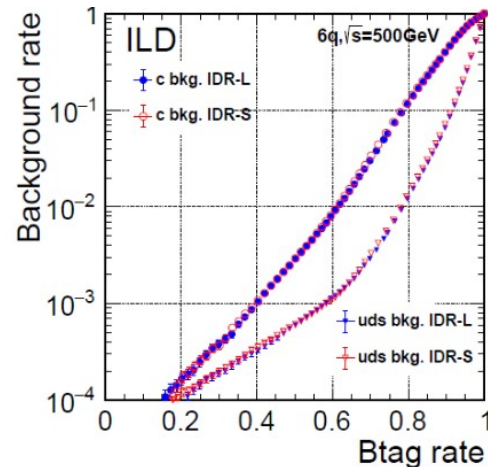
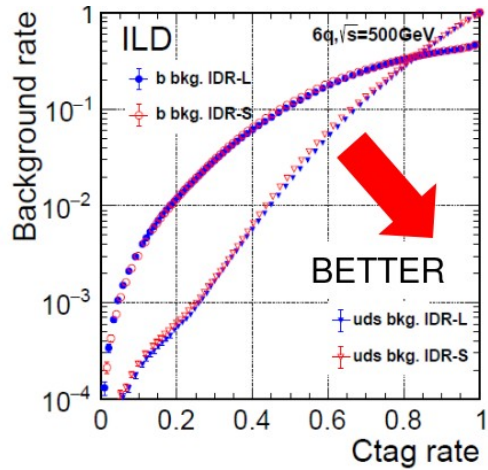
LEP

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SLC

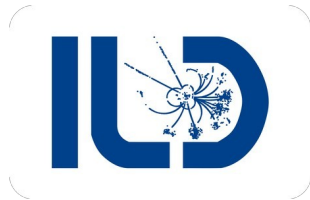
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ILC



## ► 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  $\sigma(d_0) < 5 \oplus 10 / (p[\text{GeV}] \sin^{3/2}\theta) \mu\text{m}$
- Transverse momentum resolution  $\sigma(1/p_T) = 2 \times 10^{-5} \text{ GeV}^{-1} \oplus 1 \times 10^{-3} / (p_T \sin^{1/2}\theta)$

Experiment	<i>b</i> -quark		light quarks	
	Eff. [%]	Pur. [%]	Eff. [%]	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  $\cos(\theta)$ )
- ▶ 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.

$$\begin{aligned}N_{acc} &= Np^2 + Nq^2 \\N_{rej} &= 2Npq \\1 &= p + q\end{aligned}$$

The **pq-equation** allows for correcting for migrations (finding the correct N) and in particular for the last and ultimate migration (dilution) due to  $B^0$  oscillations

- ▶ Alternatives to  $m(2\text{jets})$  ?
- ▶ 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):

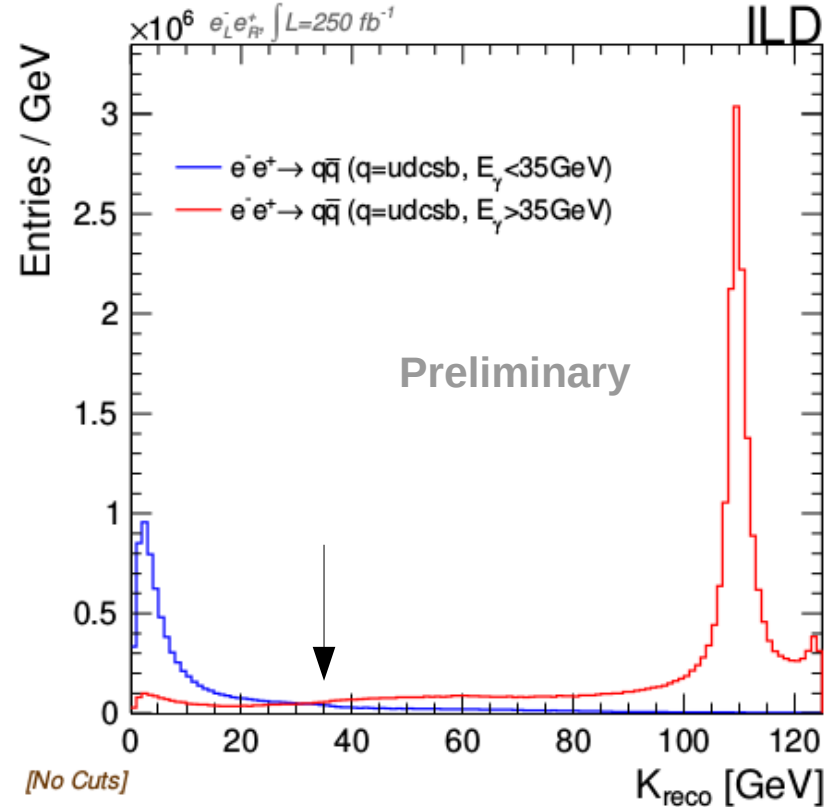
$$|\vec{k}| \approx K_{reco} = \frac{250 \text{ GeV}}{\sin \Psi_{acol} + \sin \theta_1 + \sin \theta_2}$$

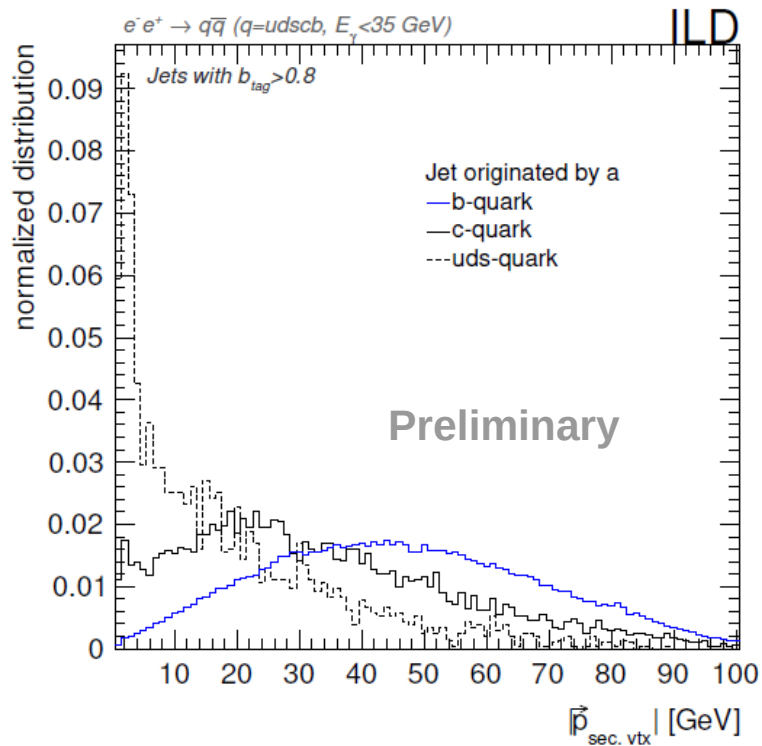
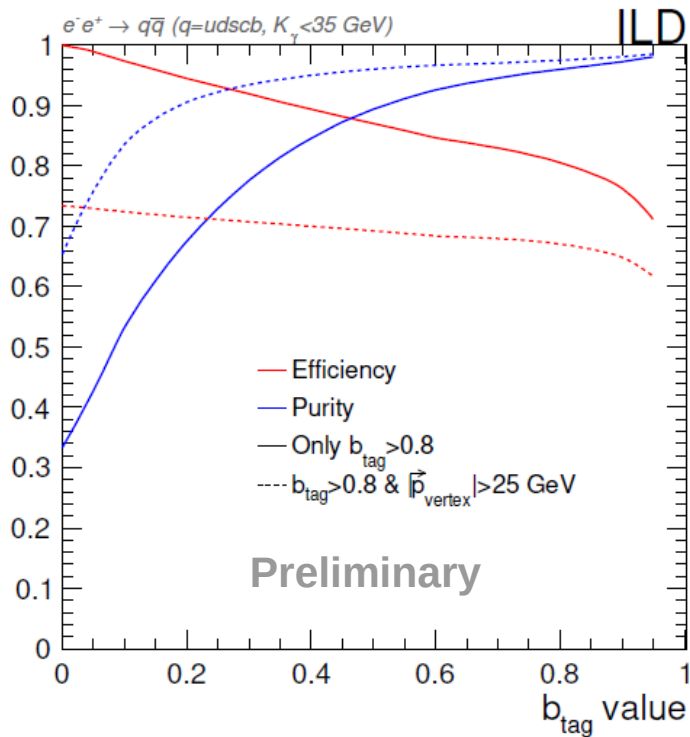
Two jet acolinearity

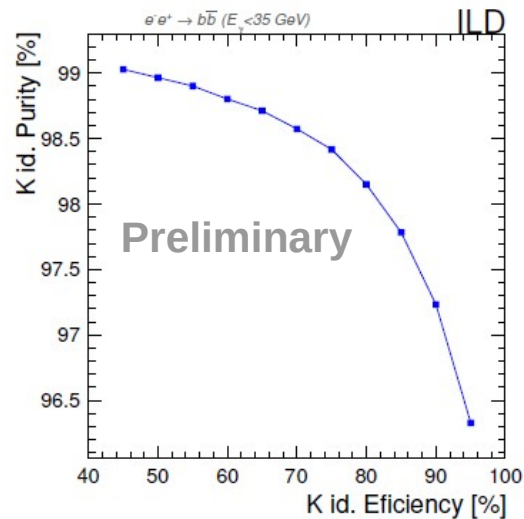
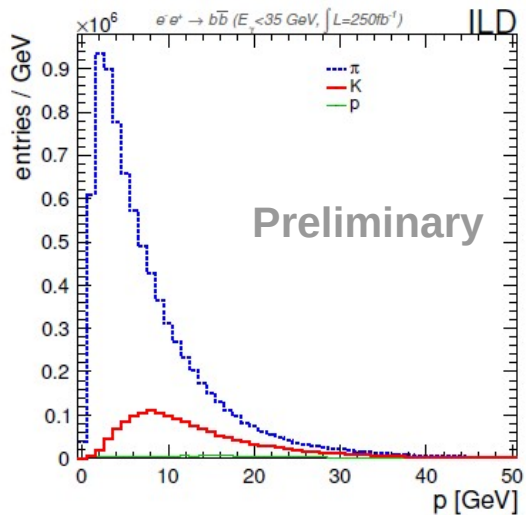
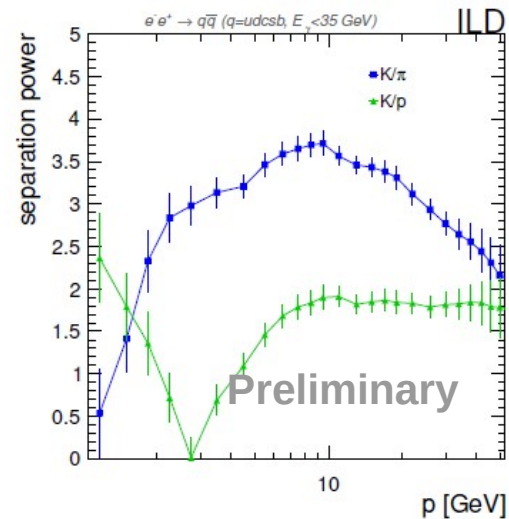
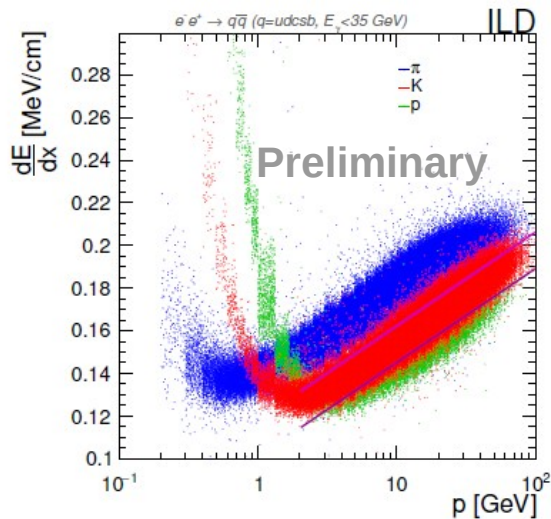
$$\sin \Psi_{acol} = \frac{|\vec{p}_{j_1} \times \vec{p}_{j_2}|}{|\vec{p}_{j_1}| \cdot |\vec{p}_{j_2}|}$$

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

- ▶ Estimator of the energy of the photon ISR
- ▶ We apply a cut of  $K_{reco} < 35$  GeV
- ▶ Some signal events have larger  $K_{reco}$  (~15%)
  - Because of detector resolution and double photon ISR
- ▶ Some radiative return events have  $K_{reco} < 35$  GeV (~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?

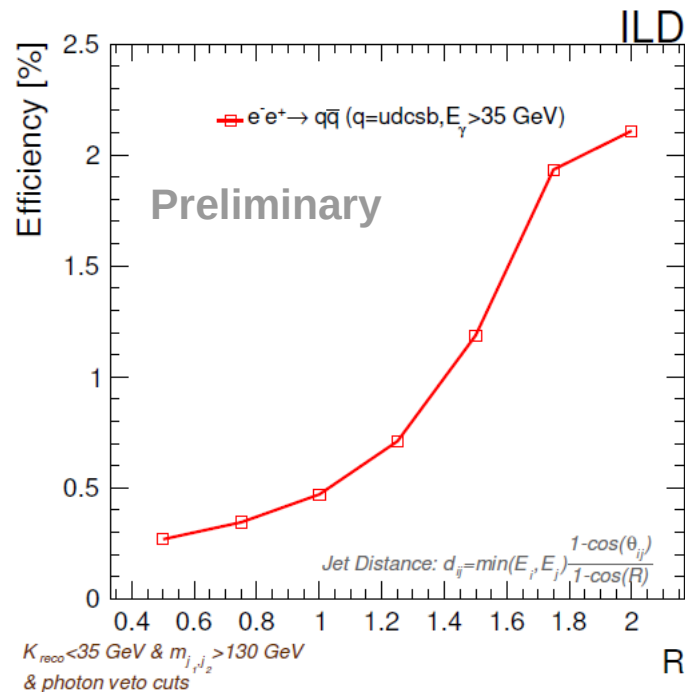
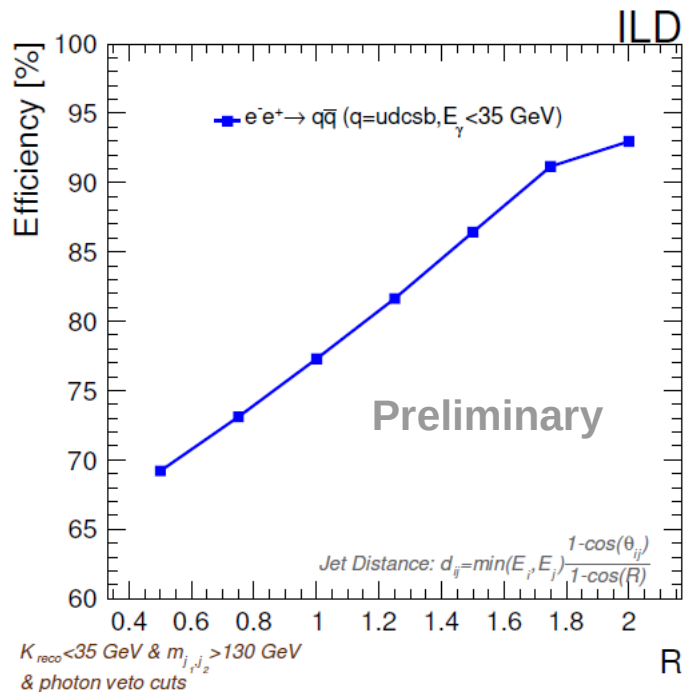






$$d_{ij} = \min(E_i^{2p}, E_j^{2p}) \frac{1 - \cos(\theta_{ij})}{1 - \cos(R)}$$

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





# Final steps of the preselection

- ▶ Cut on  $y_{23} < 0.015$  (jet distance at which the 2 jet event would be clustered in 3 jets)
- ▶ Cut on  $m_{j1} + m_{j2} < 100$  GeV

