Heavy Quark cross section and forward backward asymmetries at ILC250

Adrián Irles* on behalf of the ILD collaboration

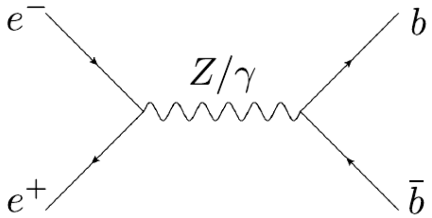
and the IJCLab/Tohoku U./IFIC HQ-ILC team

**AITANA group at IFIC - CSIC/UV*

Updated results with the newest and more realistic mc2020 simulations

Two fermion processes

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



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

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

- The helicity amplitudes Σ_{IJ}, contain the couplings g_L/g_R (or Form factors or EFT factors)
- Left≠right (characteristic for each fermion)

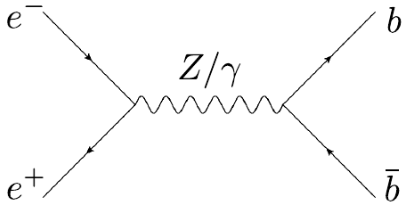
▶ **Only beam polarisation allows inspection of the 4 helicity amplitudes for all fermions**

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 Rb and Rq

Double Tag Method

- **Assuming that:**
  - Minimal contribution from the backgrounds
  - the preselection efficiency is the same for all flavours

$\varepsilon_c = c - tagging\ eff.$

$\widetilde{\varepsilon_x} = x - quark\ mis - tagging\ effi.(prob\ of\ tagging\ x\ as\ c - quark)$

$(1+\rho) = angular\ correl.term$

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

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

Measured quantities

Double Tag Method

IFIC INSTITUT DE FÍSICA CORPUSCULAR

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  - the preselection efficiency is the same for all flavours

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

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Measured quantities

Inputs (MC or independent measurements

Double Tag Method

- **Assuming that:**
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Measured quantities

PHYSICS!

Inputs (MC or independent measurements

Double Tag Method

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  - the preselection efficiency is the same for all flavours

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

- **We are interested in Rc / epsilon_c (or b)**

ideally ⇒

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

What about the backgrounds ? Not a problem at Z-Pole runs ILC250 ?

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]
$X = WW \to q_1\bar{q}_2q_3\bar{q}_4$	14874.4	136.4
$X = ZZ \to q_1\bar{q}_1q_2\bar{q}_2$	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
  - **C1-2:** Energy_photon Kreco < 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 --> y23=2 vs 3 jet likeness

    (cut against dibosons)

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

eLpR

	Signal Efficiency (%) bb	cc	qq (uds)	B/S (%) 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 (%) bb	cc	qq (uds)	B/S (%) 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
CUT 6	64.0	64.1	63.6	5.8	0.0	0.3	0.1

Preselection

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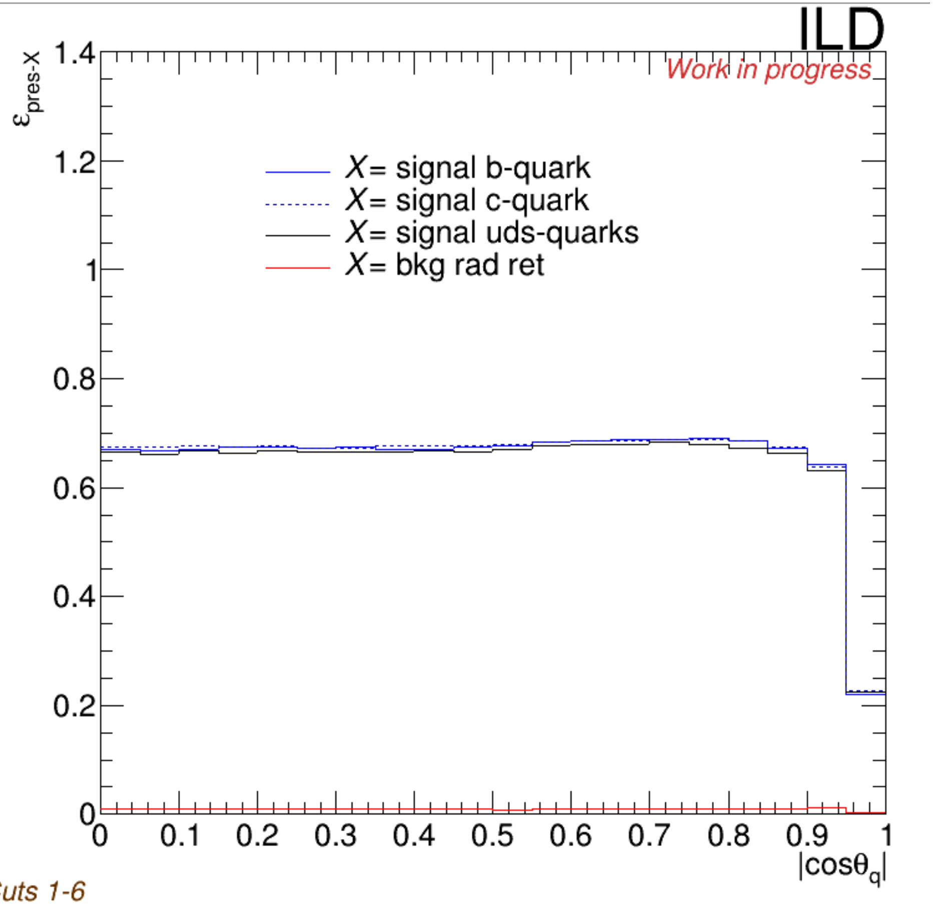
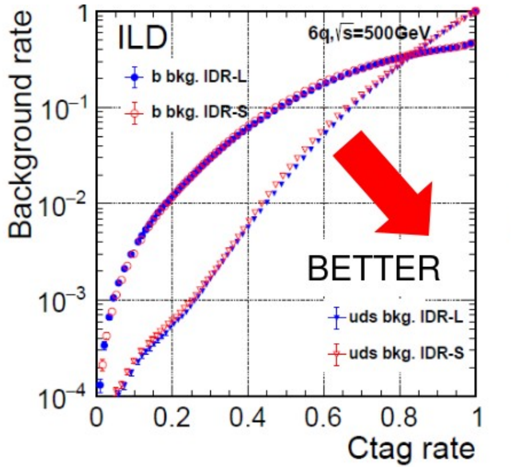
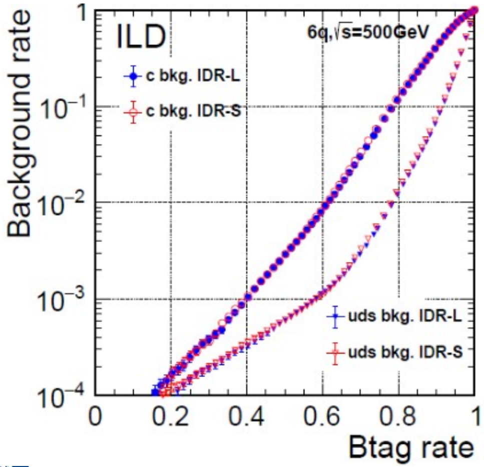


Cuts 1-6

Flavour tagging





Irles A., ILCX2021

▶ 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

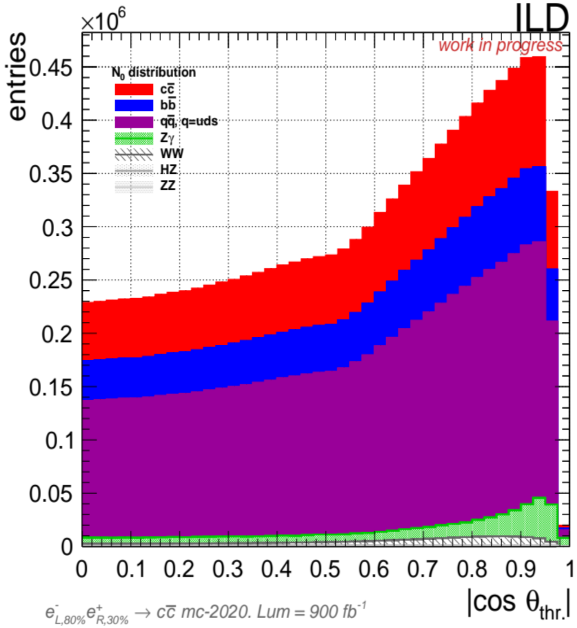
Design goals

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

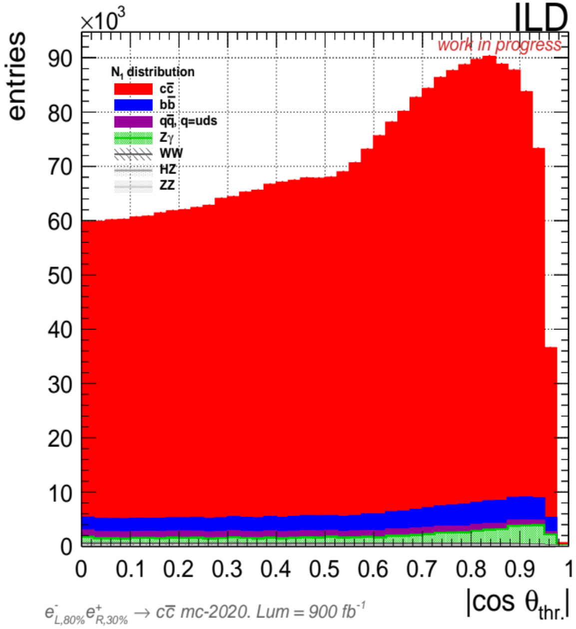
Double Tag Method

eLpR (80,30)

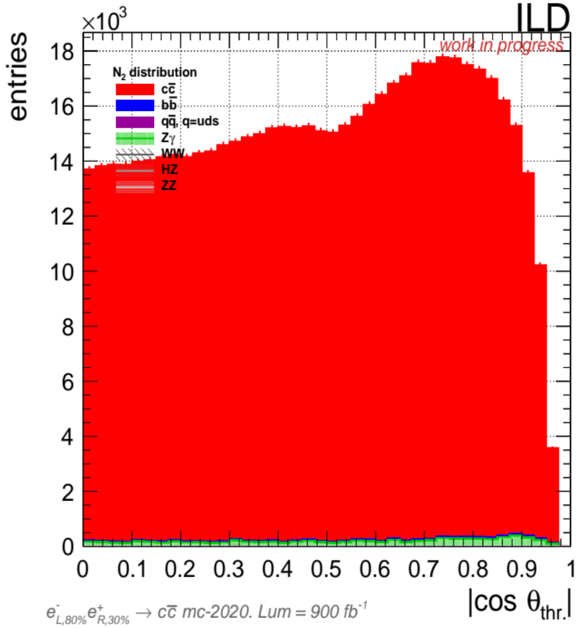
N0
(preselected ev)



N1
(jets with tag)



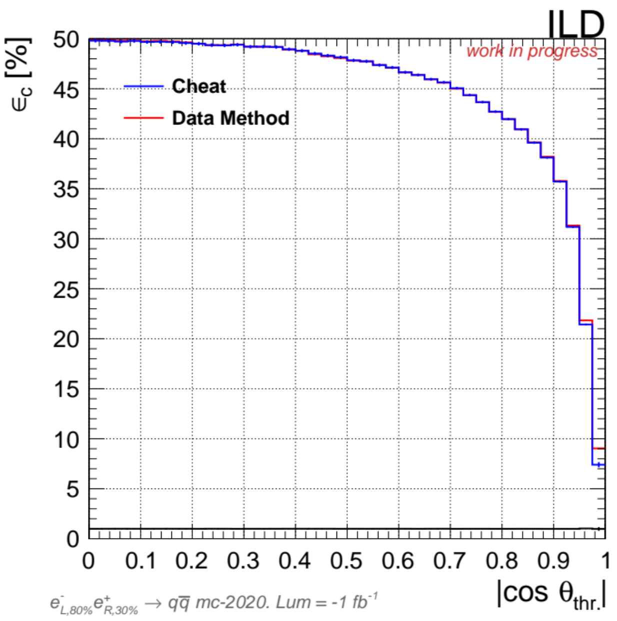
N2
(events with double tag)

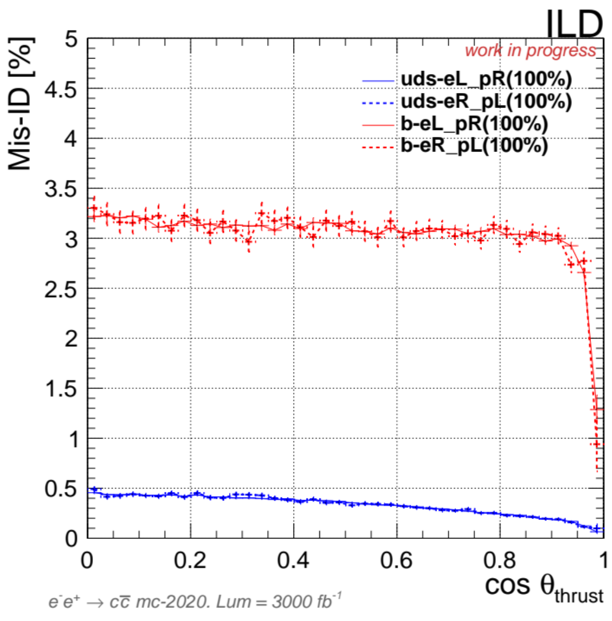


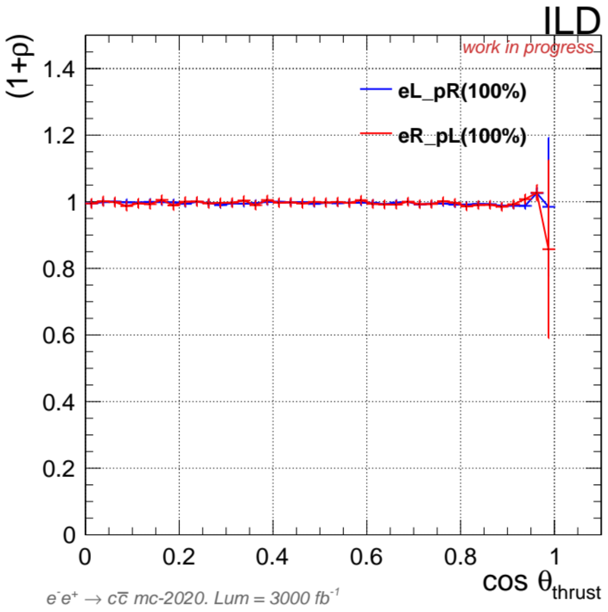
$$f_{1\,tag} = \frac{(N1 - Bkg)}{2(N0 - Bkg)} = (N\ jets\ with\ 1\ c-tag)/(N\ preselected\ jets)$$

$$f_{2\,tag} = \frac{(N2 - Bkg)}{(N0 - Bkg)} = (N\ events\ double\ tag)/(N\ preselected\ events)$$

Results (eLpR 80,30, **c-quark)**

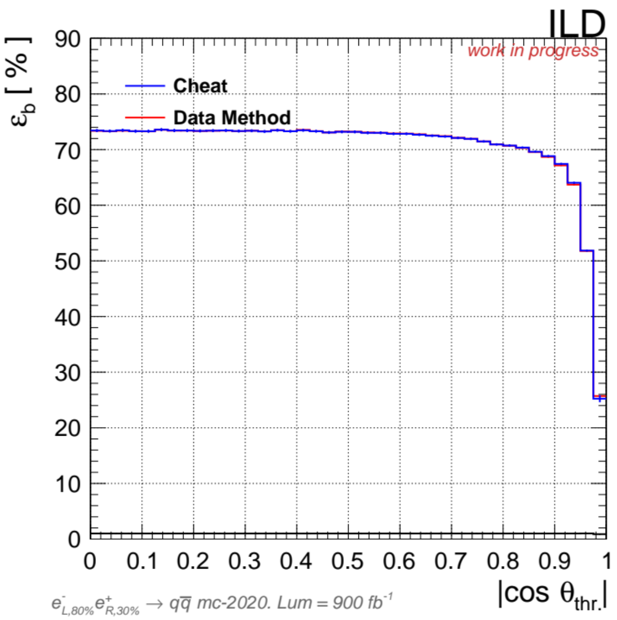


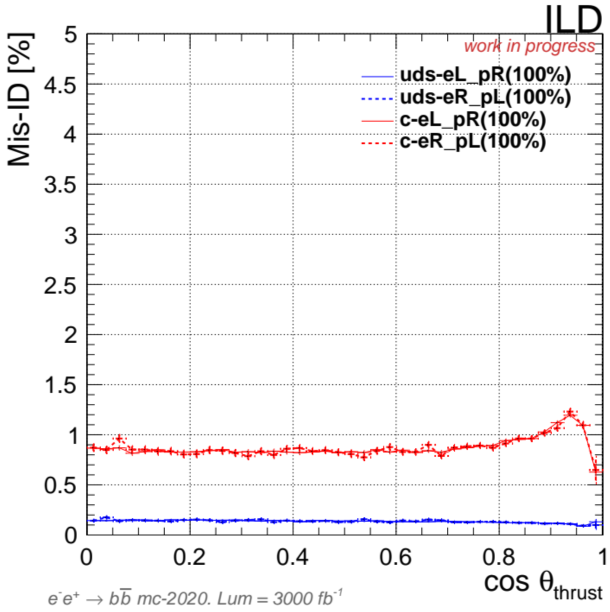


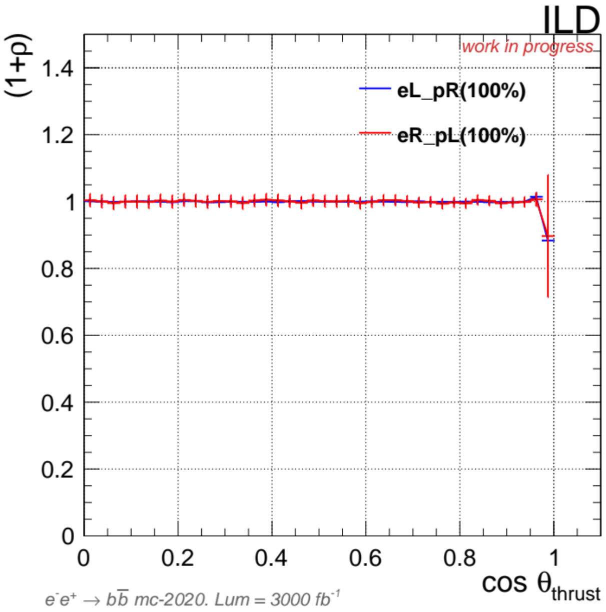


Excellent flavour tagging capabilities expected
Small angular correlations ~0% (similar to SLD, smaller than LEP – 1-2%)

Results (eLpR 80,30, **b-quark)**







Excellent flavour tagging capabilities expected
Small angular correlations ~0% (similar to SLD, smaller than LEP – 1-2%)

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**

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

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

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

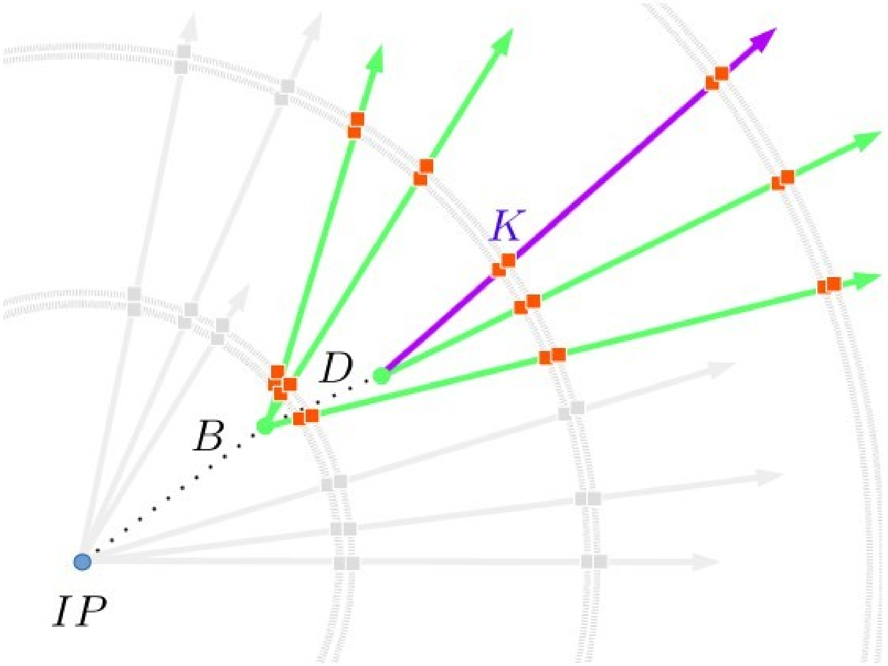
Measuring AFB

AFB measurement: basis

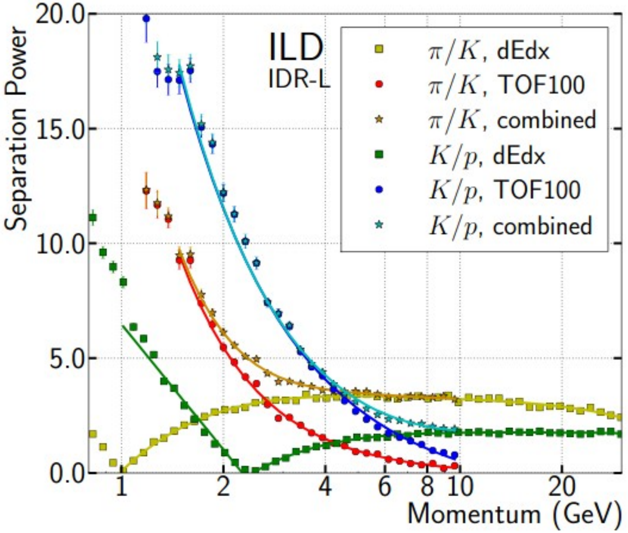
- We are required to **measure the jet charge**
  - Using K-ID and/or full Vtx charge measurement
  - K-ID is better suited for the C-quark (Vtx is better suited for b-quark)

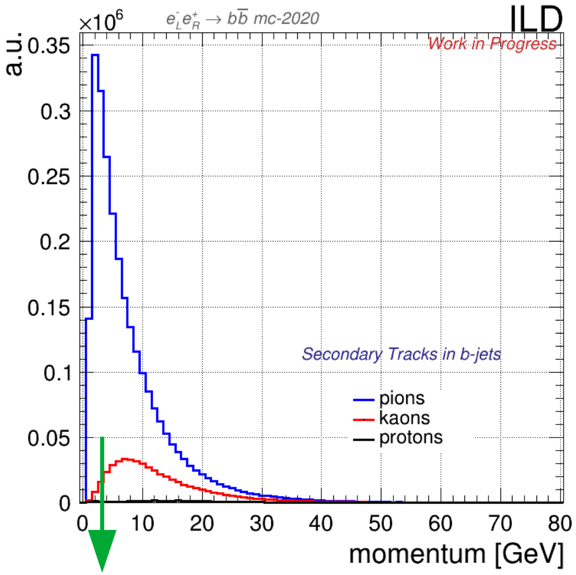
- Ideally we would use the **double charge** measurements
  - To control / reduce the systematic uncertainties

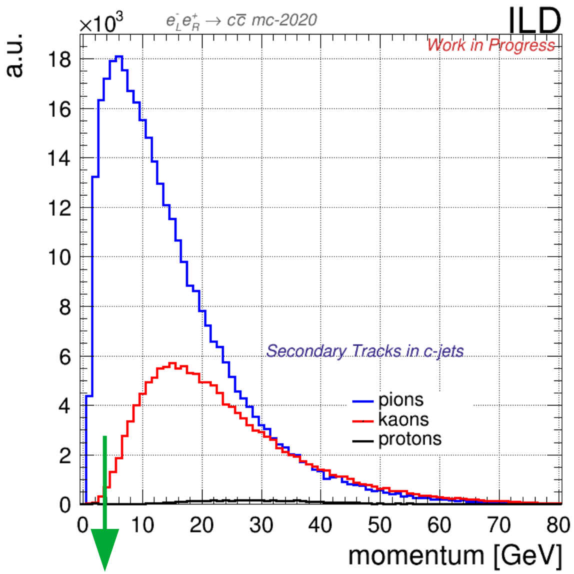
- **Today I give only a taste on the K-method**
  - **Results on b/c AFB are being updated**
  - **Cooming soon**



High Level Reco Challenges: Particle ID





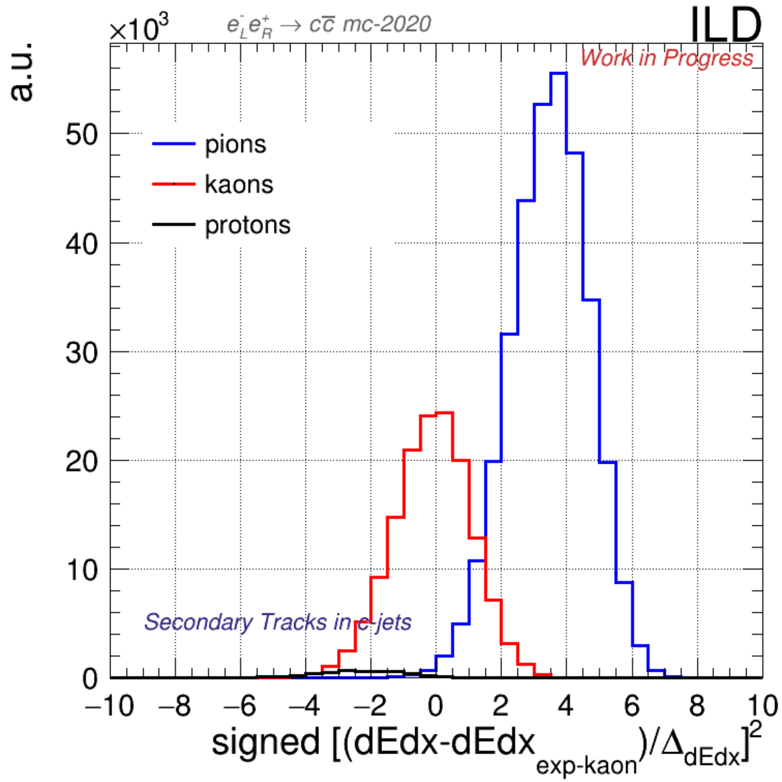


TOF or dEdx
(left) (right)

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

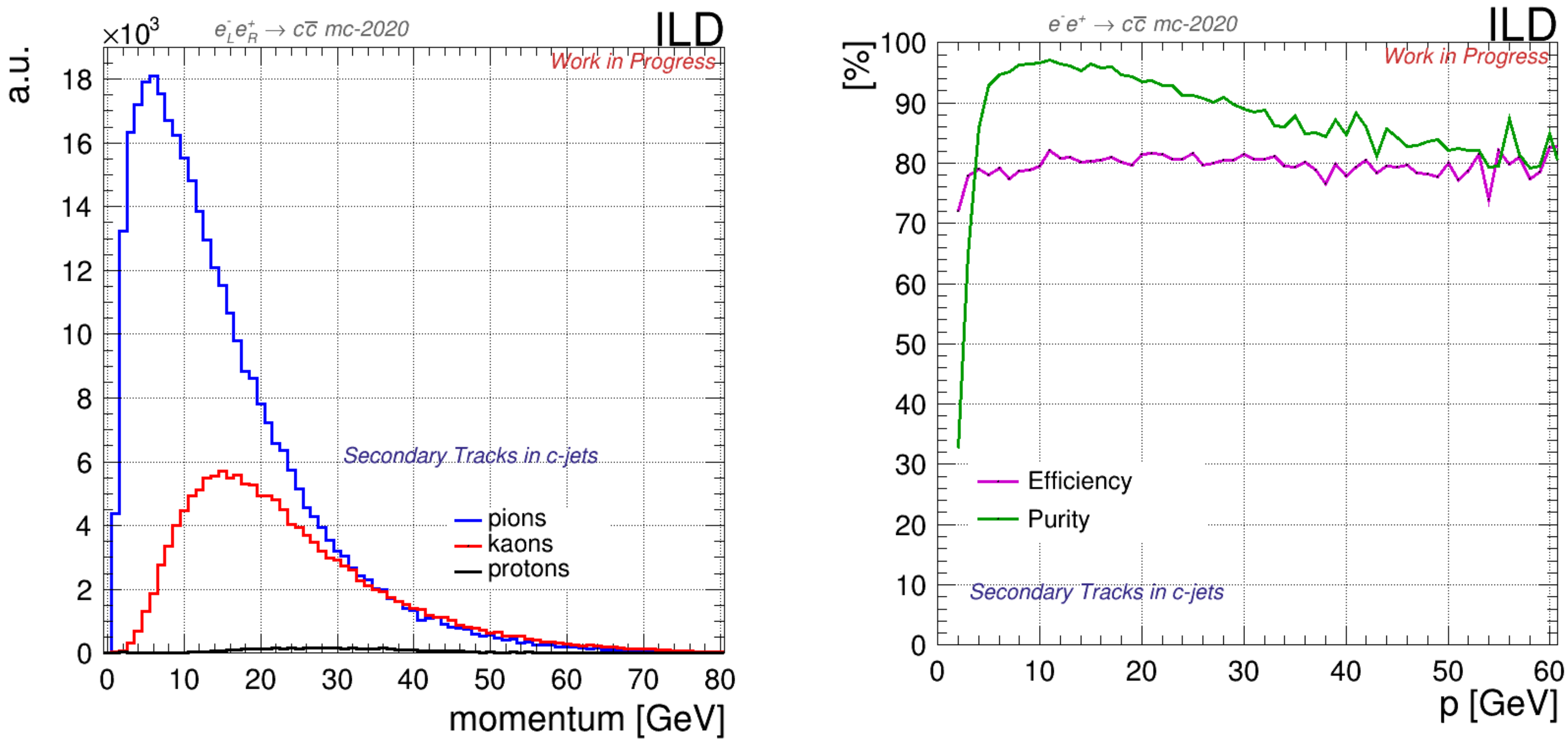


▶ Using **dEdx separation power:**

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

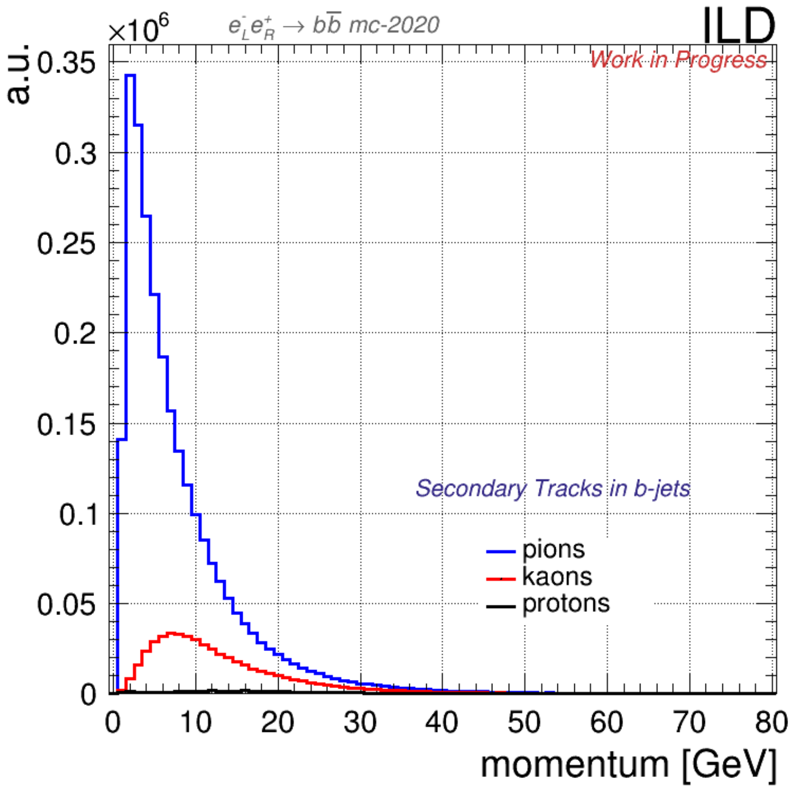
- $dEdx_{exp\text{-}kaon}$ = theoretical curve (B.Bloch)
- Delta dEdX = experimental uncertainty
- Zero worries about protons

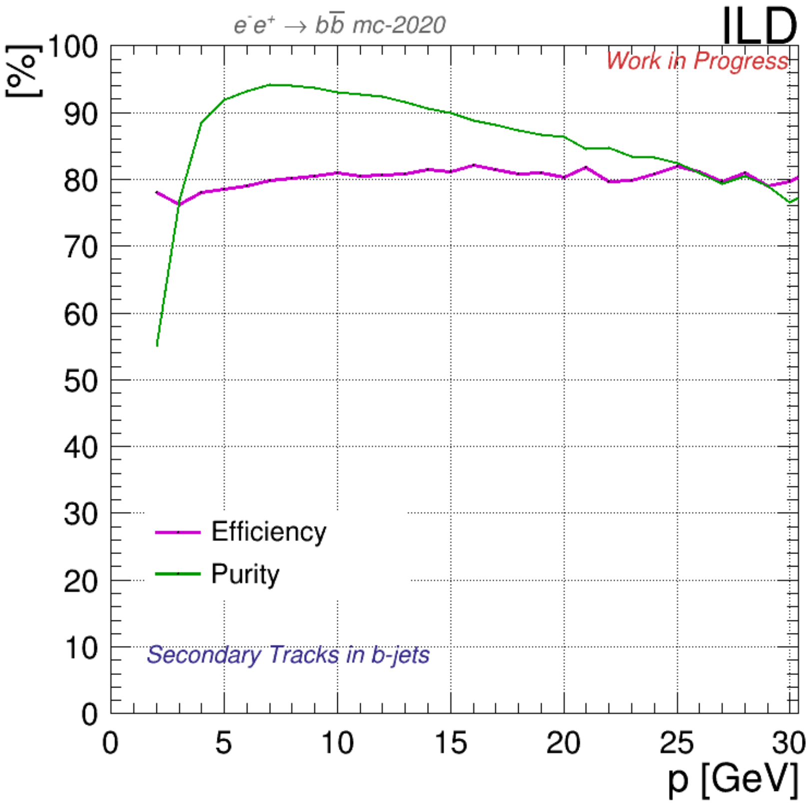
Efficiency / Purity of K ID



c-quark

Efficiency / Purity of K ID





b-quark

Summary

- We show updated results for b/c R-observable and AFB-observable
- **ILC offers a unique framework for** these studies to reach the maximal experimental precision
  - Tiny beam spot
  - Excellent vertexing capabilities
  - Kaon identification thanks to the TPC
  - **Beam polarisation**
- Comprehensive assessment of systematic uncertainties
  - To be updated for the AFB studies
- Experimental per mile level accuracy reachable
  - Avoiding MC for efficiency estimations
  - Un-sensitive to luminosity systematics

thanks

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

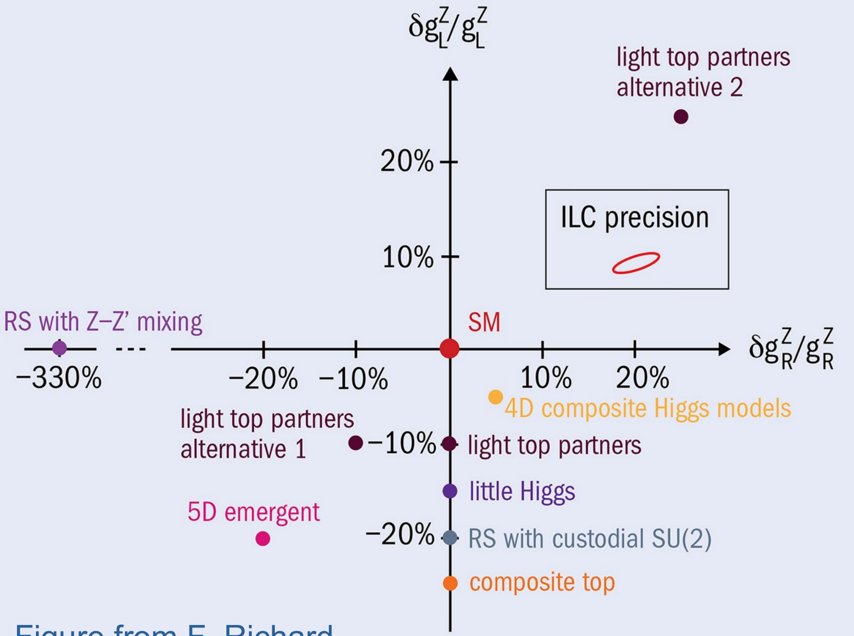


Figure from F. Richard

Detector Technologies

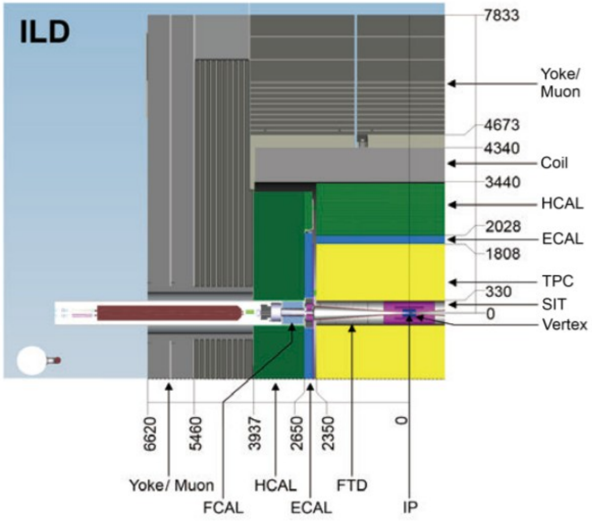
Vertex: CMOS, DEPFET, FPCCD, …

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 High precision design

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→bb,cc,gg,ττ
• 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} ~100 GeV)	H→invisible
• Hermeticity θ_{min} = 5 mrad	H→invisible; BSM

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

9

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**

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

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

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

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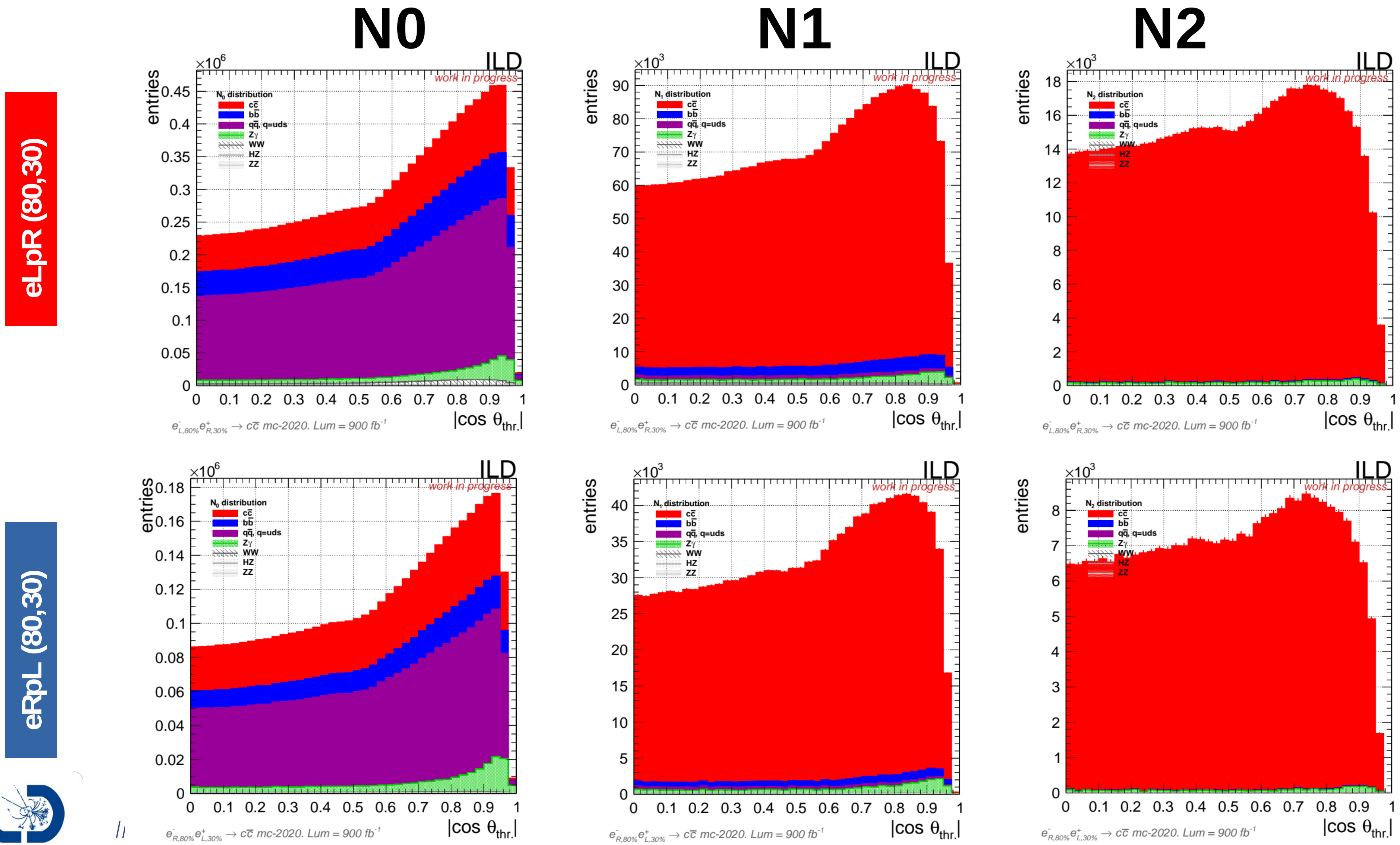
$$N_0^{signal} = N_{presel} = [\varepsilon_{pres-signal} \sigma_{q\bar{q}}] \cdot Lum$$
$$N_{1tag,c}^{signal} = [\varepsilon_{pres-signal} (\varepsilon_c \sigma_{c\bar{c}} + \varepsilon_b \sigma_{b\bar{b}} + \varepsilon_q \sigma_{q\bar{q}})] \cdot Lum$$
$$N_{2tag,c}^{signal} = [\varepsilon_{pres-signal}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

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

Double Tag Method



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

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

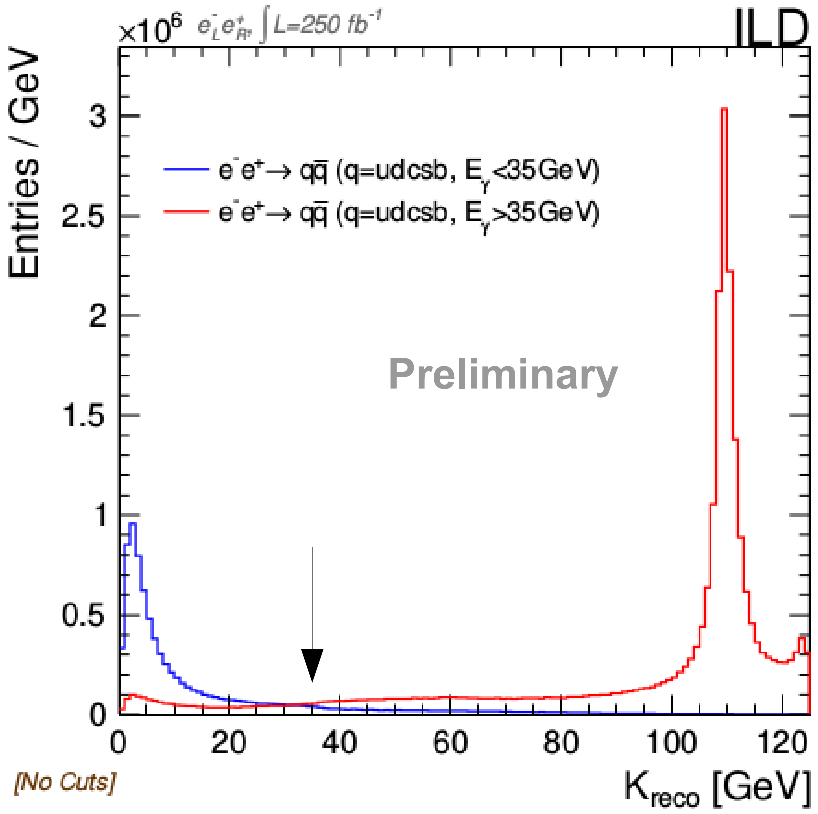
Jet angular variables (w.r.t. detector frame)

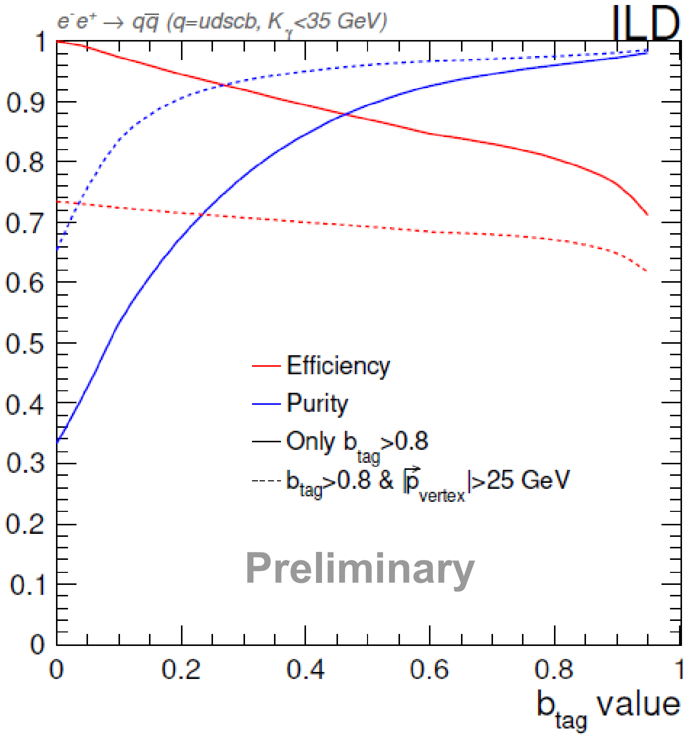
Preselection : Kreco

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

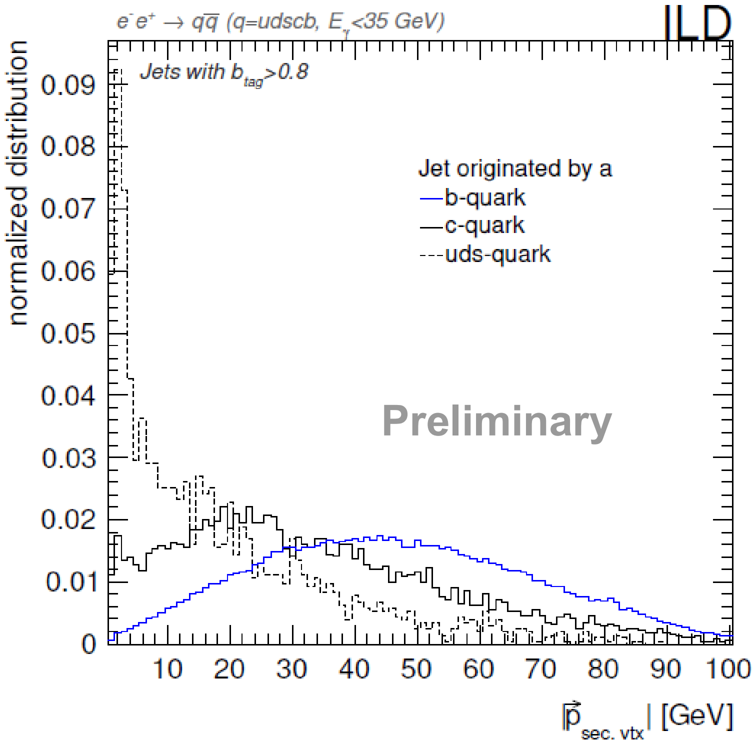
- Some signal events have larger Kreco (~15%)
  - Because of detector resolution and double photon ISR

- 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?

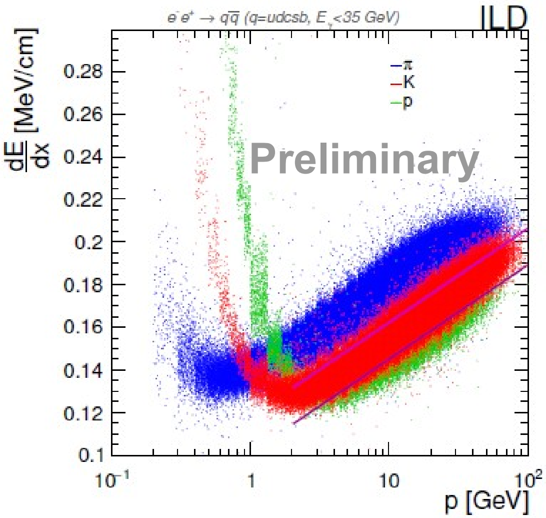


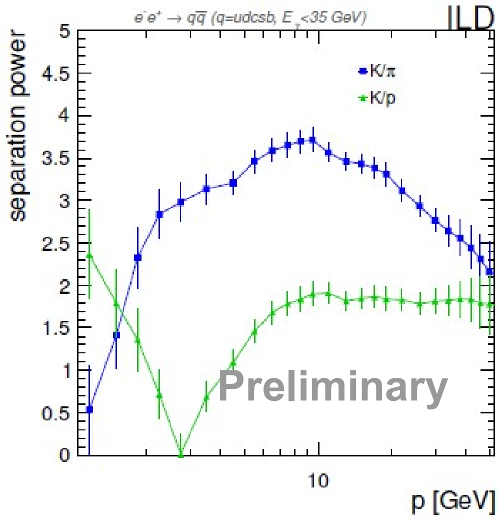


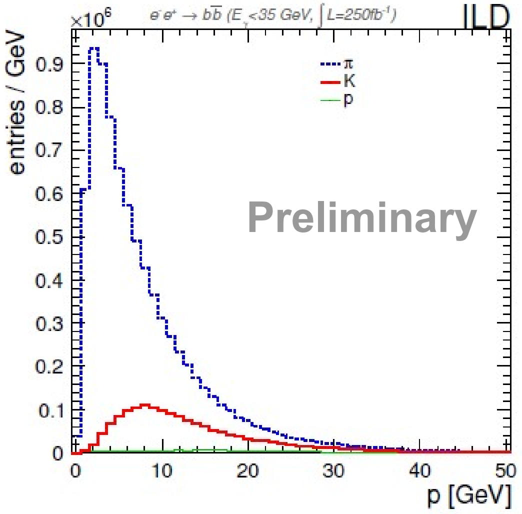
$e^-e^+ \to q\bar{q}$ (q=udscb, K_γ<35 GeV)
ILD
Efficiency
Purity
Only b_{tag}>0.8
b_{tag}>0.8 & $|\vec{p}_{vertex}|$>25 GeV
Preliminary
b_{tag} value

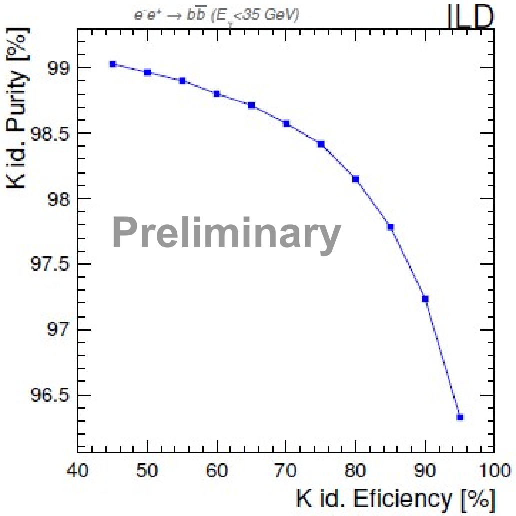


$e^-e^+ \to q\bar{q}$ (q=udscb, E_γ<35 GeV)
ILD
Jets with b_{tag}>0.8
Jet originated by a
b-quark
c-quark
uds-quark
Preliminary
normalized distribution
$|\vec{p}_{sec. vtx}|$ [GeV]


$e^-e^+ \to q\bar{q}$ (q=udcsb, E_γ<35 GeV)
ILD
$\frac{dE}{dx}$ [MeV/cm]
p [GeV]
π
K
p
Preliminary

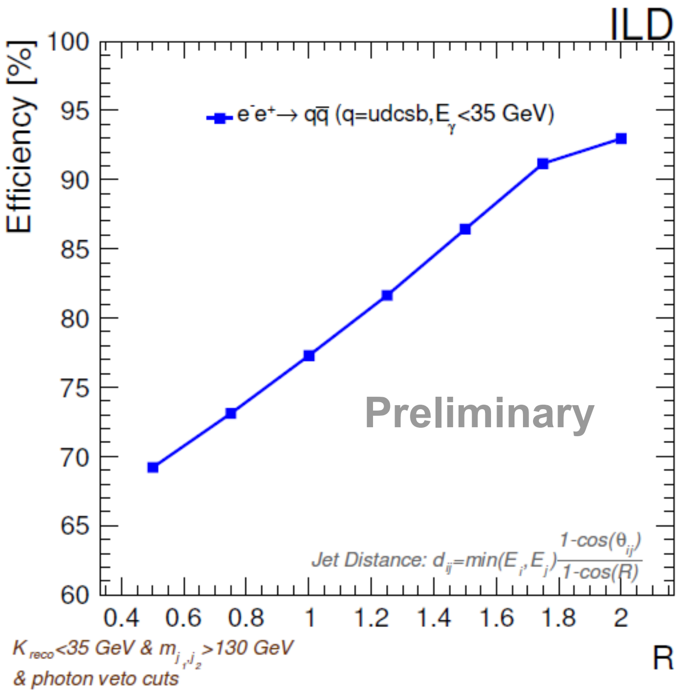

$e^-e^+ \to q\bar{q}$ (q=udcsb, E_γ<35 GeV)
ILD
separation power
p [GeV]
K/π
K/p
Preliminary

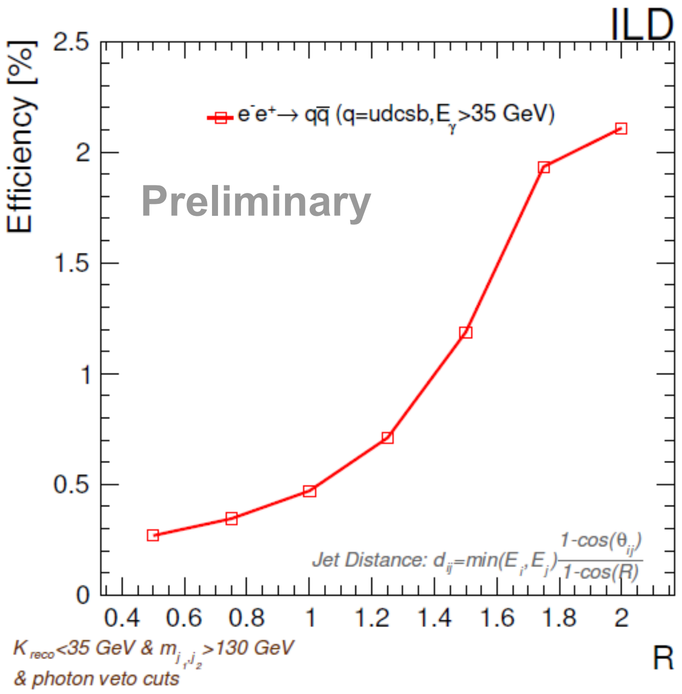

$e^-e^+ \to b\bar{b}$ (E_γ<35 GeV, $\int L$=250fb^{-1})
ILD
×10^6
entries / GeV
p [GeV]
π
K
p
Preliminary


$e^-e^+ \to b\bar{b}$ (E_γ<35 GeV)
ILD
K id. Purity [%]
K id. Eficiency [%]
Preliminary

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

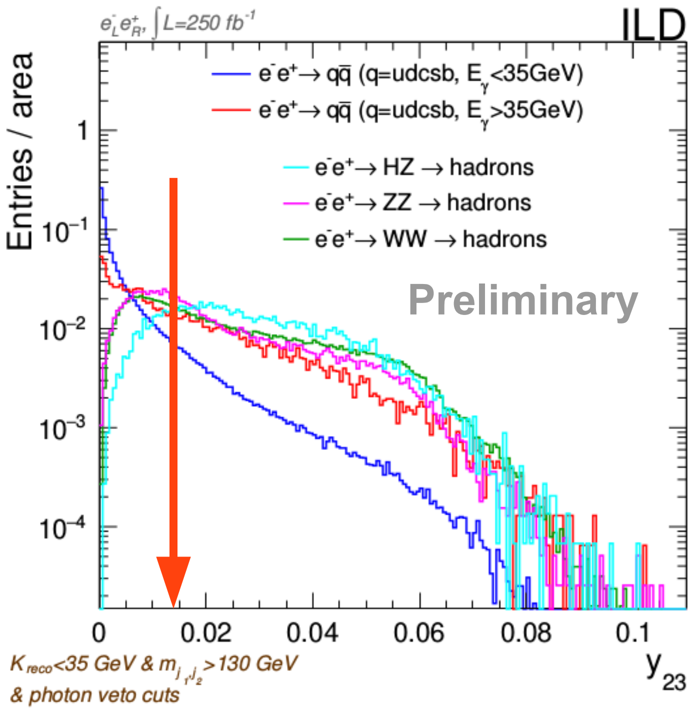
$$d_{iB} = E_i^{2p}$$

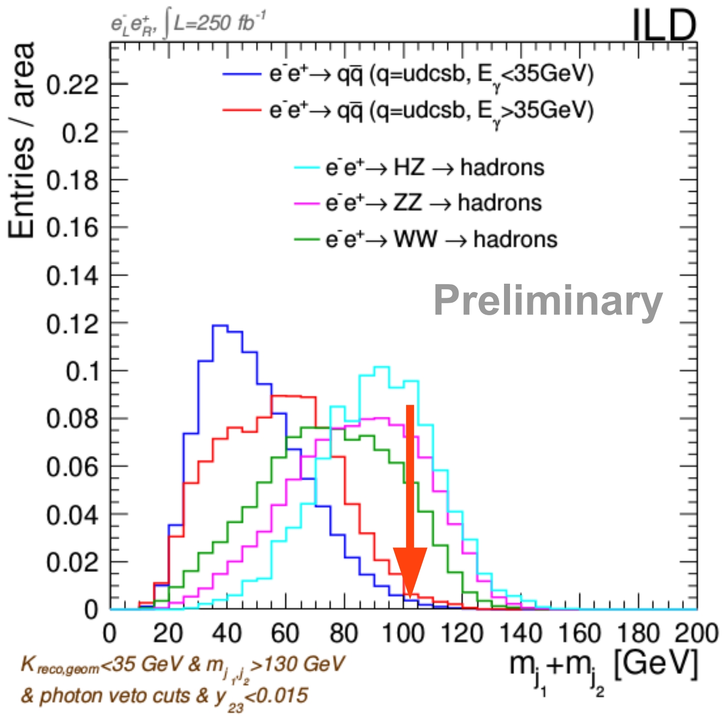




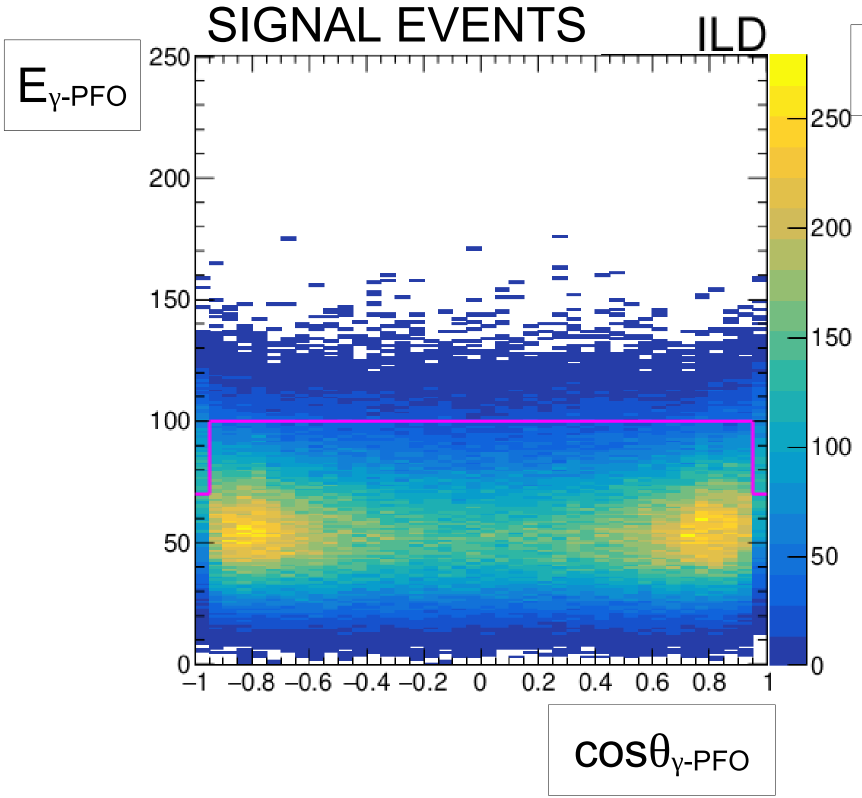
Final steps of the preselection

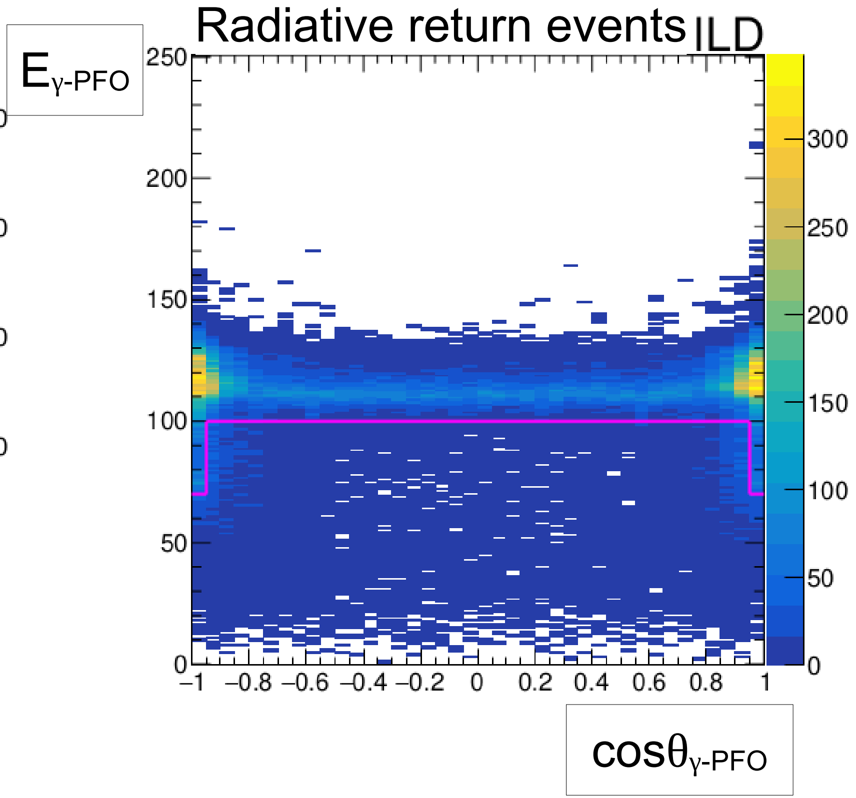
- Cut on y23<0.015 (jet distance at which the 2 jet event would be clustered in 3 jets)
- Cut on mj1+mj2<100 GeV



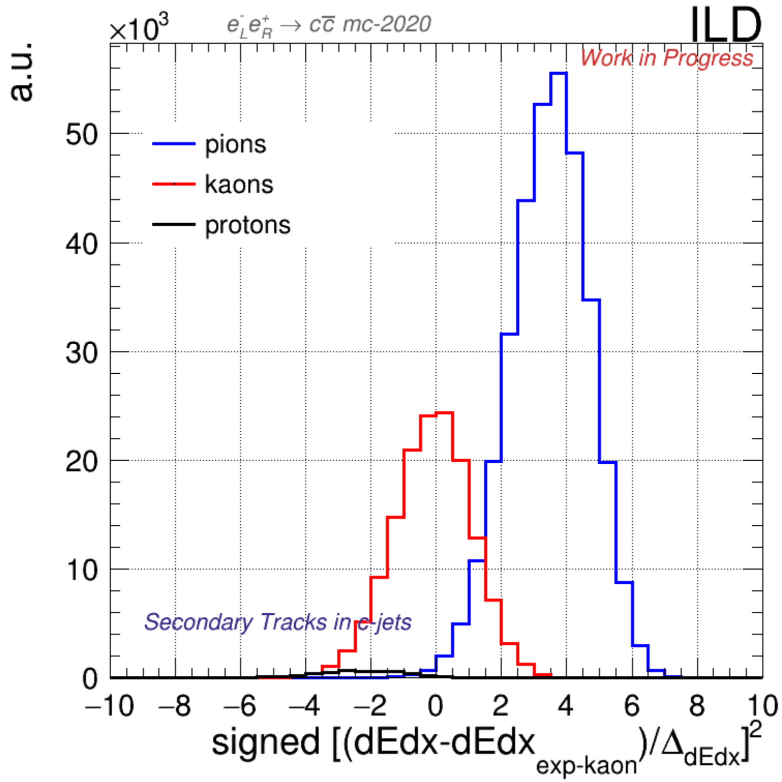


▶ Cut 2: veto of events in which the ISR photon was reconstructed and identified inside the detector





Kaon identification for the ccbar case



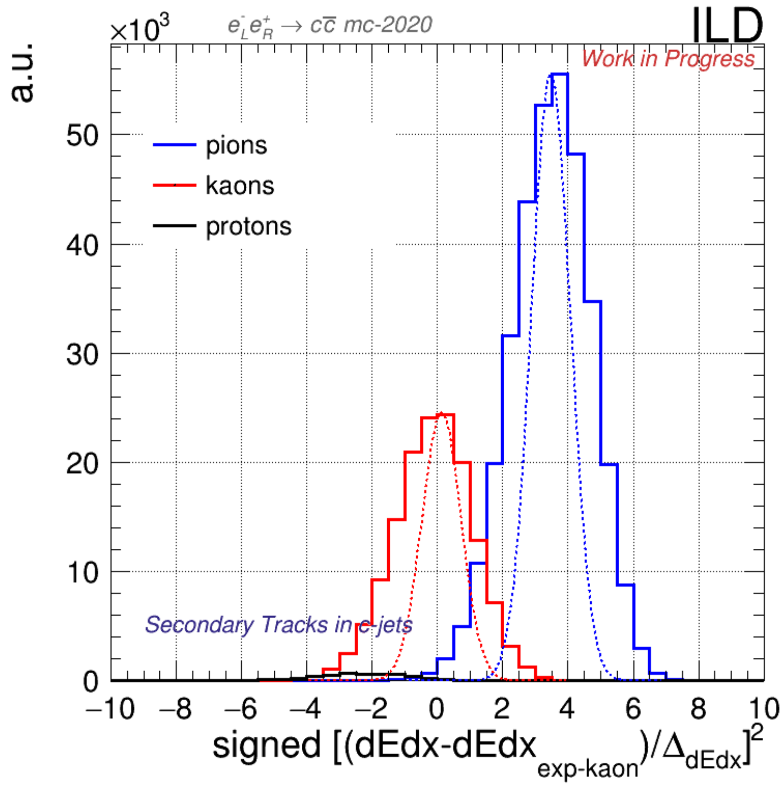
▶ Using **dEdx separation power:**

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

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

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

Kaon identification for the ccbar case



▶ Using **dEdx separation power:**

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

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

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

- Then the kaon ID performance will be almost perfect

Factor 1.3-1-4 seems more realistic than a factor 2

With current TPC testbeam prototypes