Heavy quark production in high energy electron positron collisions: experimental prospects

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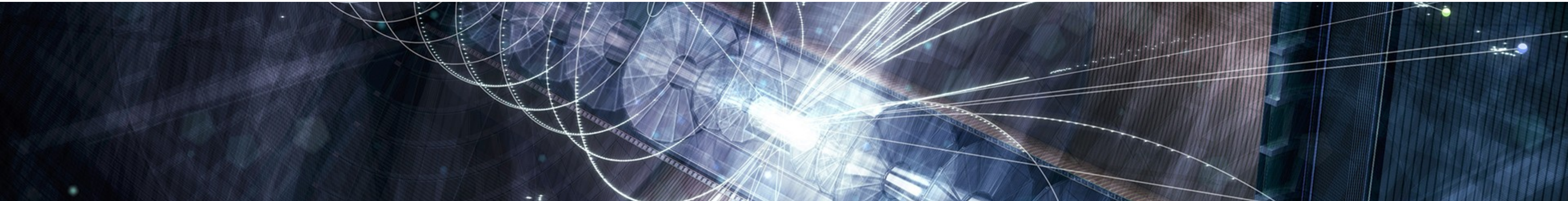


Work done by the Tohoku/Orsay/Valencia ILD-Top/HeavyQuark Working Team

ILD

ilc international linear collider

Two fermion processes

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

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

$$Q^{SM}_{e_X q_Y} = \frac{e^2}{s} + \frac{g^X_{Ze} g^Y_{Zq}}{(s - m_Z^2) + i m_Z \Gamma_Z}$$

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
STANFORD LINEAR ACCELERATOR CENTER

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

arXiv:hep-ex/0509008v3 27 Feb 2006

Precision Electroweak Measurements on the Z Resonance

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

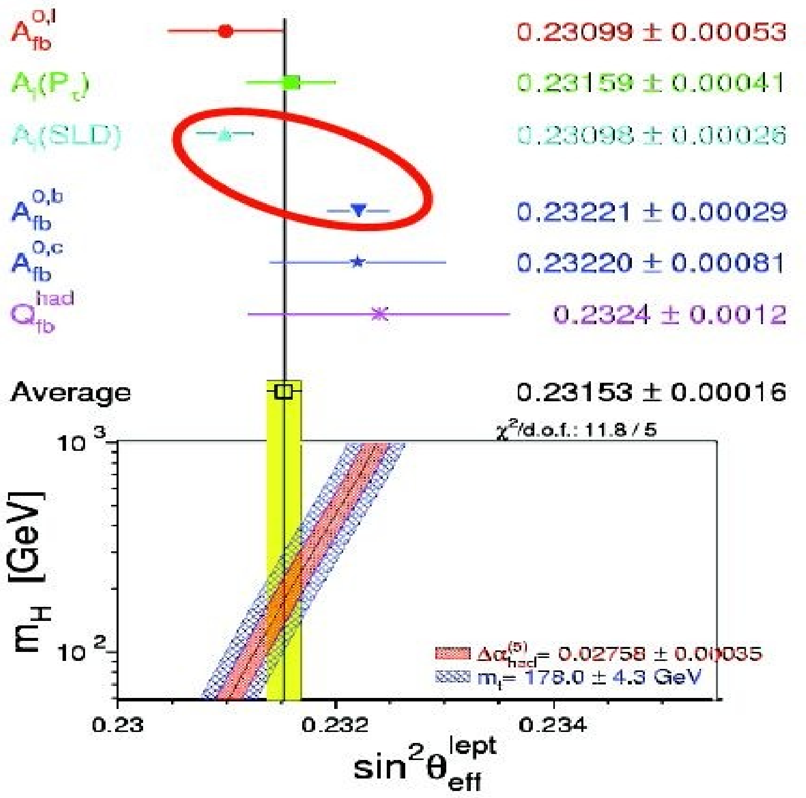
Accepted for publication in *Physics Reports*

Updated: 20 February 2006

Motivation: LEP/SLC tension

- ▶ Current LEP & SLC best $sin^2\theta^l_{eff}$ **measurements** show **tension**
  - This measurement is the one with **largest tension with the SM fit.**
  - SLC: $sin^2\theta^l_{eff}$ →from Left-right asymmetry of leptons
  - LEP: $sin^2\theta^l_{eff}$ from forward backward asymmetry (b-quark)
- ▶ Heavy quark effect, effect on all quarks/fermions, no effect at all?

The **resolution** of this issue requires improving the the measurements precision an order of magnitude



Per mil level of experimental precision is required

Motivation: BSM Z' resonances

▶ Many **BSM scenarios** (i.e. Randal Sundrum, compositeness, Gauge Higgs unification models...) predict heavy resonances coupling to the (t,b) doublet and also lighter fermions (i.e. c/s quarks)

- **BSM resonances** tend to **couple** to the **right components.**
- Only coupling to (t,b) doublet
  - → Peskin, Yoon arxiv:1811.07877
  - → Djouadi et al arxiv:hep-ph/0610173
- Coupling also to lighter fermions
  - → Hosotani et al arxiv:1705.05282 arxiv:2006.02157

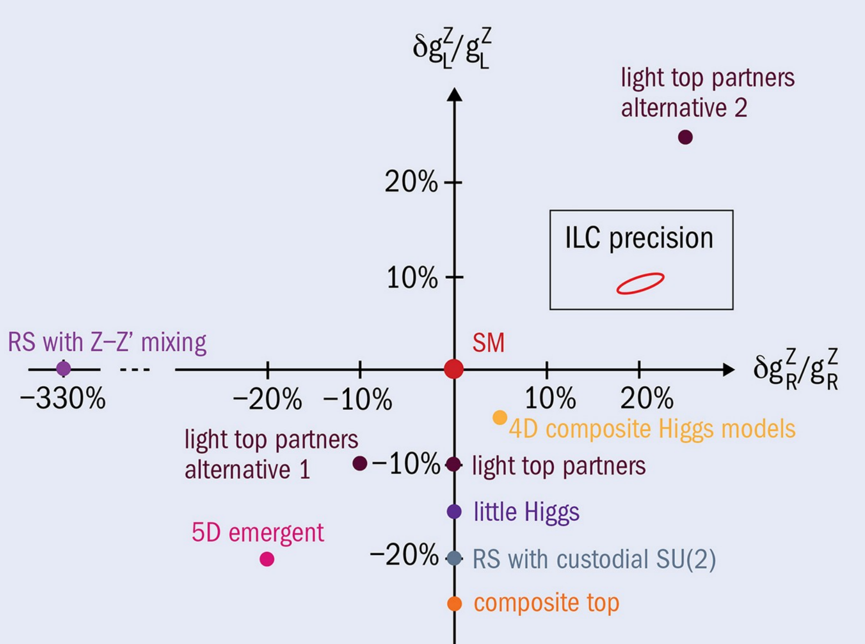


Figure from F. Richard

Probe such scenarios require at least per mil level for experimental precision
tt/**bb**/cc/ss/... **Can we do it?**

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Gauge-Higgs Unification Models

▶ The symmetry breaking pattern is different than in the SM and features the so-called Hosotani's mechanism.

▶ Only one parameter, Hosotani angle , determines the projection of the 5D fields, fixing all physical effects:

- KK resonances of the Z/γ with mkk~10TeV
- Modifications and new EW couplings/helicity amplitudes.
- Already visible effects at 250GeV

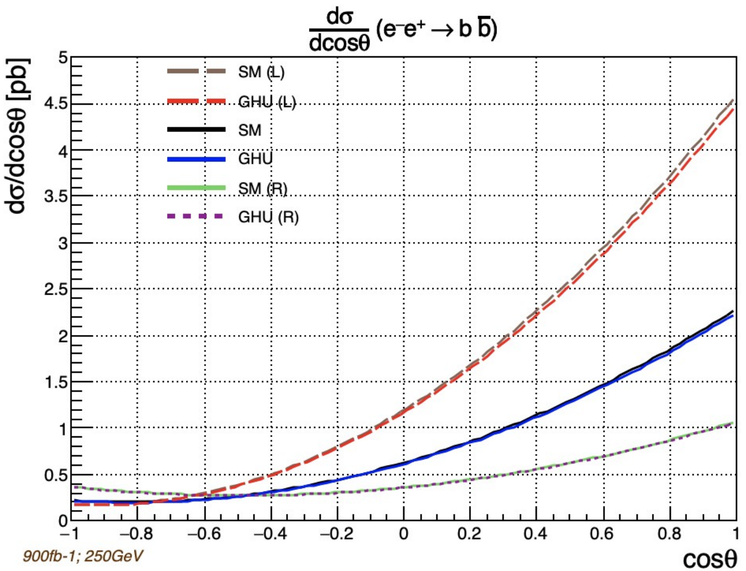
As **Benchmark**, we will use the [Funatsu, Hatanaka, Hosotani, Orikasa, Yamatsu] models:

▶ A models:

- (arxiv:1705.05282) tuned to fit LEP1 and LEP2 data
- Z' mass 7.4-10 TeV

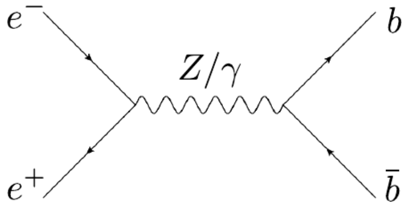
▶ B models:

- (arxiv:2006.02157) tuned to fit LHC data non observation of Z'
- Z'mass 10-13 TeV



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)

Normalized & differential observables are highly preferred: to control (remove) **systematic uncertainties**

ILD-PHYS-PUB-2023-001

(to appear soon:
on the last stage of ILD
approval)

ILD
ILC250, 2ab^{-1}

$P_{e^-e^+}(-0.8,+0.3)$

$P_{e^-e^+}(+0.8,-0.3)$

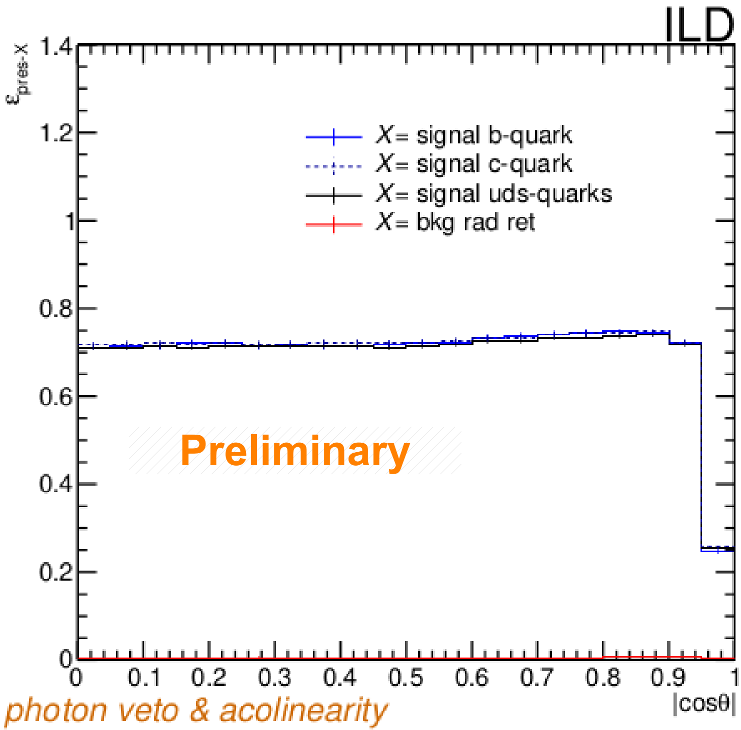
Full simulation (realistic detector model) backgrounds including beam induced one

ILD-PHYS-PUB-2023-001

(to appear soon: on the last stage of ILD approval)

Preselection

- **Topology: 2 back-to-back jets (pencil-like topology)**
- **Preselection aiming for high background rejection and high efficiency.**
- Main bkg ee→ Zγ(radiative return through ISR)
  - ~x10 larger than signal
  - **~90% of such ISR photons are lost in the beam pipe** → events filtered by energy & angular mom. conservation arguments
  - The **remaining ~10% are filtered by identifying photons** in the detector (efficiency of >90%)
  - PFA detector!!
- Other backgrounds from diboson production decaying hadronically are removed with extra toplogical cuts.



photon veto & acolinearity & m_{j1j1} & y_{23} cuts

Double Tag Method : minimizing flavour tagging unc.

- **Compare samples with 1 tag vs 2 tags (after preselection)**
- **Assumptions**
  - Minimal contribution from the backgrounds (next slide)
  - the preselection efficiency is the same for all flavours (seen in previous slide)

$$f_{1q}(|\cos\theta|) = \frac{N_q(|\cos\theta|) - N_q^{bkg.}(|\cos\theta|)}{2 \times (N_0(|\cos\theta|) - N_0^{bkg.}(|\cos\theta|))}$$

$$f_{2q}(\cos\theta) = \frac{N_{2q}(|\cos\theta|) - N_{2q}^{bkg.}(|\cos\theta|)}{N_0(|\cos\theta|) - N_0^{bkg.}(|\cos\theta|)}$$

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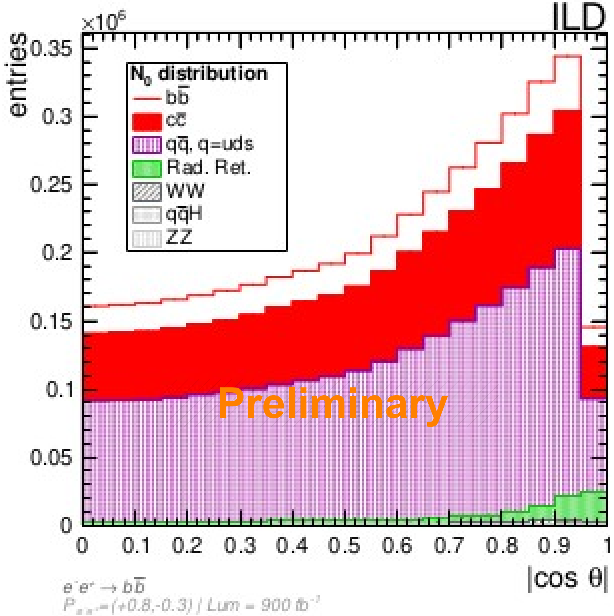
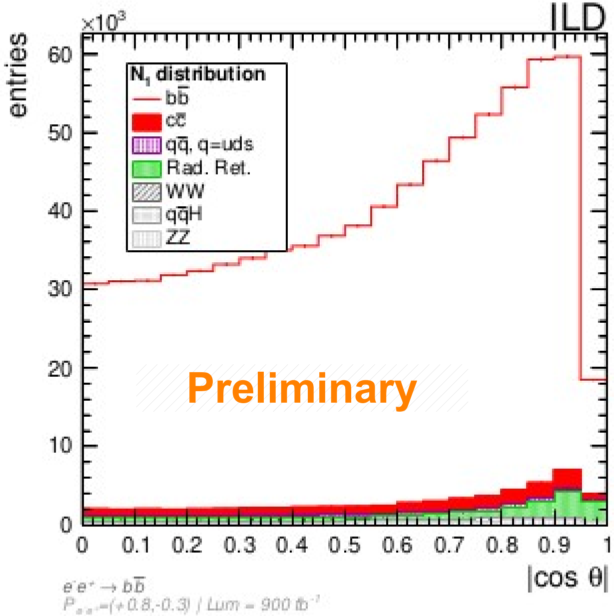
Double Tag Method

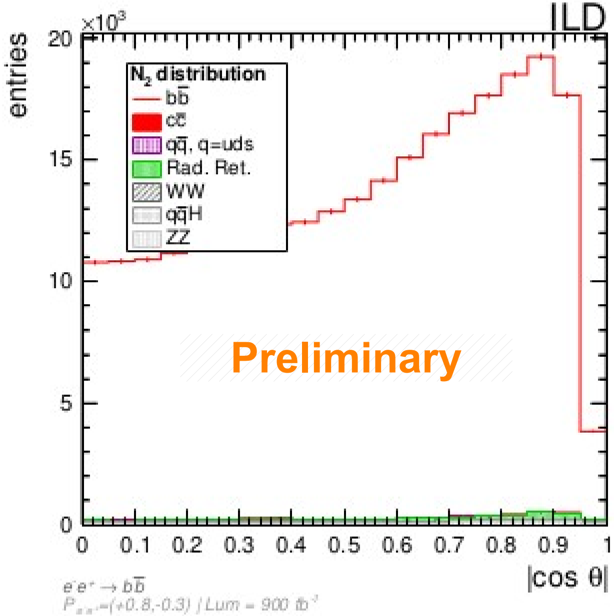
Minimal contribution from the backgrounds

green and gray histograms

N0, N1, N2 for e+e- → $b\bar{b}$







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Double Tag Method

- Compare samples with 1 tag vs 2 tags (after preselection)

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

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

Measured observables

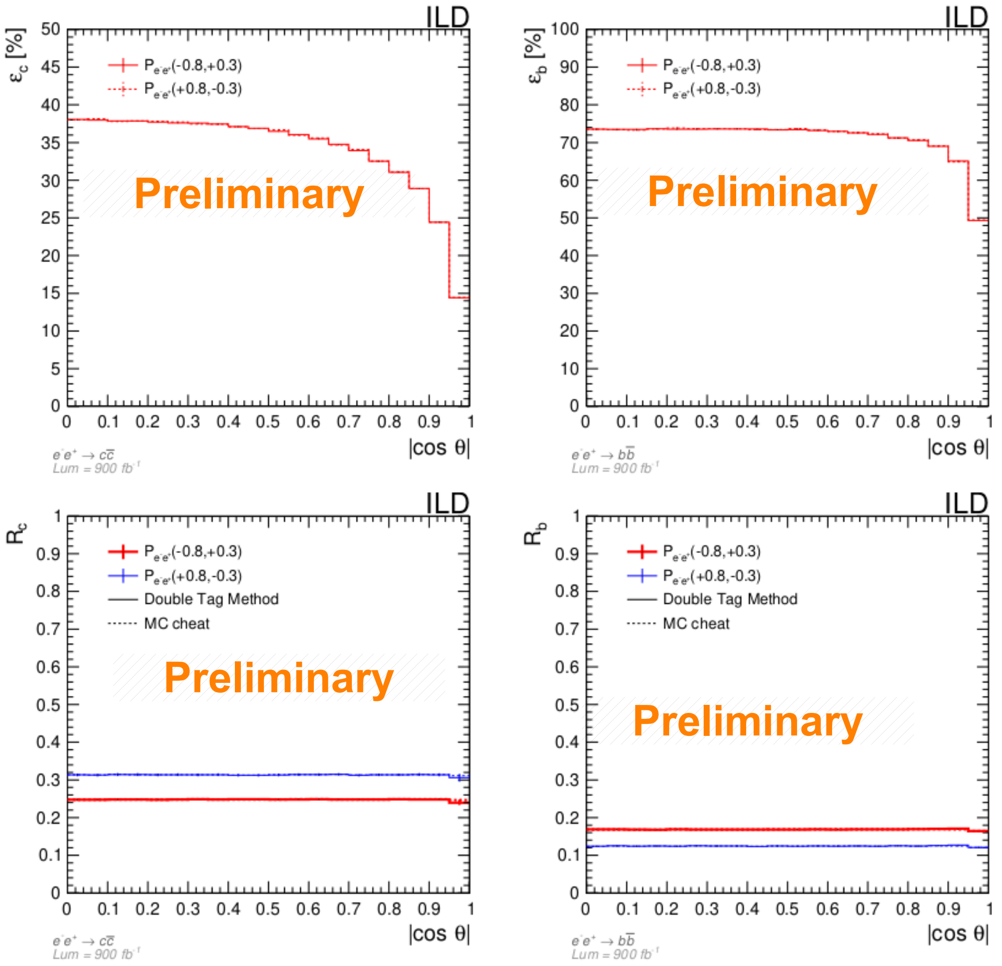
PHYSICS!
Indirect observables

Inputs (MC or independent measurements)

Similar set of equations for the c-quark
solved simultaneously

Summary Rq

- **Flavour tagging efficiency will be measured**
  - Not estimated with MC
  - **Per mil level reachable** because the contamination from lighter quarks is minimal and the tight IP constraint
- **Fully differential analysis !!**
- **Rb and Rc measured at the same time**
  - No assumption needed in Ruds
- **Per mil level stat. Uncertainty**
- **Comparable/lower exp syst. uncertainty**
  - Dominated by flavour tagging and followed by angular correlations



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Jet charge

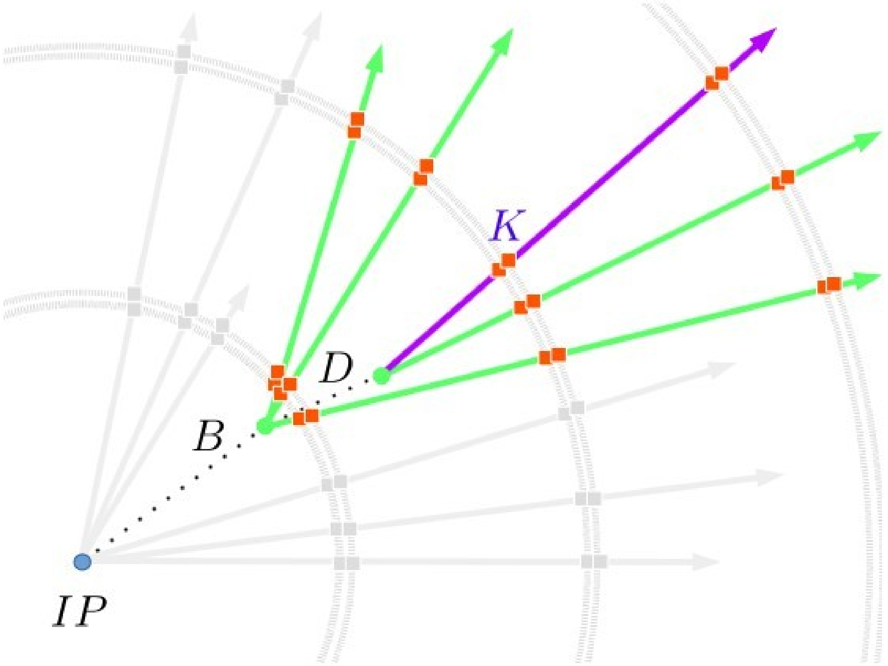
▶ We start from a very pure & background-free **double tagged** sample

▶ We are required to **measure the jet charge**

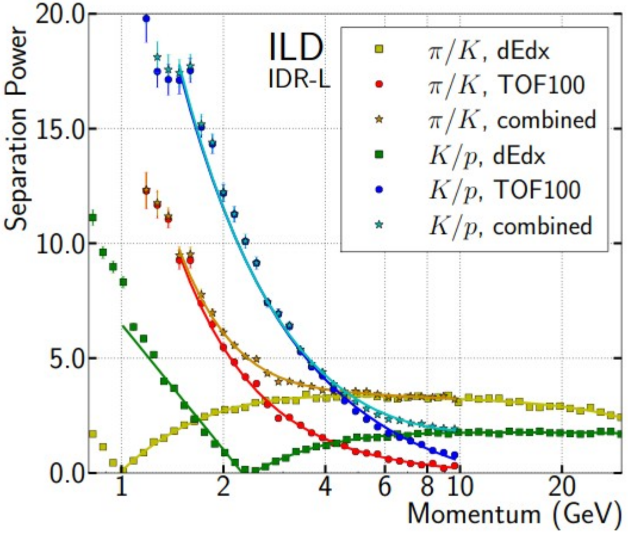
- Using K-ID and/or full Vtx charge measurement
- K-ID is better suited for the C-quark (Vtx is better suited for b-quark)

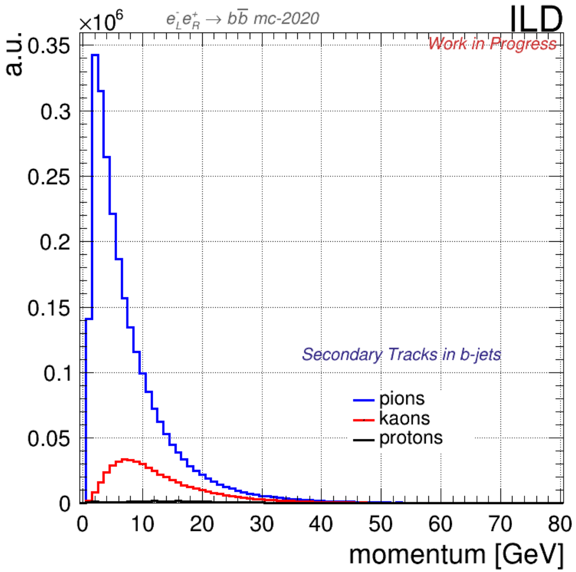
▶ We use the **double charge** measurements

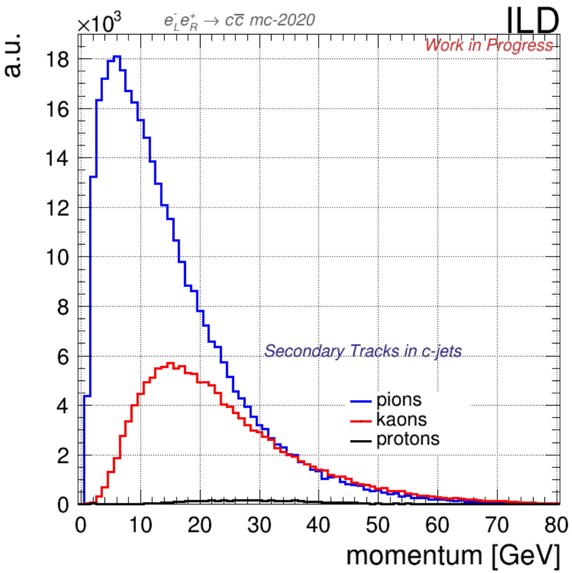
- To control / reduce the systematic uncertainties



High Level Reco Challenges: Particle ID





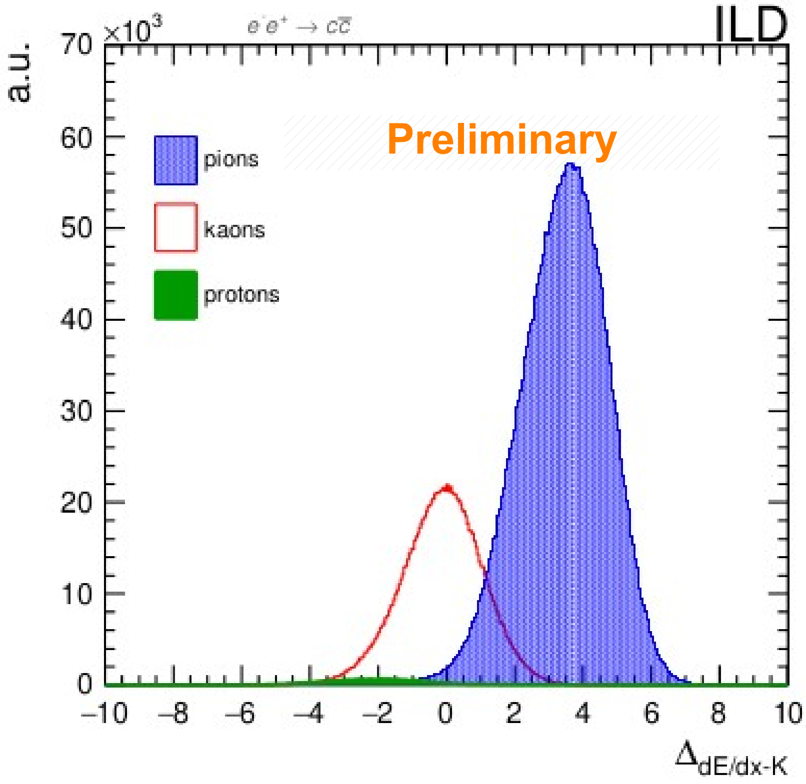


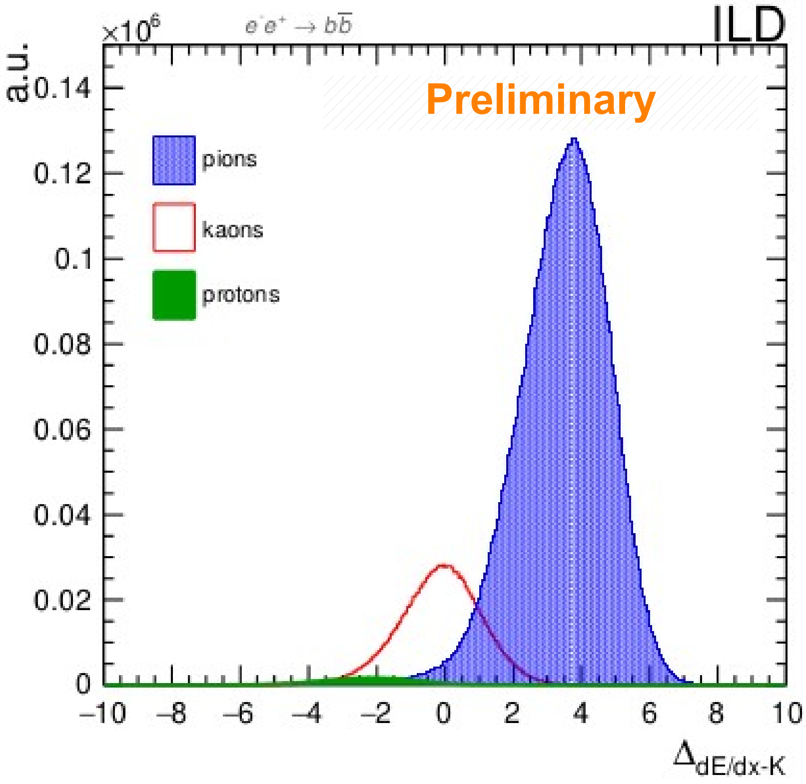
- For AFB measurements we are required to measure the jet-charge
- Therefore we are interested in a high power of K/pion separation
- Possible solutions: using TPC-PID and/or TOF → Yellow points
  - we are interested in “high” momentum tracks (i.e. dEdx!)

Efficiency / Purity of K ID – dEdx

Kaon ID Eff/purity per reconstructed secondary track
Minimizing the dEdx distance with the theory curve

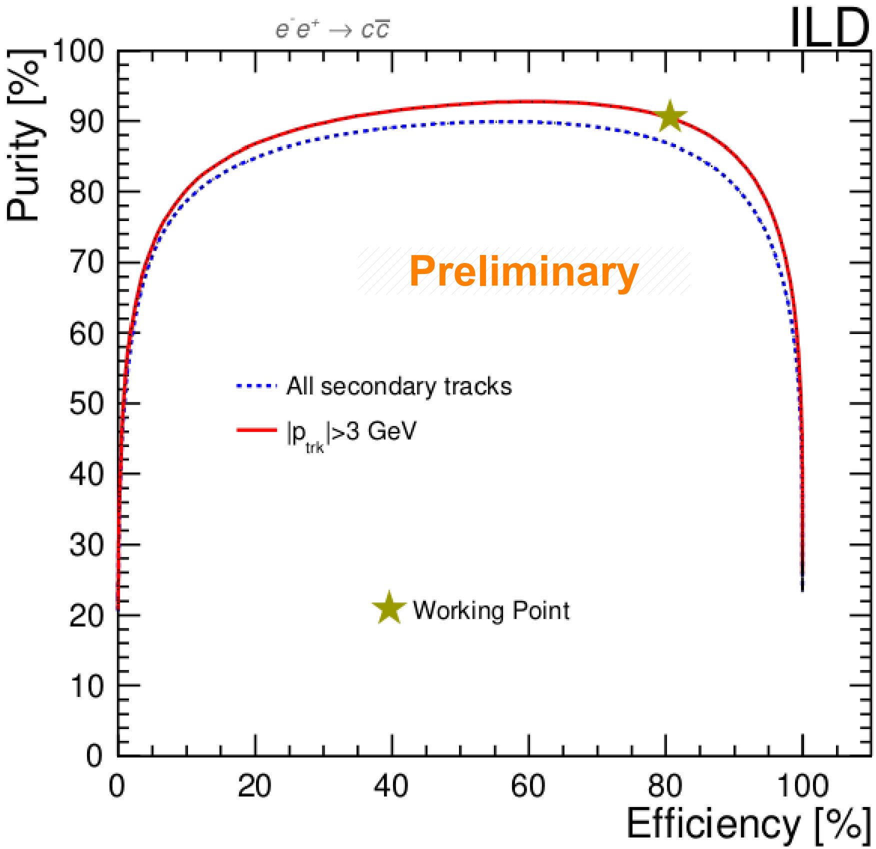
$$\Delta_{dE/dx-K} = \left(\frac{dE/dx_{exp} - dE/dx_{K,BB}}{\Delta dE/dx_{exp}} \right)$$

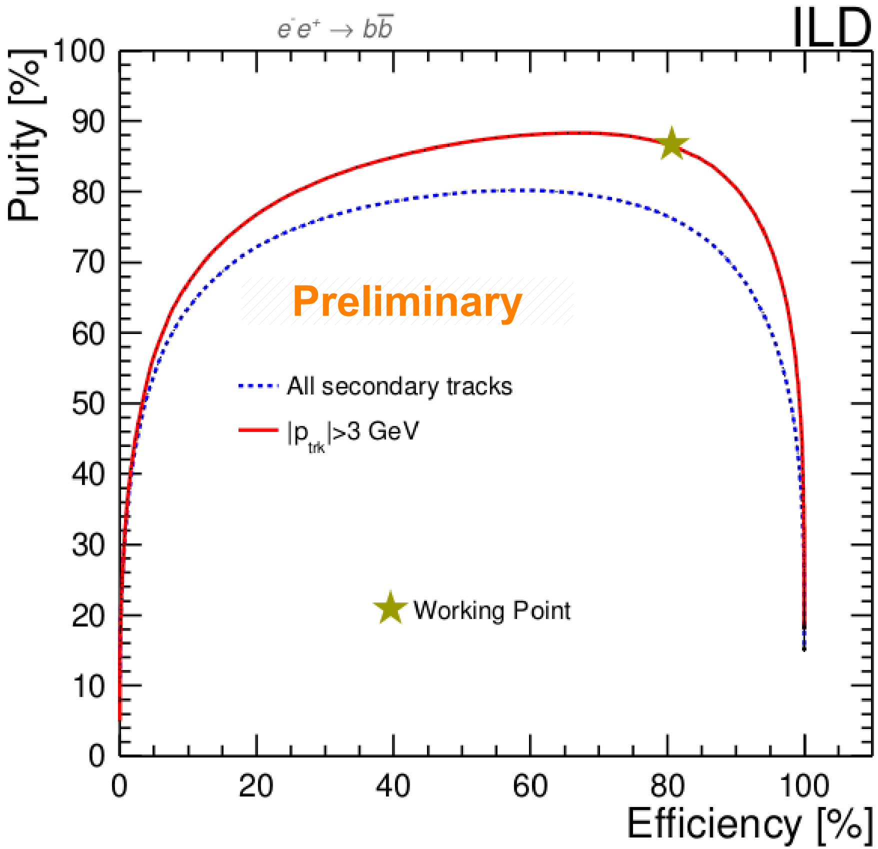




Efficiency / Purity of K ID – dEdx

Kaon ID Eff/purity per reconstructed secondary track
Using a simple template and chi2 minimzation





Double Charge Method

▶ **Double Tag + Double Charge**

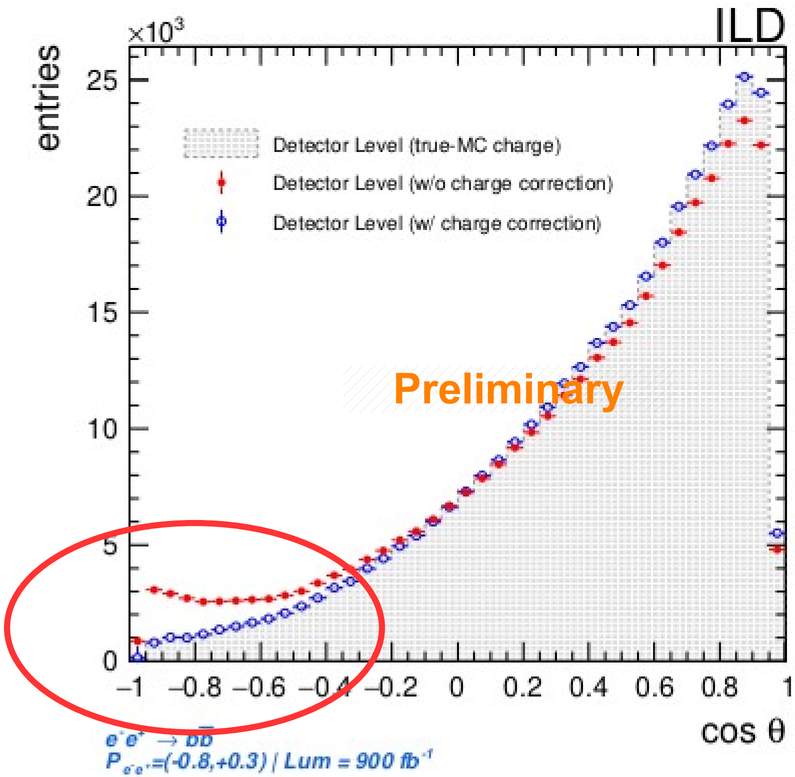
- Both jets need to have a charge measurement compatible with the 2 quarks back to back scenario

▶ Double mistakes are unlikely but still not negligible and lead to “sign flip” → migrations

BSM or simple migrations?

Red shows the distribution withtout sign correction.

Gray is the parton level distribution



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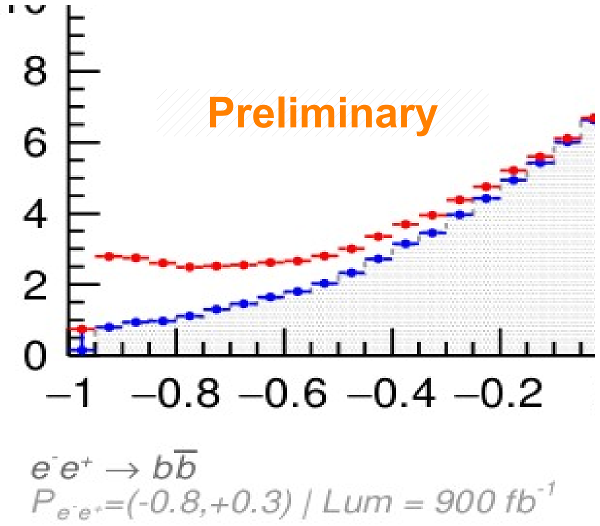
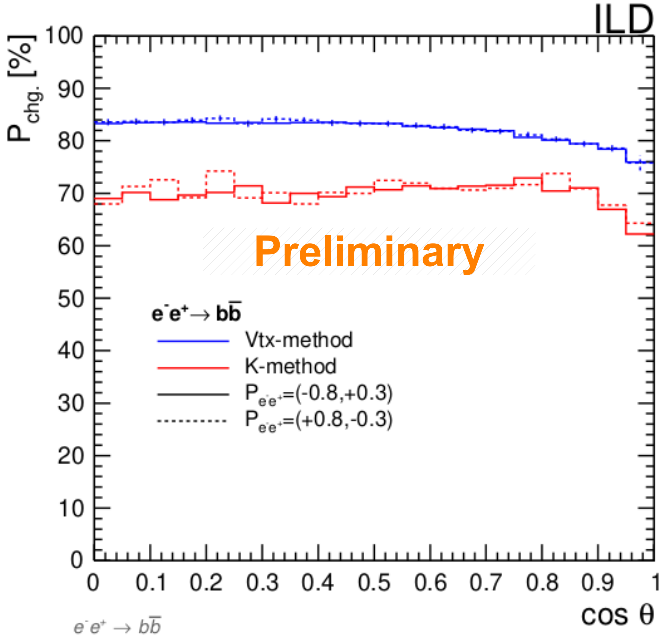
Migration correction

▶ 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 → non sensitive to fragmentation modelling.**



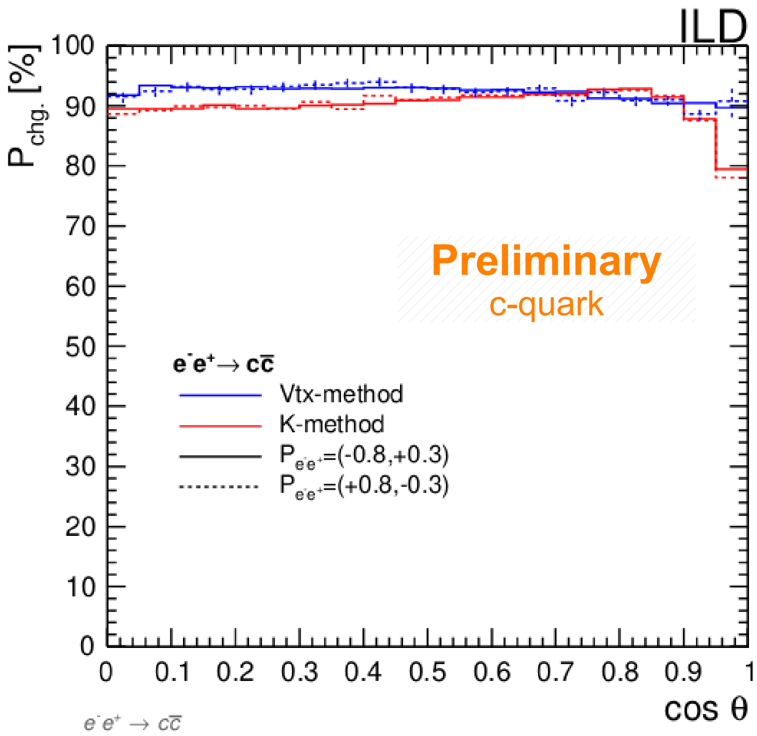


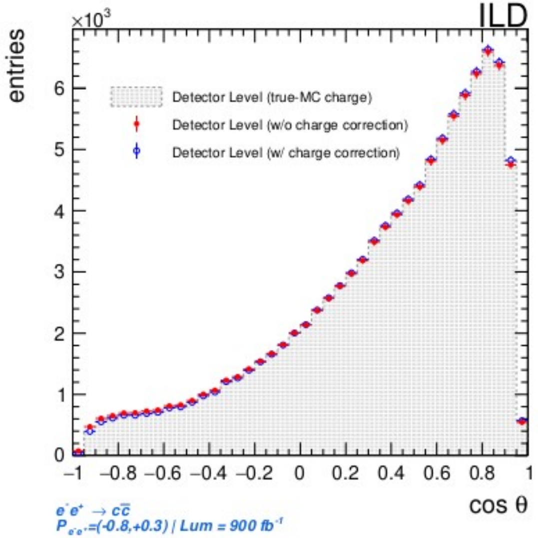
▶ **Pchg limited by vertex reconstruction efficiency, Particle ID efficiency and B0 oscillations** (b-quark case)**.**

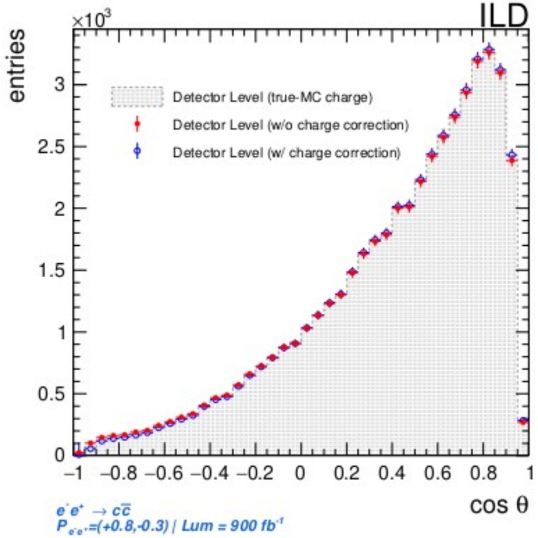
blue shows the distribution after sign correction.

Gray is the parton level distribution

Migration correction – cquark case





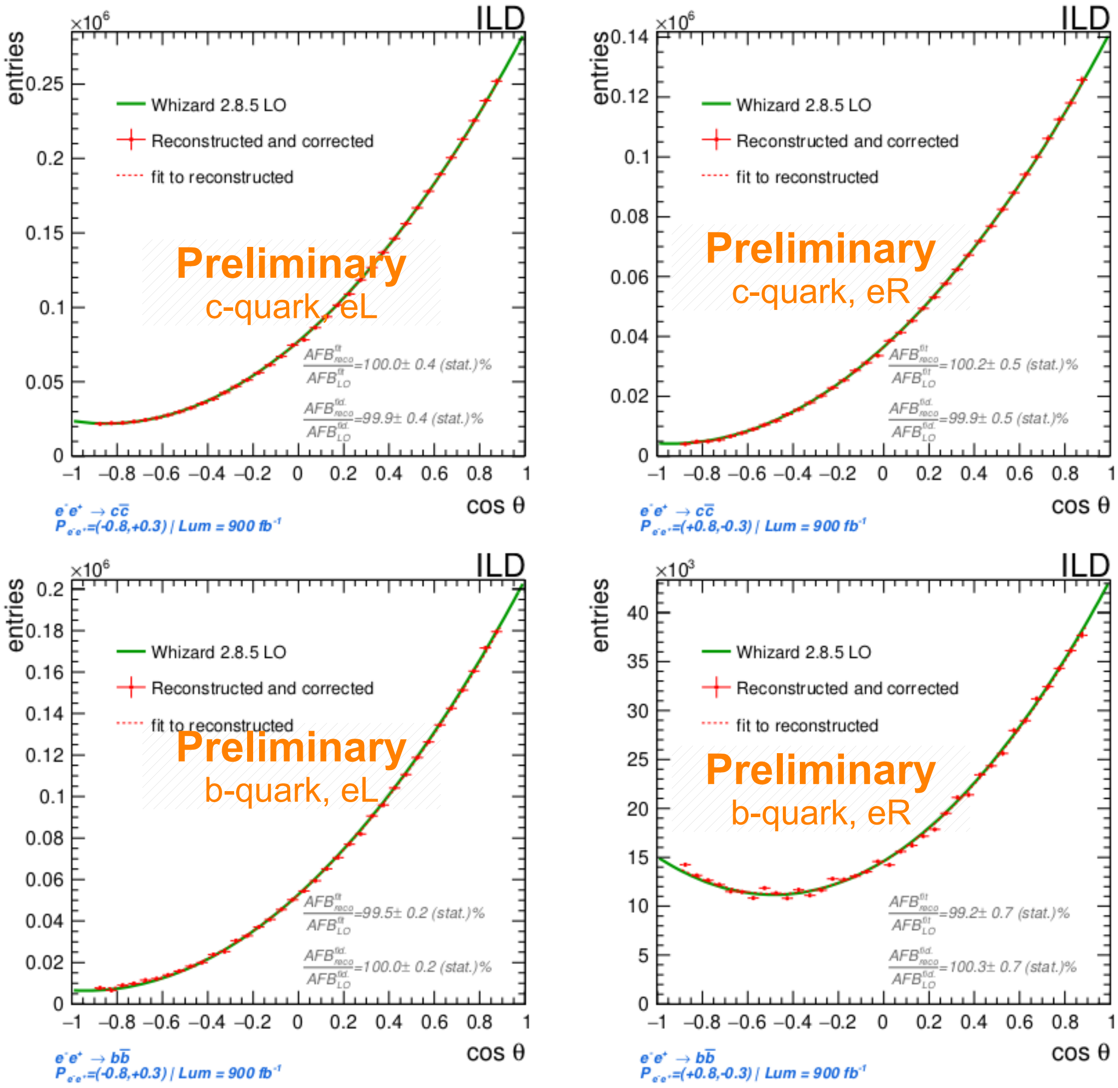


Minimal migration effects (and corrections!)

Result and fit

- Efficiency and charge miscalculation corrections → comparison to parton level
- **At least 4 observables for AFB at ILC250 per energy point**
  - 2 quarks and 2 polarisations (eLpR, eRpL)
- **Per mil level statistical uncertainties** reachable for the nominal **ILC250 program**
- **Comparable/smaller exp syst. Uncertainties**
  - Preselection efficiency (radiative return removal) followed by angular correlations

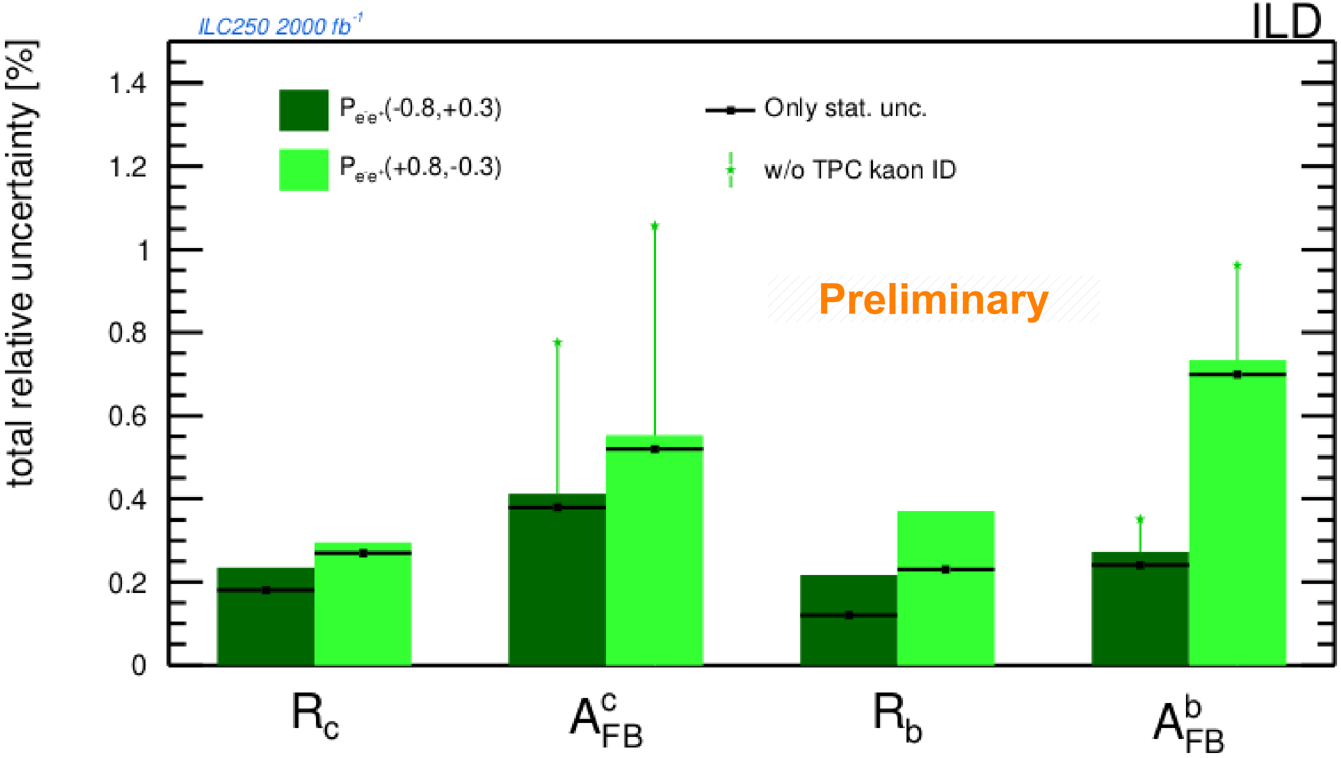
$$\frac{d\sigma}{d\cos\theta} = S \times \left(1+\cos^2\theta\right) + A \times \cos\theta.$$



Results – ILC 250GeV baseline

ILC250

2000fb^{-1}



- **More than one order magnitude improvement over previous experiments**
- **8 observables per energy point**
- **The TPC plays a key rol** (already with the traditional dEdx approach).

Methodology applicable to GigaZ, 500GeV and 1TeV

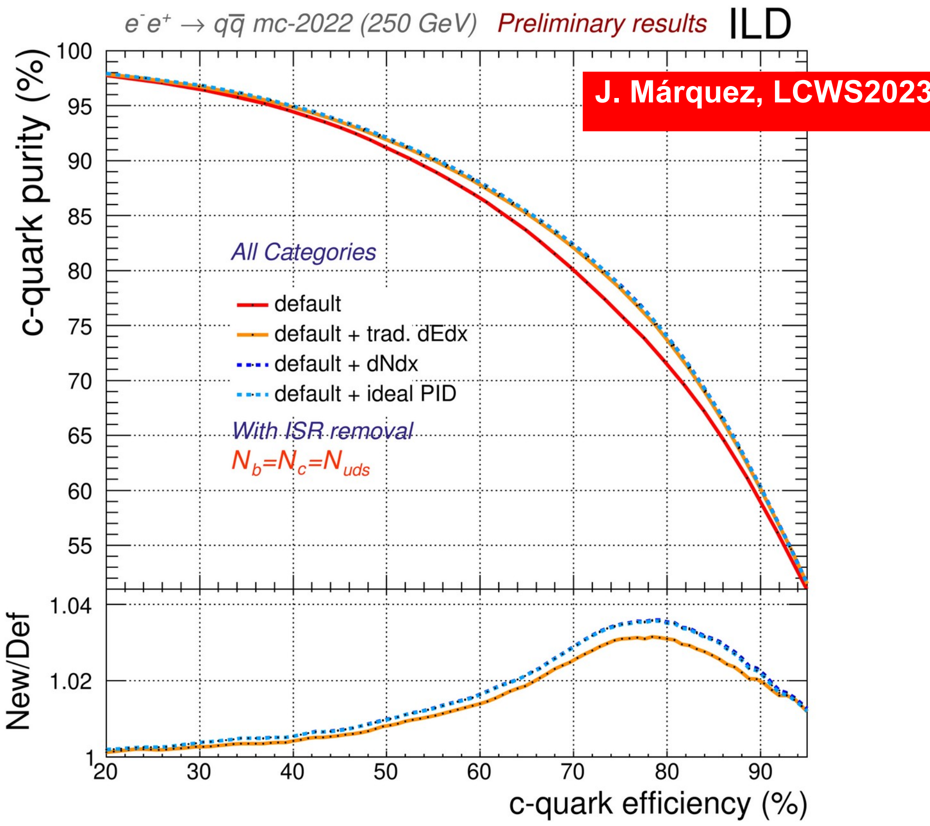
but with almost no radiative return backgrounds at GigaZ

Beyond the ILD note:

exploring the full potential of the TPC-PID

Maximizing the usage of the dEdx

- ▶ In the baseline reconstruction dEdx is only used for the charge measurement
- ▶ We implement an adaptation of the default flavor-tagger of ILD (LCFIPlus) to also use dEdx information
  - Still a “classical” multivariate analysis tool
  - More advanced techniques are being developed (check here)



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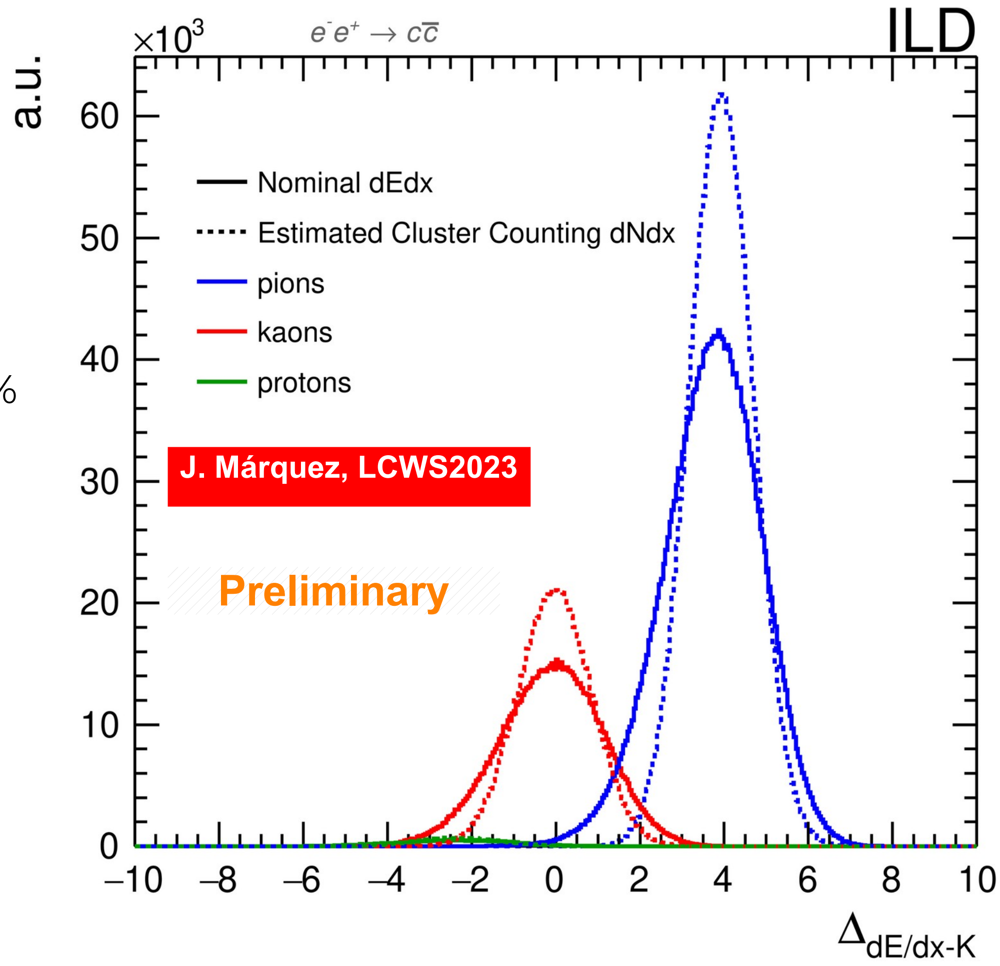
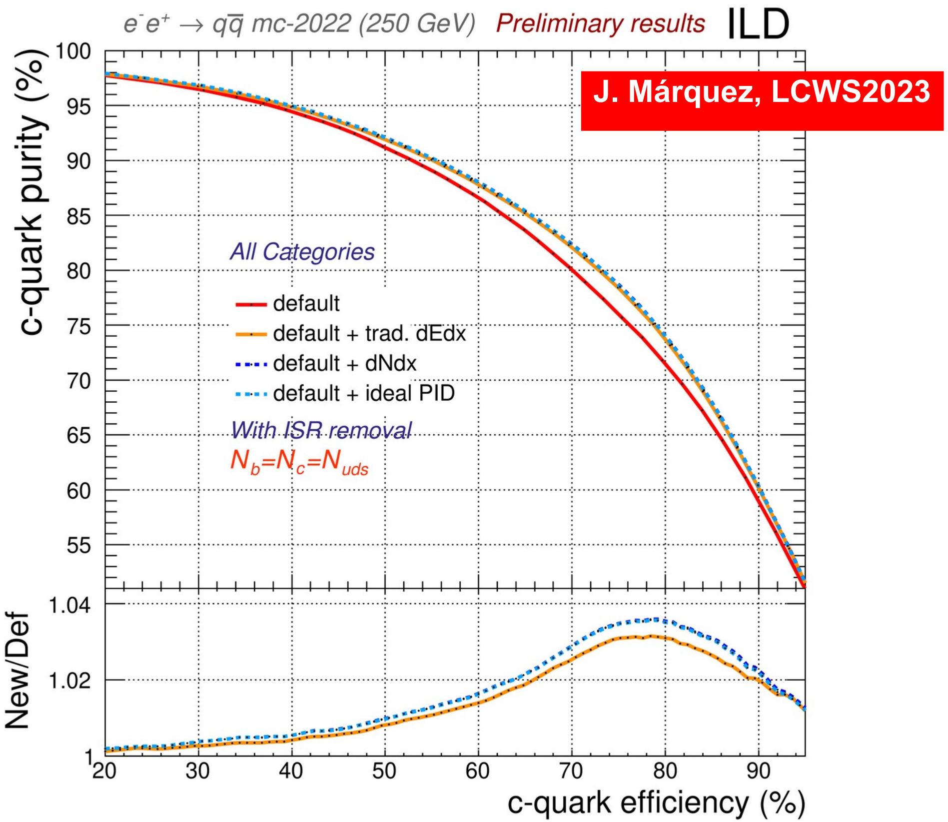
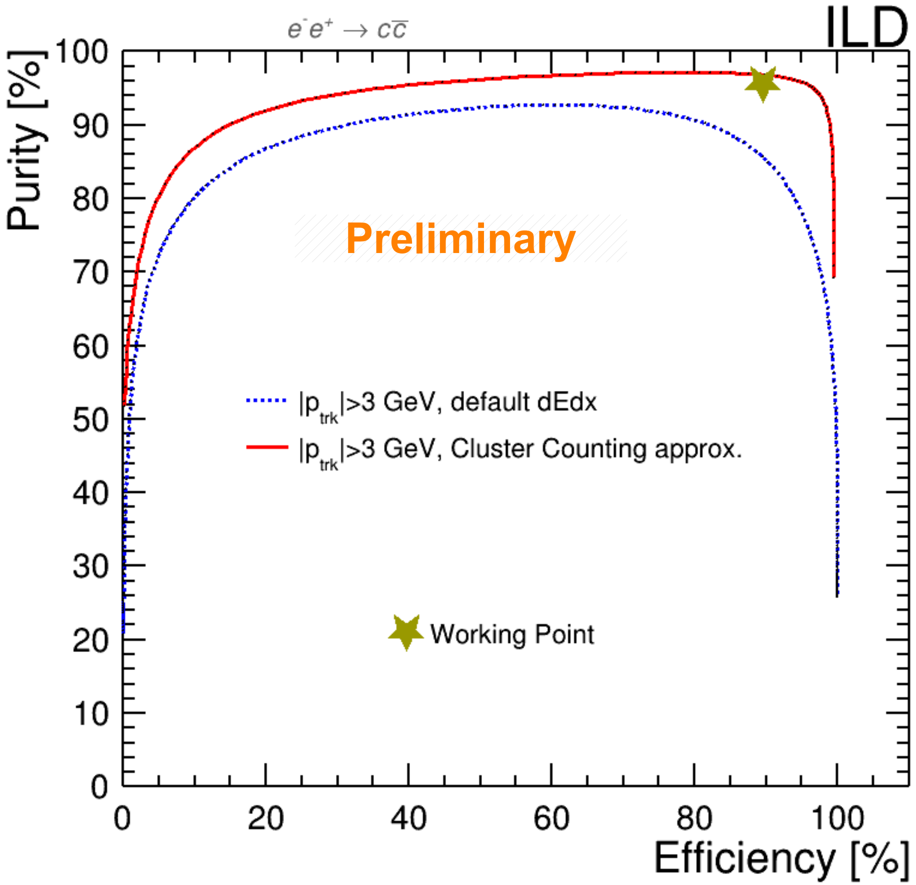
Pixel TPC → from dEdx to dNdx

- ▶ A pixel TPC seems a realistic possibility
  - Check here and here for more info
- ▶ First estimations show that a improvement on the dEdx resolution from ~5 to ~4 % is possible if we use cluster counting (i.e. dNdx)
- ▶ This improvement would translate into a 30-40% improvement of the K/Pi separation
  - Check here for more info
- ▶ dNdx reconstruction is not available in the ILD software (yet)
  - we estimate its impact on the analysis by "artificially" increasing the separation power capabilities of our discrimination variable.

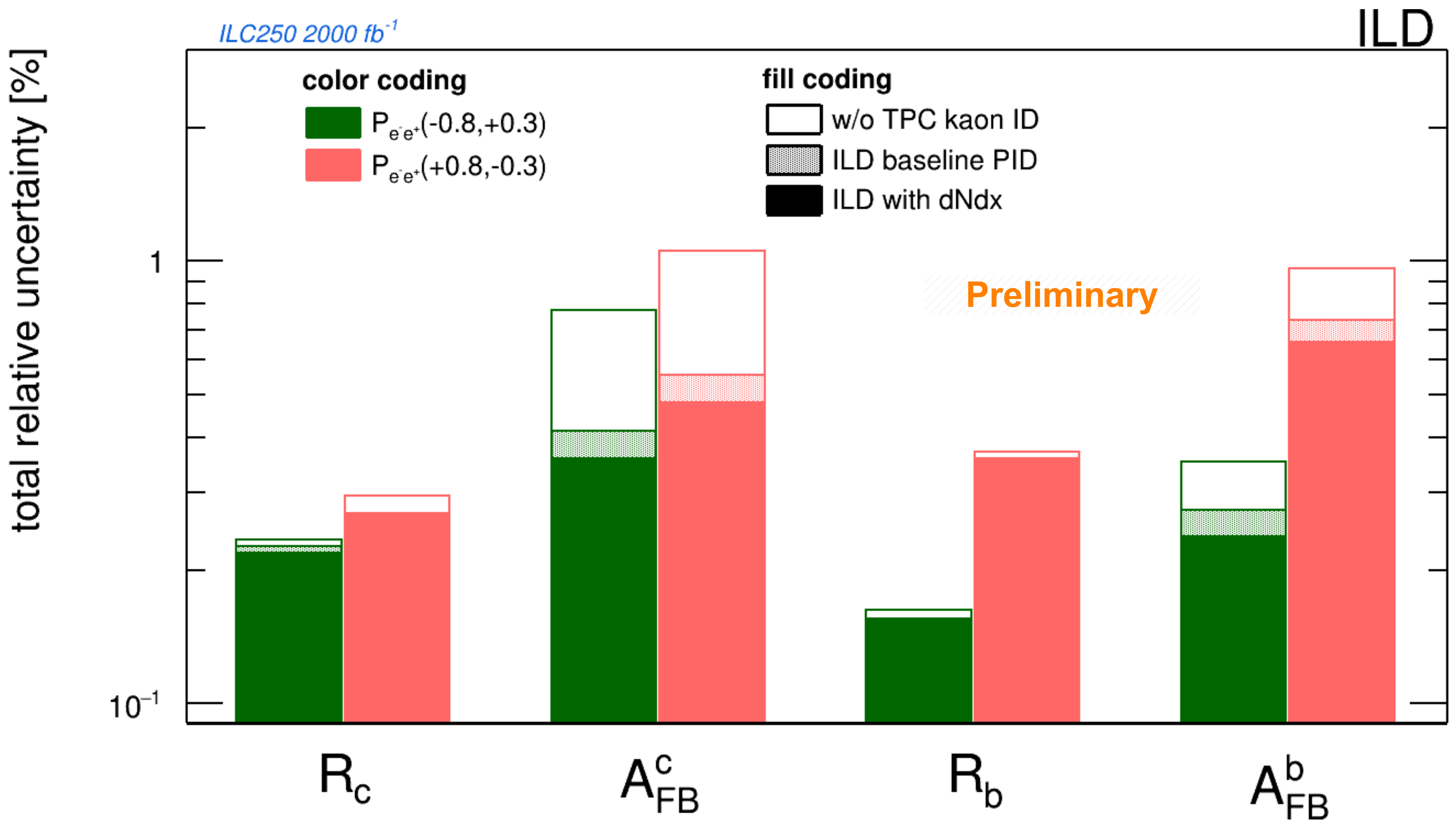


Pixel TPC → from dEdx to dNdx





Potential improvements



Beyond the ILD note:

ILC500GeV

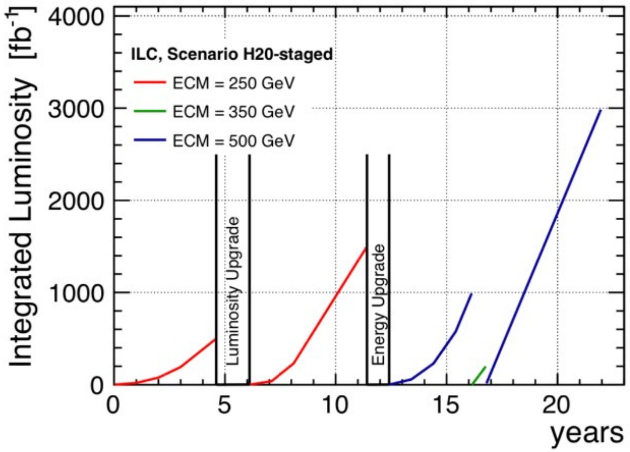
ILC500 GeV

- ▶ The setup of the analysis is the same

(some) Differences:

- ▶ Higher momentum of tracks (including kaons and pions)
  - Worst kaon-pion separation even with dNdx
- ▶ Higher contributions from backgrounds
  - ttbar
  - WW becomes dominant for eRpL
  - This can be solved with appropriate selection cuts tighter on the acolinearity or thrust
  - → from ~70% to ~50% efficency for the preselection

current ILC run plan: (basis of projections)

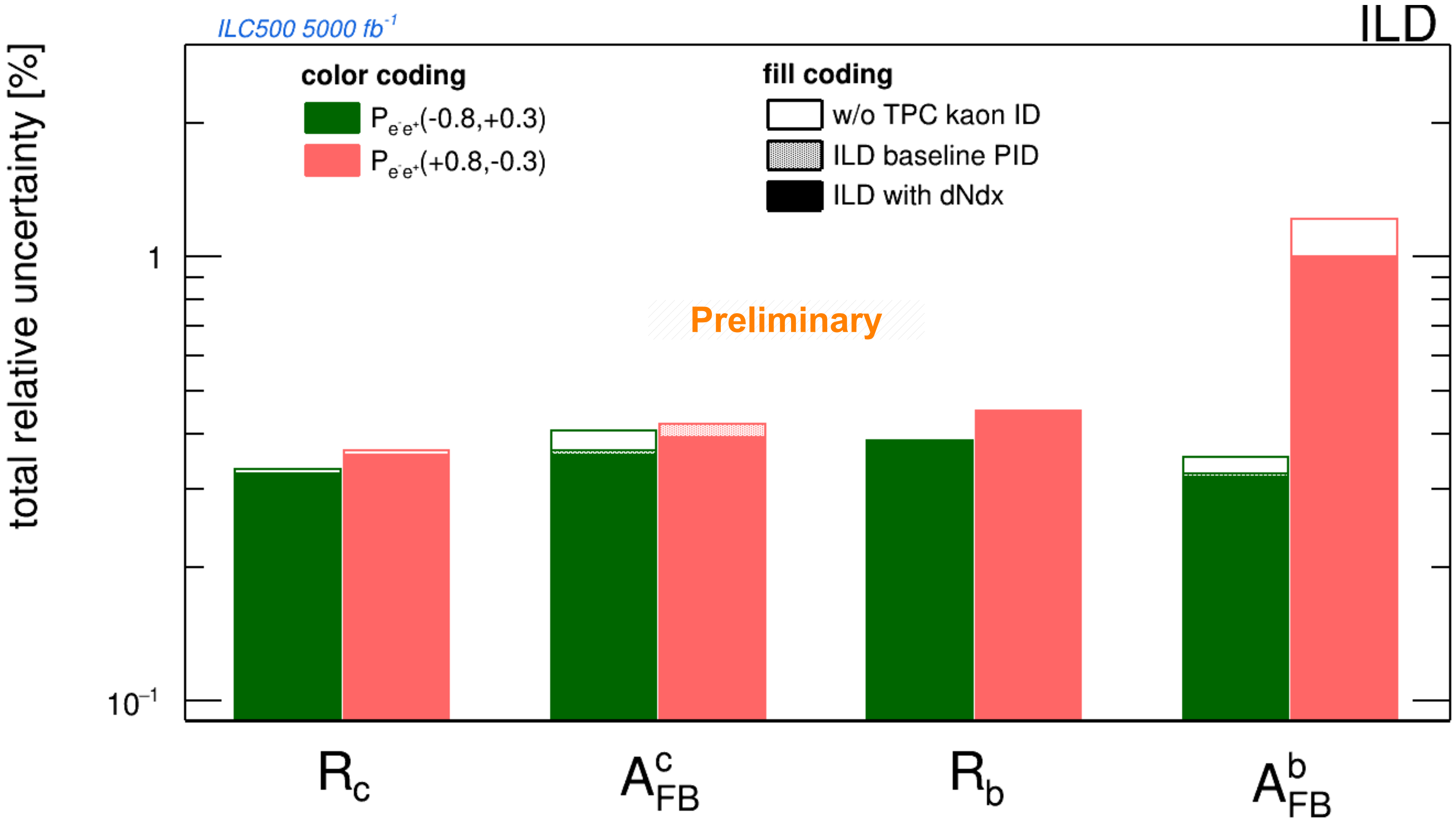


250 GeV: 2 ab-1, 500 GeV: 4ab-1, 350 GeV: 0.2 ab-1

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

ILC500 GeV



ILC500 5000 fb^{-1}
ILD
total relative uncertainty [%]
color coding
$P_{e^-e^+}(-0.8,+0.3)$
$P_{e^-e^+}(+0.8,-0.3)$
fill coding
w/o TPC kaon ID
ILD baseline PID
ILD with dNdx
Preliminary
1
10^{-1}
R_c
A^c_{FB}
R_b
A^b_{FB}

BSM Physics prospects

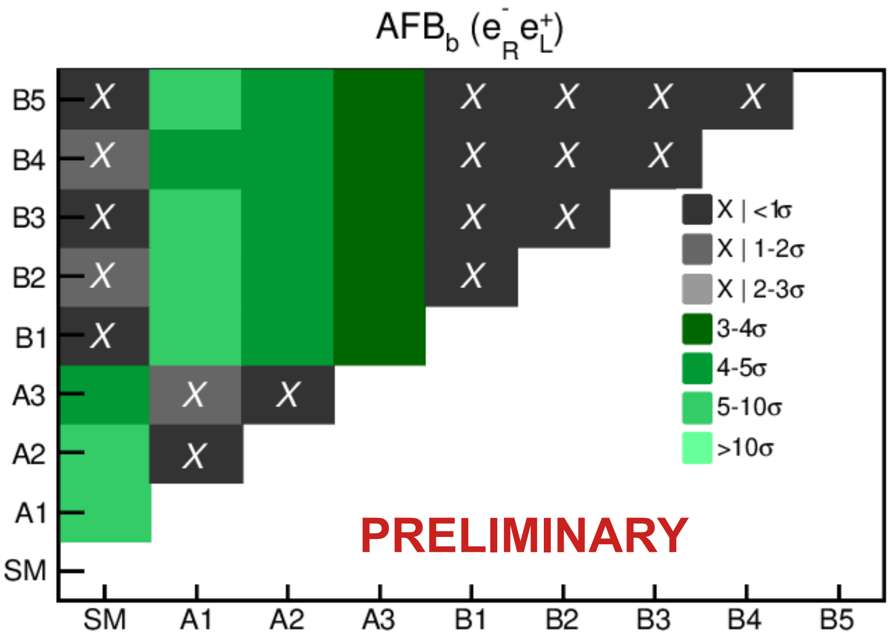
J. Márquez, A.I. et al

Work in progress

Discrimination of BSM Models (only with AFB)

- [Funatsu, Hatanaka, Hosotani, Orikasa, Yamatsu] Models A and B.
- Assumption: A measurement of one specific model is conducted.
  - Row/Column combination for comparison.
- The uncertainties are considered normally distributed
  - Significance in σ
  - P-value: Gaussian at d_σ

$$d_\sigma = \frac{|\text{AFB}_{\text{test}} - \text{AFB}_{\text{ref}}|}{\Delta_{\text{AFB}_{\text{ref}}}}$$



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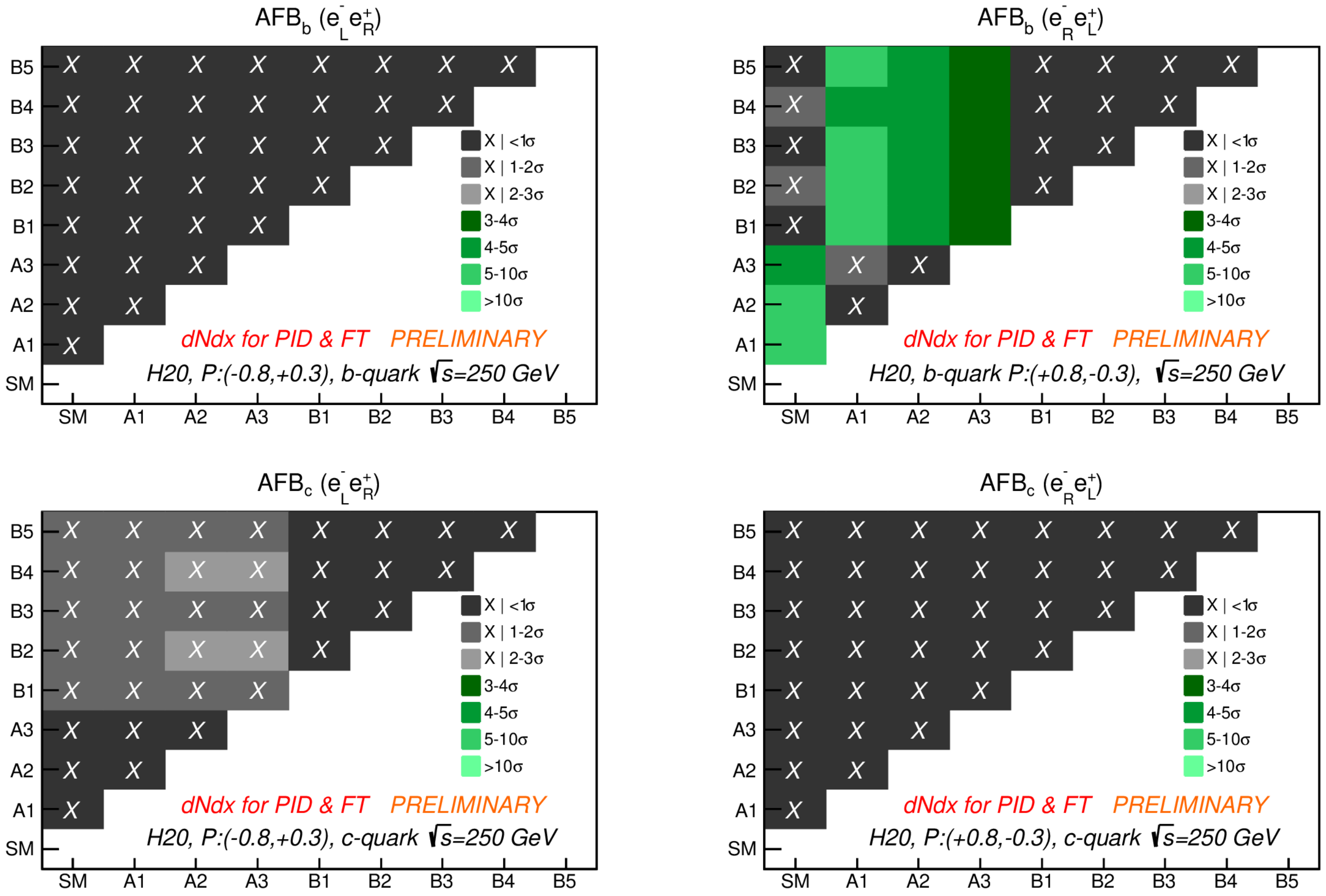
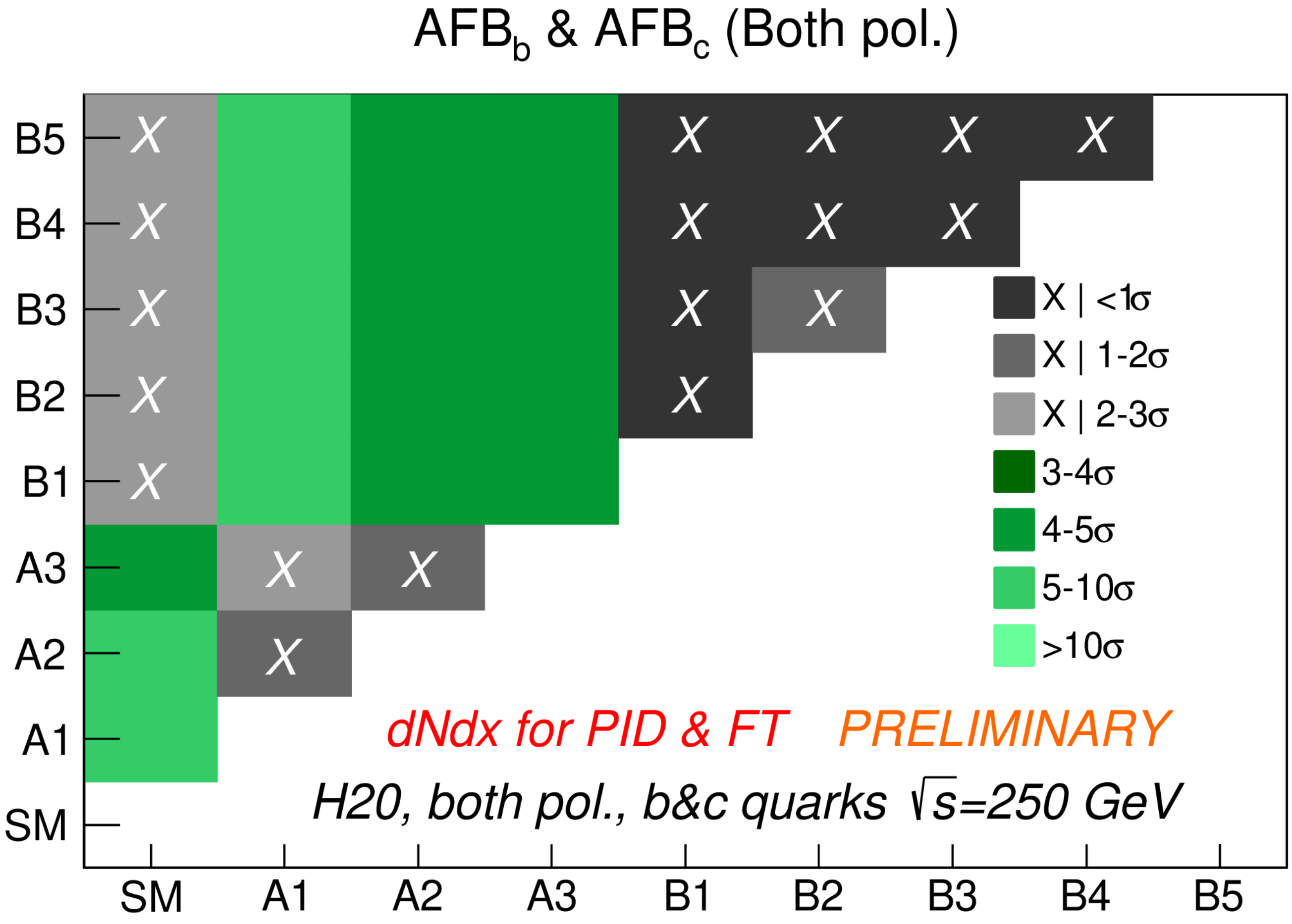
ILC250 with dNdx

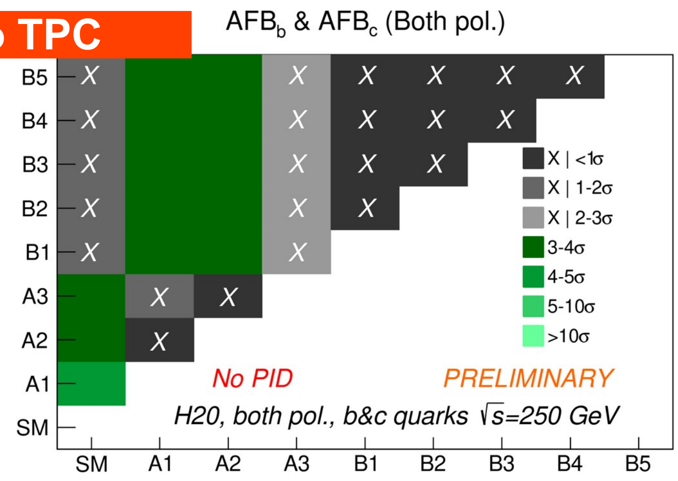


ILC250 with dNdx - combination

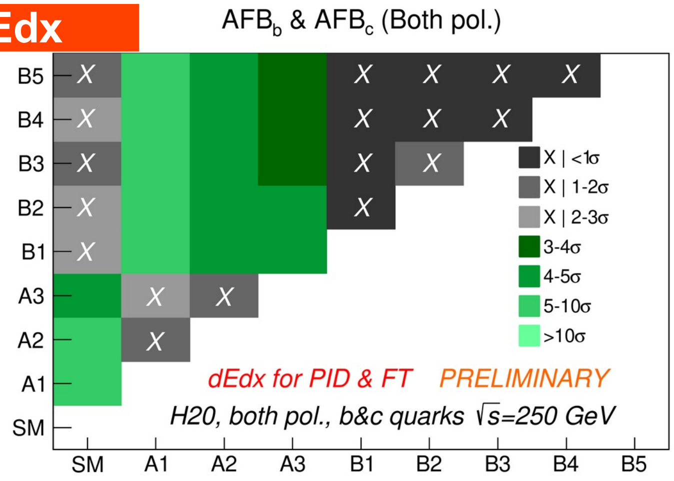


ILC250 TPC importance

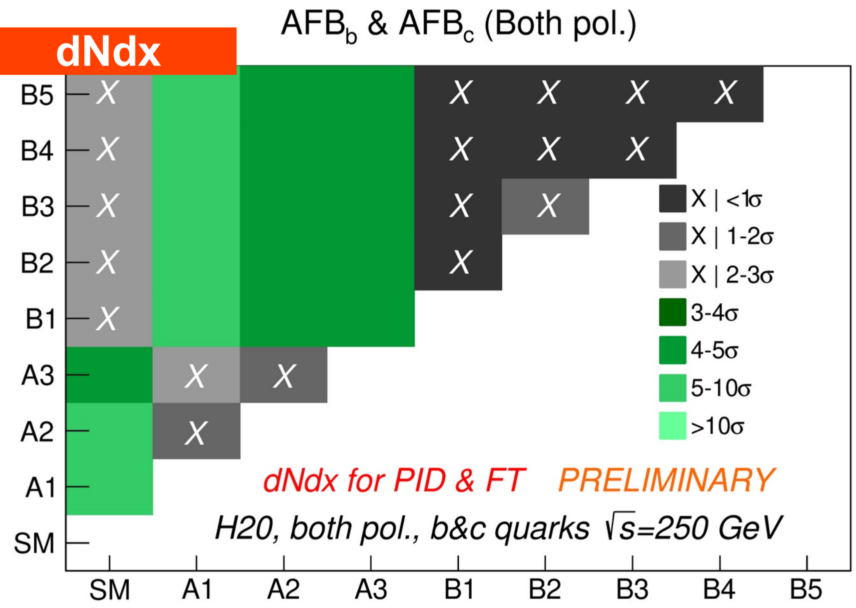
No TPC



dEdx

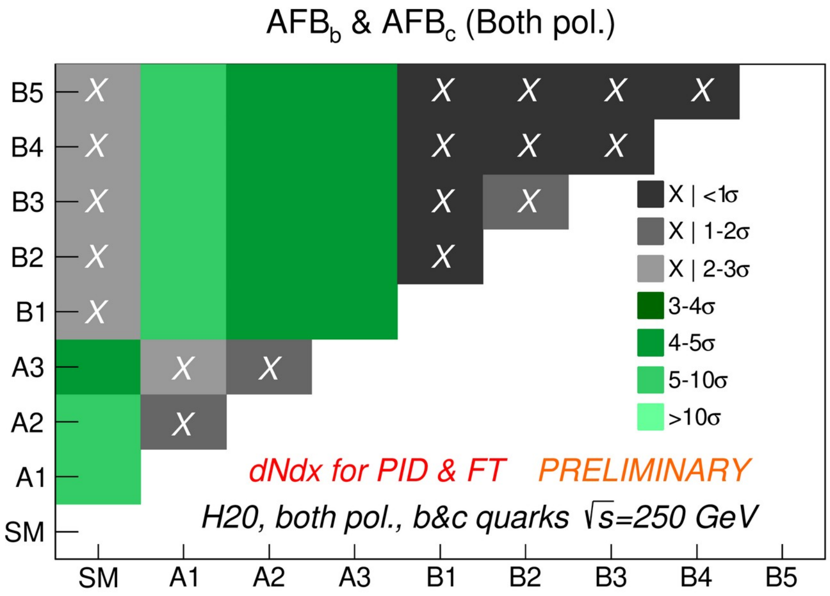


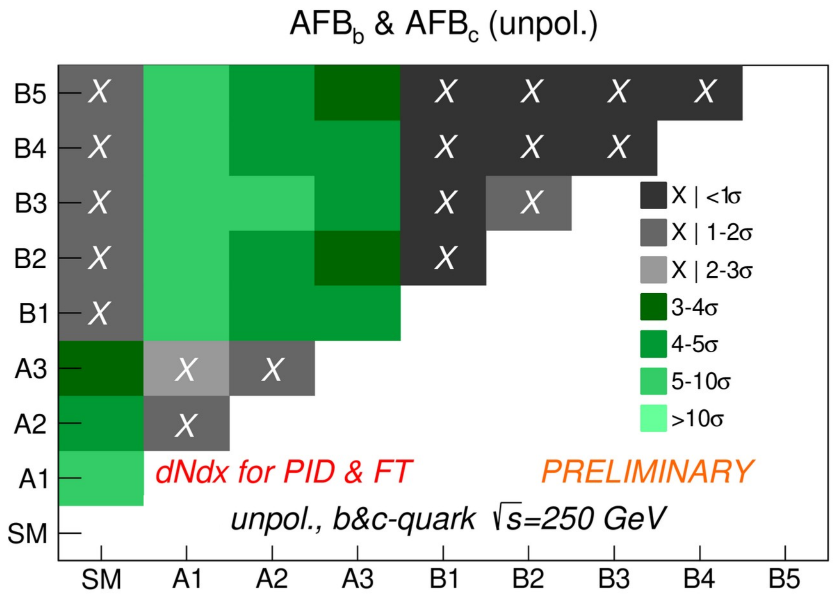
dNdx



only with TPC we can obtain full discrimination between SM and BSM models (and between A & B models)

Polarization importance



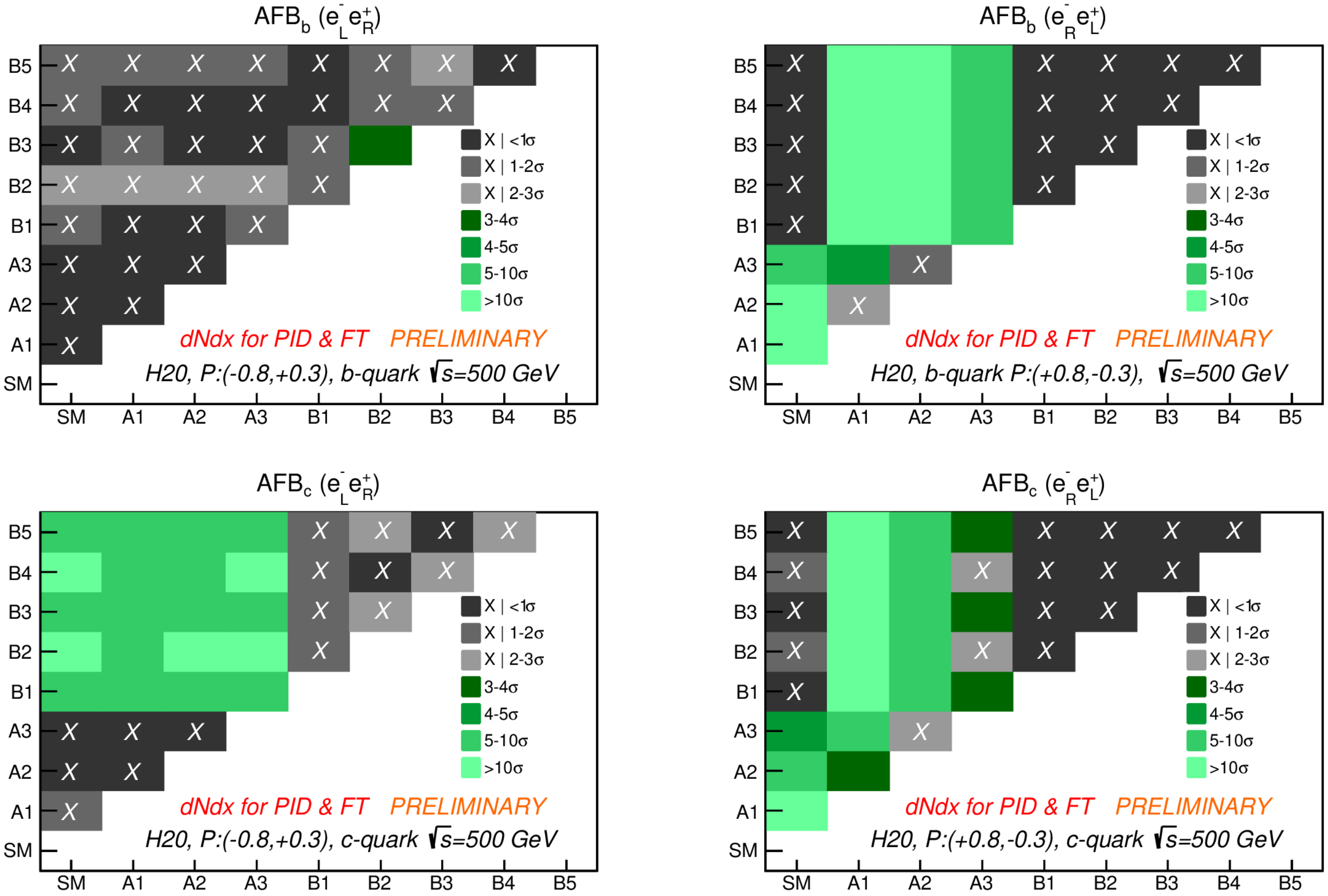


ILC250

5000fb^{-1} no polarisation

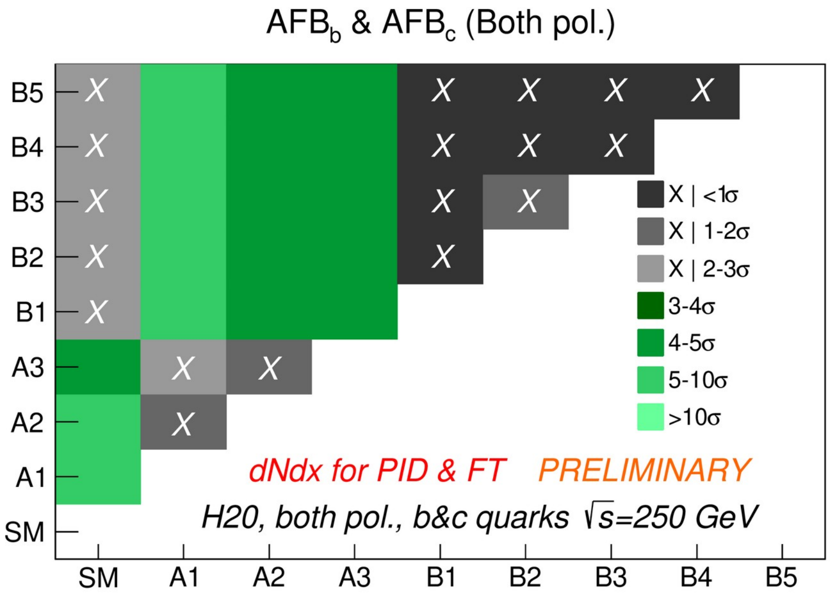
Polarization (over)compensates the extra luminosity

ILC500

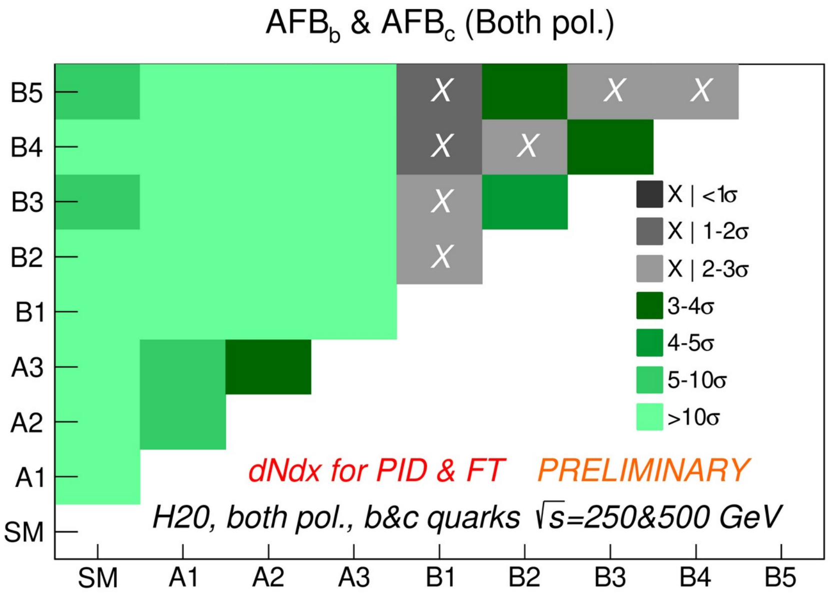


AFB_b (e-_L e+_R)
AFB_b (e-_R e+_L)
AFB_c (e-_L e+_R)
AFB_c (e-_R e+_L)
X | <1σ
X | 1-2σ
X | 2-3σ
3-4σ
4-5σ
5-10σ
>10σ
dNdx for PID & FT PRELIMINARY
H20, P:(-0.8,+0.3), b-quark √s=500 GeV
H20, b-quark P:(+0.8,-0.3), √s=500 GeV
H20, P:(-0.8,+0.3), c-quark √s=500 GeV
H20, P:(+0.8,-0.3), c-quark √s=500 GeV
SM A1 A2 A3 B1 B2 B3 B4 B5

ILC250 & ILC500



ILC250



ILC250&ILC500

We need energy upgradability and beam polarization

Summary

Summary

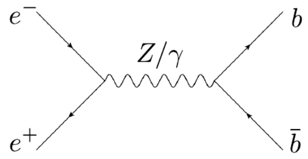
- e+e- → qqbar in the continuum are challenging analysis
  - Require excellent tracking and vertexing, flavour tagging, PID, ...
  - Excellent for detector benchmarking and optimization
- A comprehensive experimental study has been performed
  - With detailed assessment of the major systematic uncertainties (more details in the ILD note to appear soon)
- Requirements for indirect BSM searches (a short list)
  - High kaon/pion separation for tracks above 10GeV (aka pixel TPC)
  - Longitudinal beam polarisation
  - Energy upgradability
- Excellent capabilities for indirect BSM searches
  - Work in progress

thanks

We would like to thank the LCC generator working group and the ILD software working group for providing the simulation and reconstruction tools and producing the Monte Carlo samples used in this study. This work has benefited from computing services provided by the ILC Virtual Organization, supported by the national resource providers of the EGI Federation and the Open Science GRID

Back-up slides

Two fermion processes at ILC



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

$$\frac{d\sigma_{e^-_L e^+_R \to q\bar{q}}}{d\cos\theta_q} = \frac{s}{32\pi}\left[(1+\cos\theta_q)^2|Q_{e_L q_L}|^2 + (1-\cos\theta_q)^2|Q_{e_L q_R}|^2\right]$$

$$\frac{d\sigma_{e^-_R e^+_L \to q\bar{q}}}{d\cos\theta_q} = \frac{s}{32\pi}\left[(1+\cos\theta_q)^2|Q_{e_R q_R}|^2 + (1-\cos\theta_q)^2|Q_{e_R q_L}|^2\right]$$

$$Q_{e_X q_Y} \equiv \sum_i \frac{g^X_{V_i e} g^Y_{V_i q}}{(s - m^2_{V_i}) + i m_{V_i}\Gamma_{V_i}}$$

- The helicity amplitudes Q_{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**

$$\frac{d\sigma_{e^- e^+ \to q\bar{q}}}{d\cos\theta_q}(P_{e^-}, P_{e^+}, \cos\theta_q) = (1 - P_{e^-}P_{e^+})\frac{1}{4}\left[(1-P_{eff})\frac{d\sigma_{e^-_L e^+_R \to q\bar{q}}}{d\cos\theta_q} + (1+P_{eff})\frac{d\sigma_{e^-_R e^+_L \to q\bar{q}}}{d\cos\theta_q}\right]$$

$$P_{eff} \equiv \frac{P_{e^-} - P_{e^+}}{1 - P_{e^-} \cdot P_{e^+}}$$

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GHU models [Hos et al]

A models

Table 1: Masses and widths of Z' bosons, $Z^{(1)}$, $\gamma^{(1)}$, and $Z_R^{(1)}$ ($N_F = 4$)

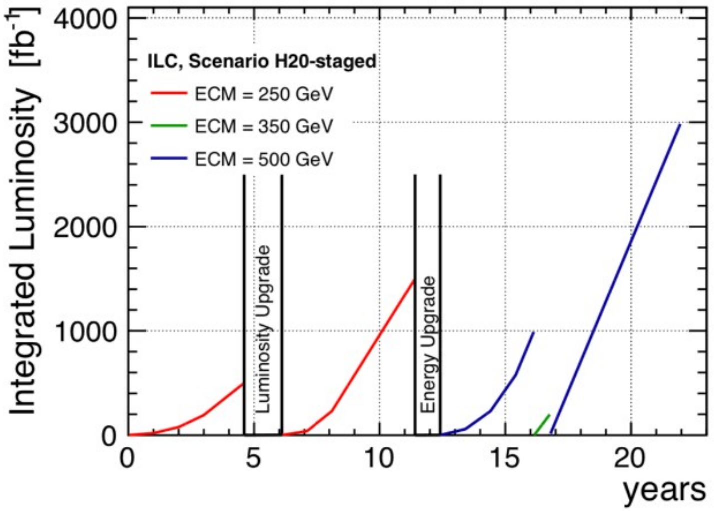
θ_H [rad.]	$\frac{z_L}{10^4}$	m_{KK} [TeV]	$m_{Z^{(1)}}$ [TeV]	$\Gamma_{Z^{(1)}}$ [GeV]	$m_{\gamma^{(1)}}$ [TeV]	$\Gamma_{\gamma^{(1)}}$ [GeV]	$m_{Z_R^{(1)}}$ [TeV]	$\Gamma_{Z_R^{(1)}}$ [GeV]
0.115	10	7.41	6.00	406	6.01	909	5.67	729
0.0917	3	8.81	7.19	467	7.20	992	6.74	853
0.0737	1	10.3	8.52	564	8.52	1068	7.92	1058

ILC physics program

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

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

current ILC run plan: (basis of projections)



250 GeV: 2 ab-1, 500 GeV: 4ab-1, 350 GeV: 0.2 ab-1

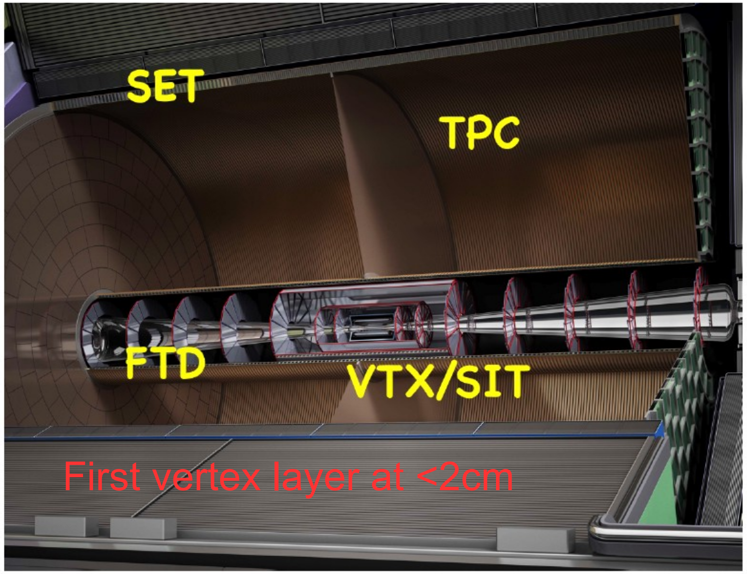
also, runs at 91 GeV (5B Z's) and 1000 GeV (8 ab-1)

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

Access to e+e- → $f\bar{f}$ at 91, 250, 500 and 1000 TeV and 4 different beam polarisation conditions

ILD highlights

▶ ILD snapshot



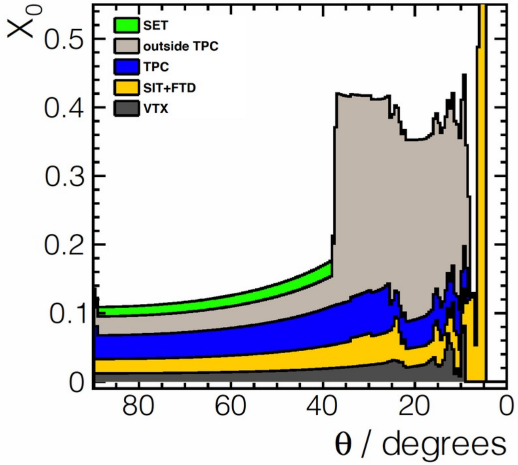
▶ **High** angular **coverage** with **minimum material budget** and **PID (TPC)**

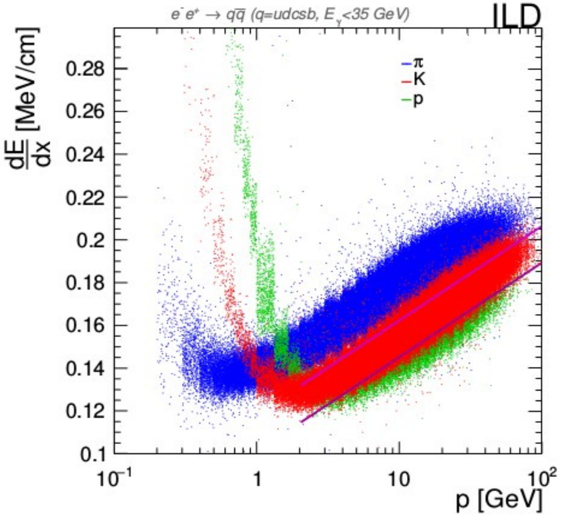
▶ **Linear Colliders favour tiny beam spots**

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

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

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





ILD: Interim Design Report arXiv:2003.01116

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(few) Experimental challenges

- **C-quark pairs**
- High efficient **flavour tagging** for c-quarks expected at future colliders
- **Charge measurement**
  - **Primary method:** identification of Kaons produced D-meson decays → **K-method (requires PID)**
  - **Secondary method:** reconstruction of charged mesons → **Vtx-method**

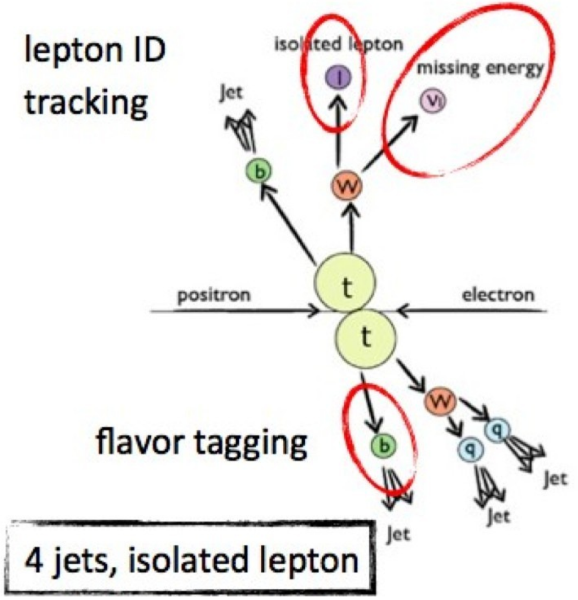
<u>PID is mandatory</u> to reach competitive ac curacies

- **B-quark pairs**
- High efficient **flavour tagging** for b-quarks expected at future colliders
- **Charge Measurement**
  - **Primary method:** reconstruction of charged mesons → **Vtx-method**
  - **Secondary method:** identification of Kaons produced in b-hadron decays → **K-method (requires PID)**

<u>PID is very useful</u>

Other approaches involving final state leptons are not studied here

- **top-quark pairs… decay before hadronising**



Not covered here but in the poster session

- **s-quark pairs**
  - Search of **two high energy kaons back to back and with opposed charges.**
    <u>PID is mandatory</u> to have a measurement
  - General flavour tagging requires optimized tools (including charged kaon identification) → ML, DNN , etc See talk by T. Suehara

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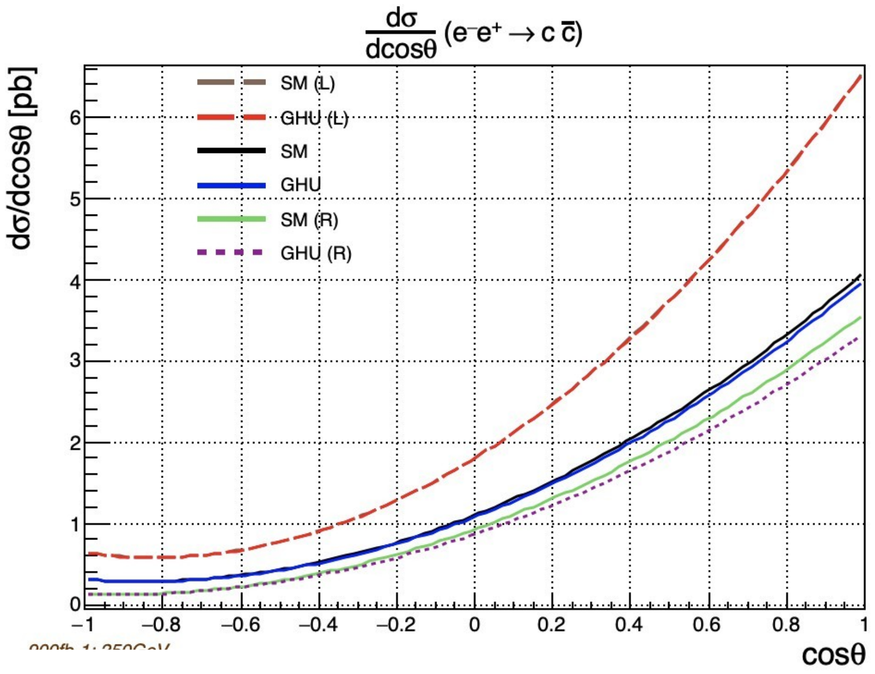
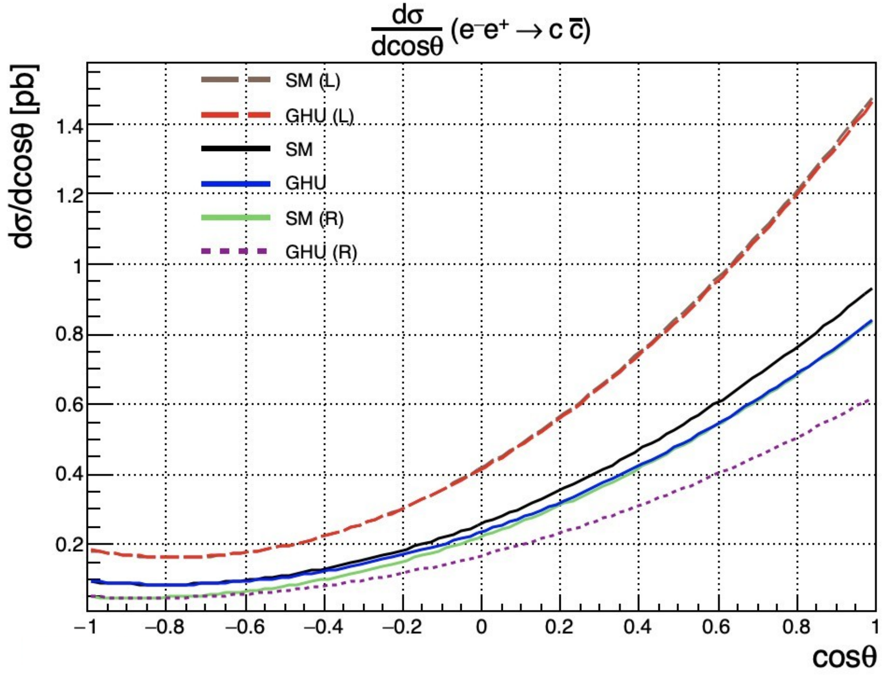
Motivation

- ▶ qqbar production in the continuum (no return to the Z-pole)
- ▶ Many models that predict visible deviations at 250GeV, predict larger deviations at higher energies.

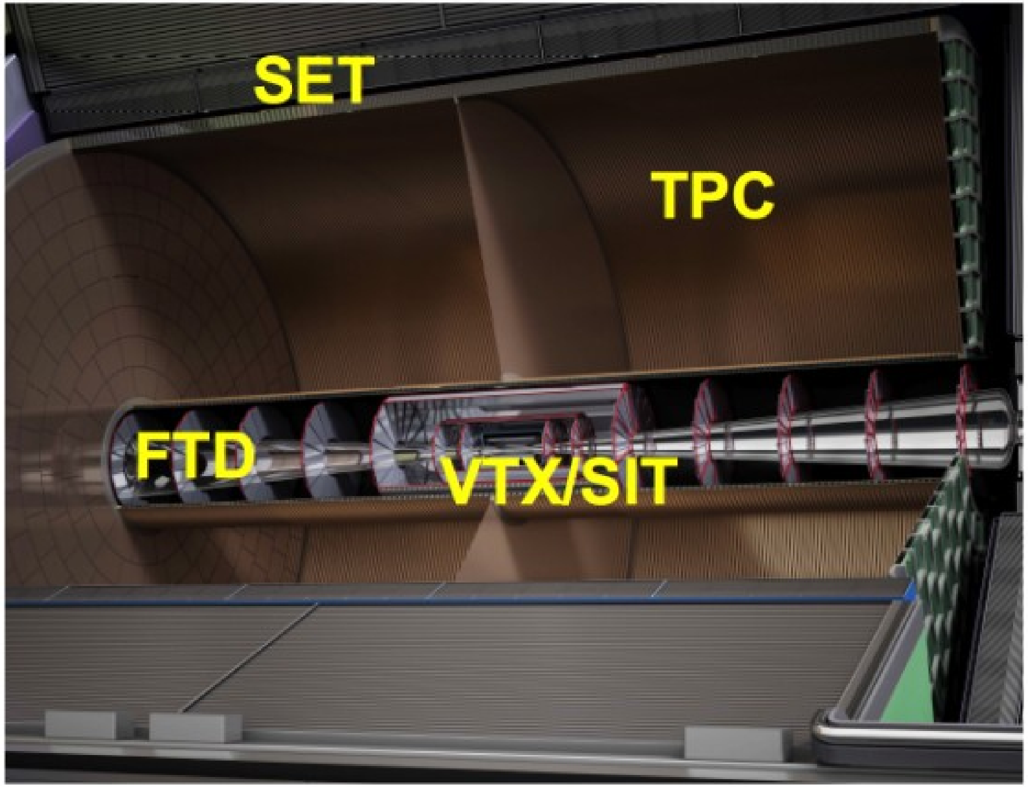




[ref] Shuichiro Funatsu, Hisaki Hatanaka, Yutaka Hosotani, and Yuta Orikasa. Phys. Lett. B, 775:297–302, 2017.

The ILD tracking system

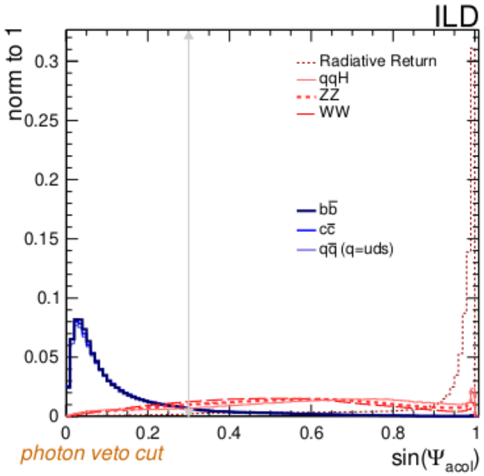
as implemented in the simulation



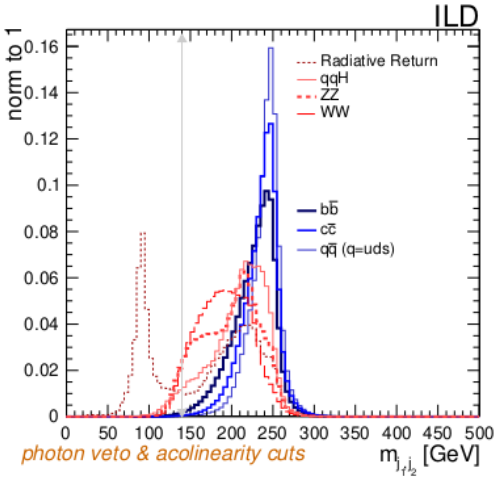
Subdetector			Point Resolution
VTX	$\sigma_{r\phi,z}$	=	3.0 µm (layers 1-6)
SIT	$\sigma_{r\phi,z}$	=	7.0 µm(layers 1-4)
SET	σ_{α_z}	=	7.0 µm(layers 1-2)
	α_z	=	$\pm 7\,^\circ$ (angle with z-axis)
FTD	σ_r	=	3.0 µm(layers 1-2)
Pixel	$\sigma_{r_\perp}$	=	3.0 µm
FTD	σ_{α_r}	=	7.0 µm(layers 3-7)
Strip	α_r	=	$\pm 5\,^\circ$ (angle with radial direction)
TPC	$\sigma^2_{r\phi}$	=	$(50^2 + 900^2 \sin^2\phi + ((25^2/22)\times (4\ \mathrm{T/B})^2 \sin\theta)(z/\mathrm{cm}))\ \mu\mathrm{m}^2$
	σ^2_z	=	$(400^2 + 80^2 \times (z/\mathrm{cm}))\ \mu\mathrm{m}^2$
			where ϕ and θ are the azimuthal and polar angle of the track direction

from: International Large Detector: Interim Design Report
The ILD Collaboration, arXiv:2003.01116

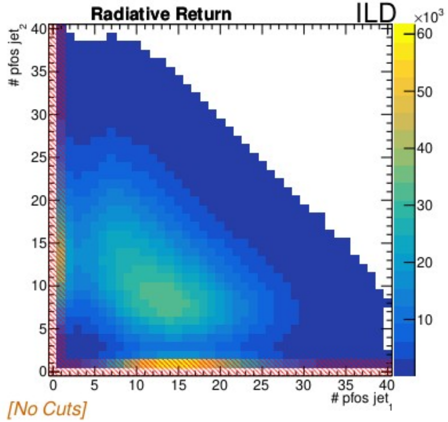
Analysis chain: preselection -bk1



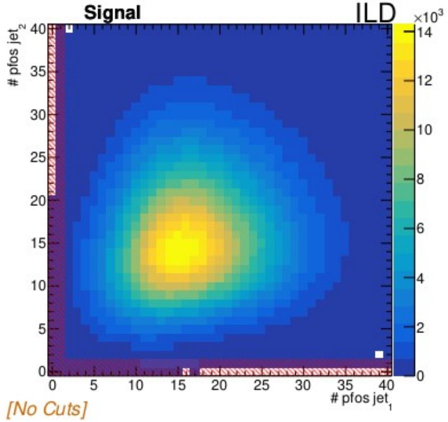
photon veto cut



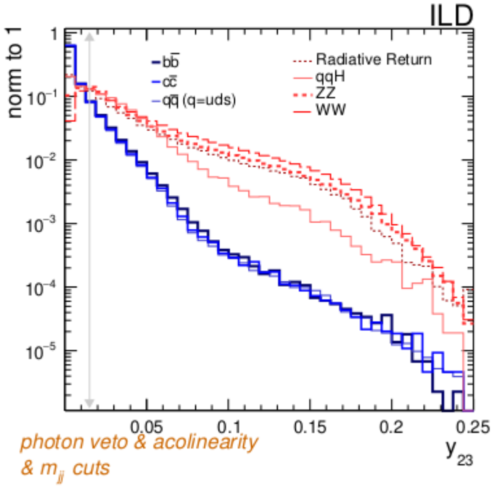
photon veto & acolinearity cuts



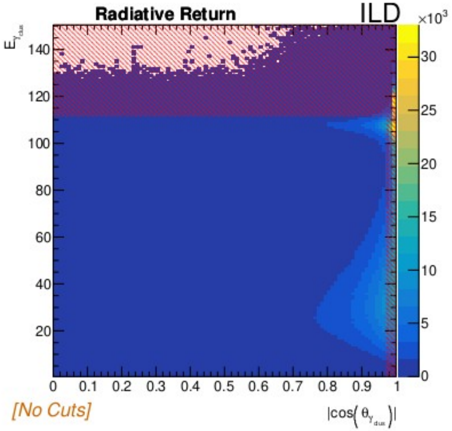
[No Cuts]



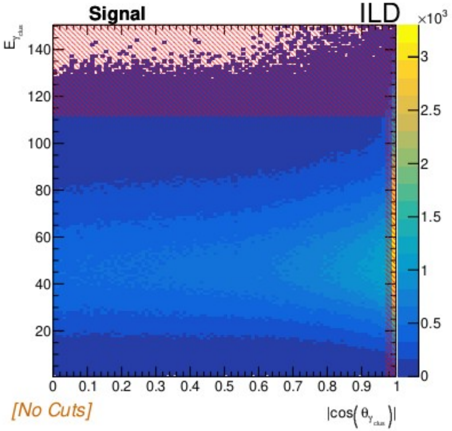
[No Cuts]



photon veto & acolinearity & m_{jj} cuts



[No Cuts]



[No Cuts]

Analysis chain: preselection -bk2

Polarisation	$\sigma_{e^- e^+ \to q\bar{q}}$[fb]			Radiative Return BKG [fb]		
	$b\bar{b}$	$c\bar{c}$	$q\bar{q}$ $(q = uds)$	$b\bar{b}$	$c\bar{c}$	$q\bar{q}$ $(q = uds)$
$e_L^- e_R^+$	4894.4	7068.1	16817.1	21087.0	18865.1	59227.7
$e_R^- e_L^+$	1087.4	3006.9	5153.3	12872.4	11886.2	36410.3

Table 1: Production cross section of the background originated by di-boson production.

Channel	$\sigma_{e_L^- e_R^+ \to X}$ [fb]	$\sigma_{e_R^- e_L^+ \to X}$ [fb]
$X = WW \to q_1\bar{q}_2q_3\bar{q}_4$	14866.4	136.8
$X = ZZ \to q_1\bar{q}_1q_2\bar{q}_2$	1405.1	606.7
$X = HZ \to q\bar{q}H$	343.0	219.5

Table 2: Cross sections at 250 GeV for processes producing at least one pair of q-quarks using fully polarised beams.

Analysis chain: preselection -bk2

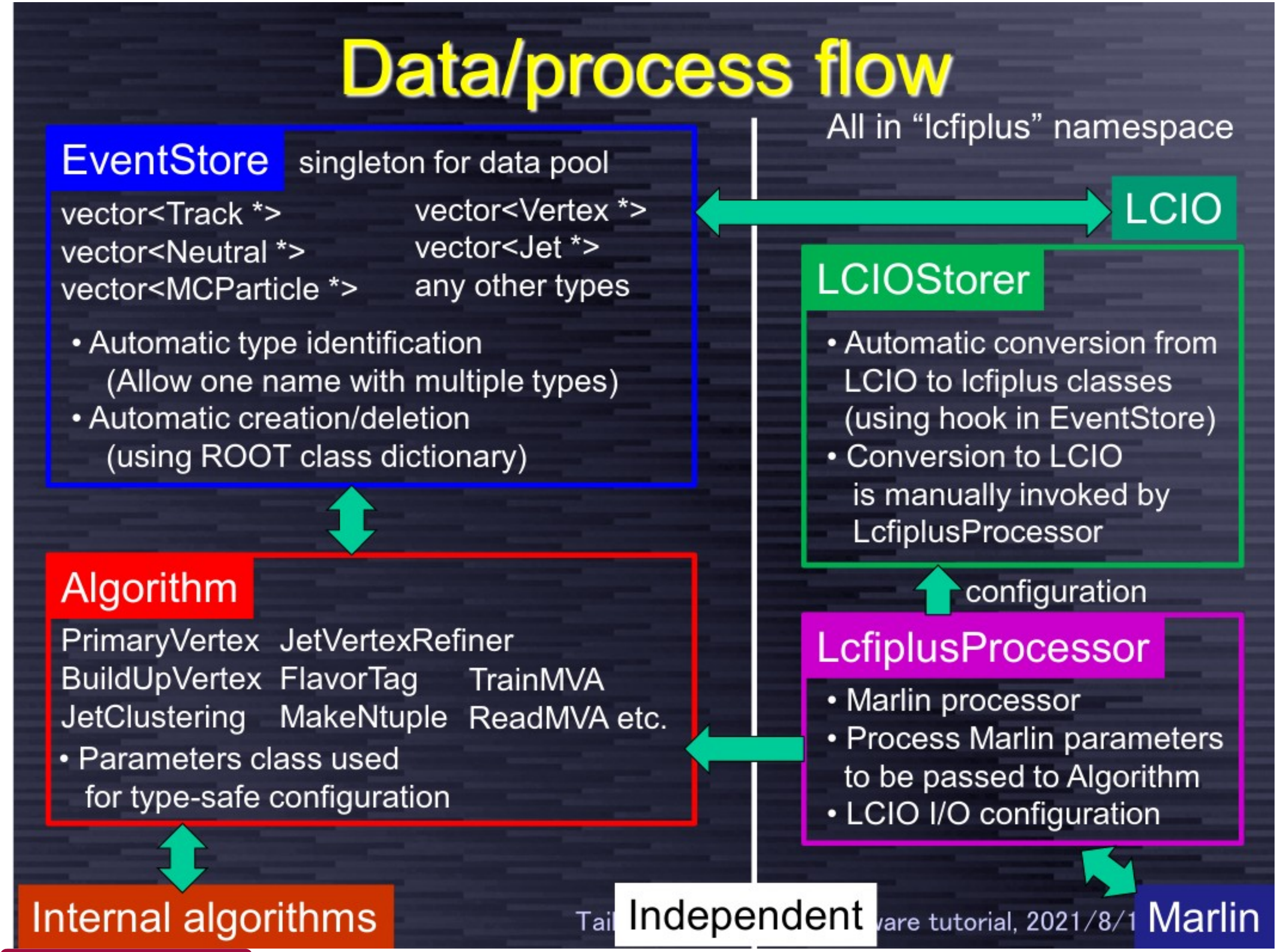
Efficiency of selection for $e_L^- e_R^+ \to X$ [%]							
	Signal			Background			
	$b\bar{b}$	$c\bar{c}$	$q\bar{q}$ $(q = udscb)$	Rad. Ret.	ZZ	WW	$q\bar{q}H$
Cut 1	93.4%	93.3%	92.9%	53.8%	89.9%	91.3%	93.1
+ Cut 2	80.1%	79.8%	78.2%	1.7%	10.4%	10.6%	11.5
+ Cut 3	79.7%	79.3%	78.1%	1.1%	9.8%	10.0%	11.0
+ Cut 4	68.6%	68.9%	68.2%	0.4%	1.5%	2.3%	3.1

Efficiency of selection for $e_R^- e_L^+ \to X$ [%]							
	Signal			Background			
	$b\bar{b}$	$c\bar{c}$	$q\bar{q}$ $(q = udscb)$	Rad. Ret.	ZZ	WW	$q\bar{q}H$
Cut 1	93.1%	93.4%	93.0%	51.5%	94.3%	89.6%	93.1
+ Cut 2	79.8%	79.5%	78.4%	1.6%	11.1%	10.8%	11.6
+ Cut 3	79.5%	79.4%	78.4%	1.0%	9.8%	10.8%	11.1
+ Cut 4	68.4%	68.9%	68.5%	0.4%	0.4%	2.5%	3.1

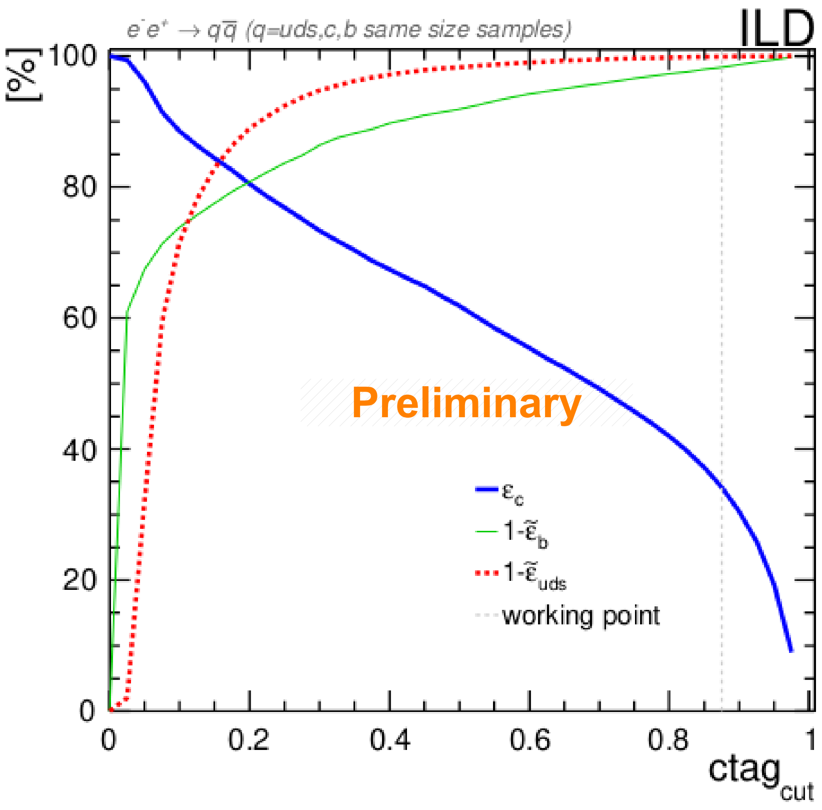
Table 3: Cut flow for signal and background events.

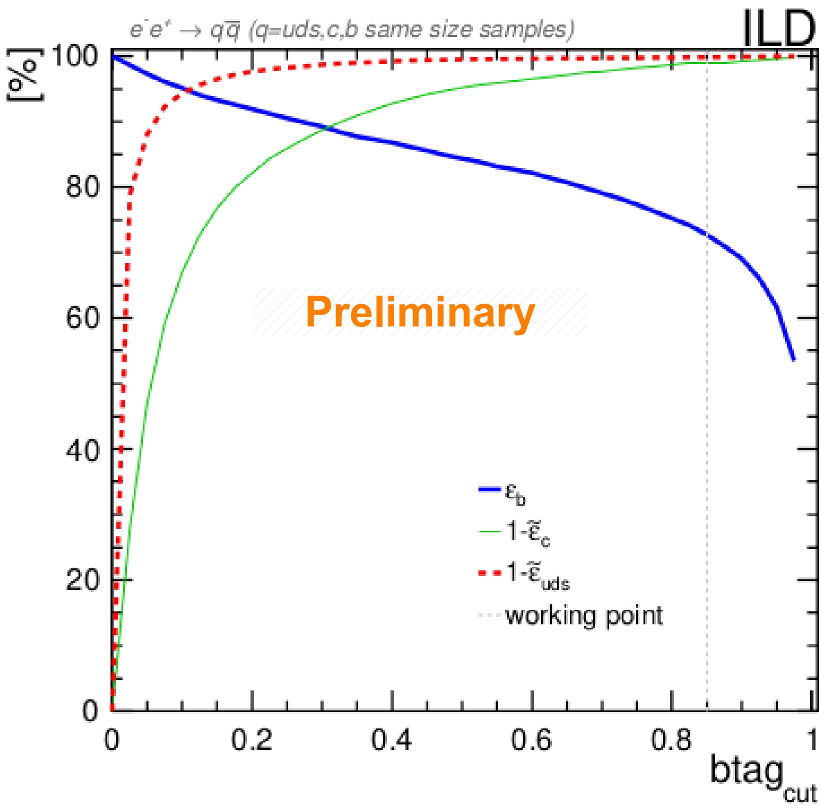
LCFIPlus

- Vertex Finder
  - PrimaryVertexFinder – tear-down method
  - SecondaryVertexFinder – build-up method
- Jet Clustering
  - Implementations of Durham, Valencia, Kt etc
  - Uses https://github.com/lcfiplusClustering using vertex information (not breaking vertices, etc)
  - Removal of beam jets
- Jet Vertex refiner
  - Connects jets and vertices → even accpts jets from external software
  - Single track vertex finder
  - Combine vertices into jets
- Flavor tagging
  - 3-class tagging b/c/q (more categories possible)
  - BDT based


Data/process flow
All in "lcfiplus" namespace
EventStore
singleton for data pool
vector<Track *>
vector<Neutral *>
vector<MCParticle *>
vector<Vertex *>
vector<Jet *>
any other types
• Automatic type identification (Allow one name with multiple types)
• Automatic creation/deletion (using ROOT class dictionary)
LCIO
LCIOStorer
• Automatic conversion from LCIO to lcfiplus classes (using hook in EventStore)
• Conversion to LCIO is manually invoked by LcfiplusProcessor
configuration
Algorithm
PrimaryVertex
BuildUpVertex
JetClustering
JetVertexRefiner
FlavorTag
MakeNtuple
TrainMVA
ReadMVA etc.
• Parameters class used for type-safe configuration
LcfiplusProcessor
• Marlin processor
• Process Marlin parameters to be passed to Algorithm
• LCIO I/O configuration
Internal algorithms
Independent
Marlin

Flavour tagging: e+e- → qqbar ILC250





MC estimations using single jets

Flavour tagging uncertainty modelling could be the dominant source of uncertainty...

Double tag - bk1

$$f_{1b} = \varepsilon_c \overline{R_b} + \widetilde{\varepsilon_c}\, \overline{R_c} + \widetilde{\varepsilon_{uds}}\,(1 - \overline{R_b} - \overline{R_c})$$

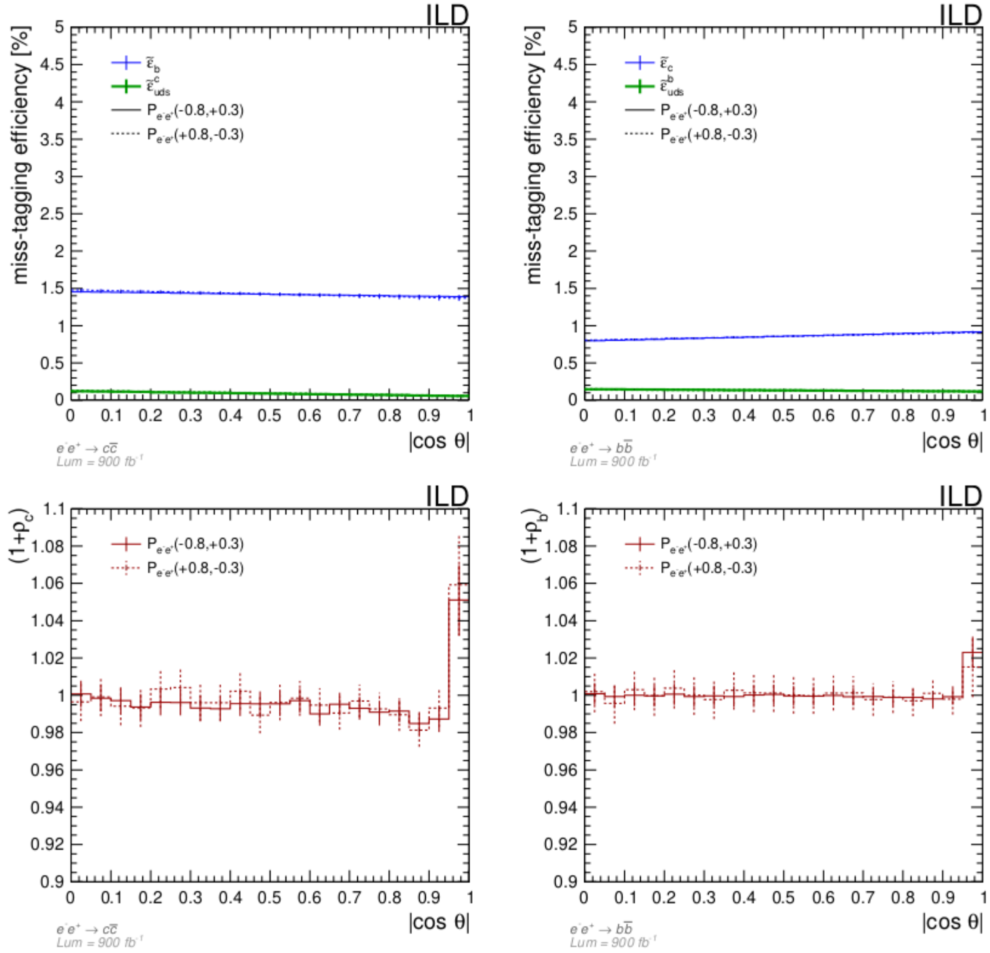
$$f_{2b} = \varepsilon_b^2 (1+\rho)\, R_b + \widetilde{\varepsilon_c}^2 R_c + \widetilde{\varepsilon_{uds}}^2 (1 - R_b - R_c)$$

Measured observables

PHYSICS!
Indirect observables

Inputs (MC or independent measurements)

Similar set of equations for the c-quark
solved simultaneously



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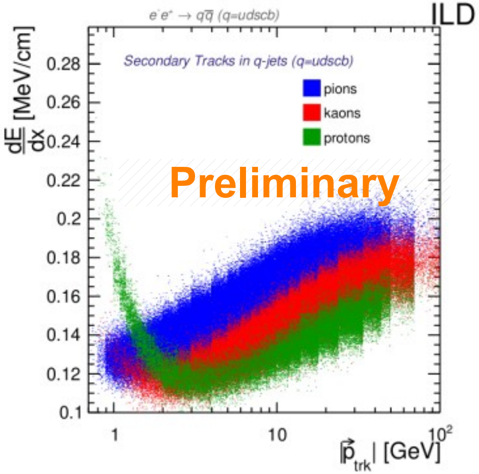
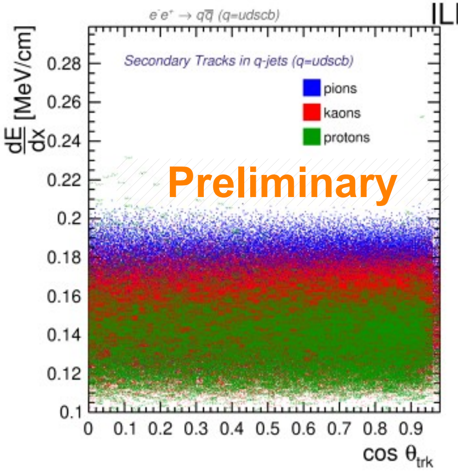
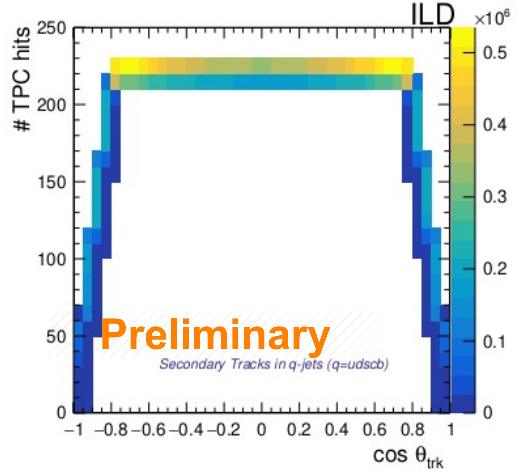
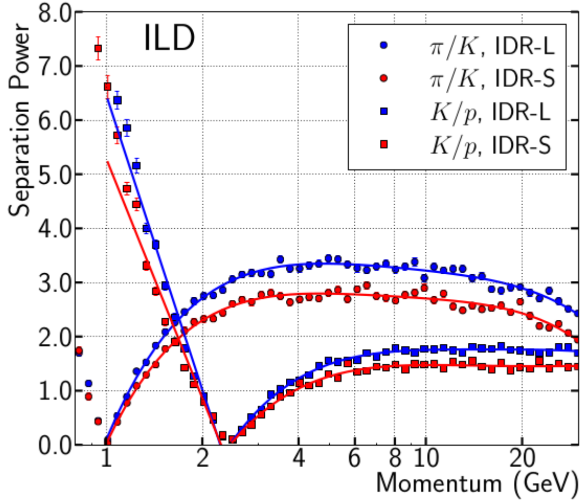
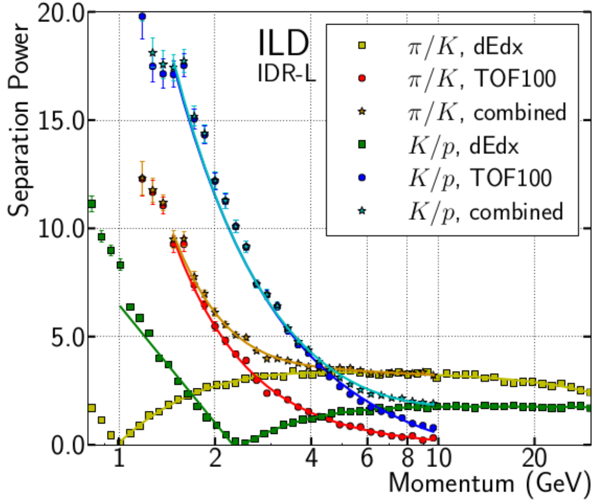
dEdx in ILD











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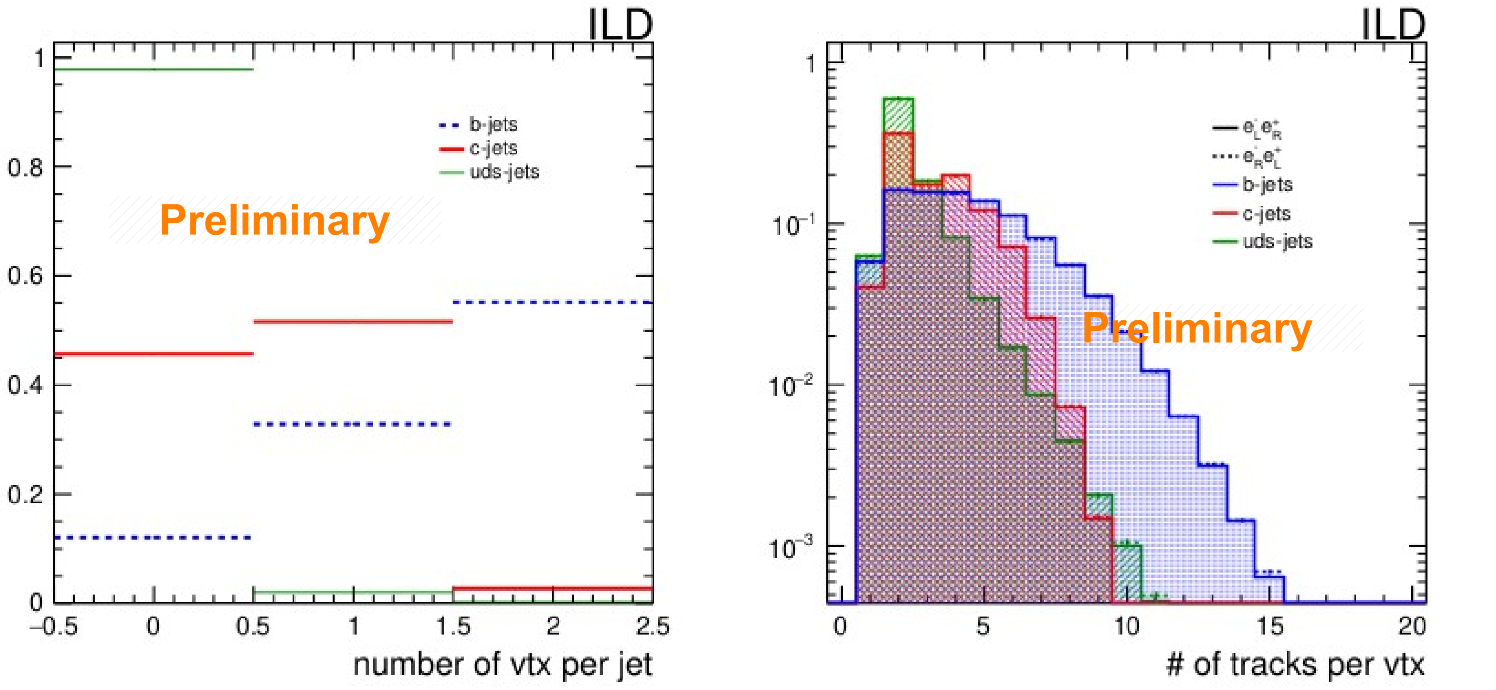
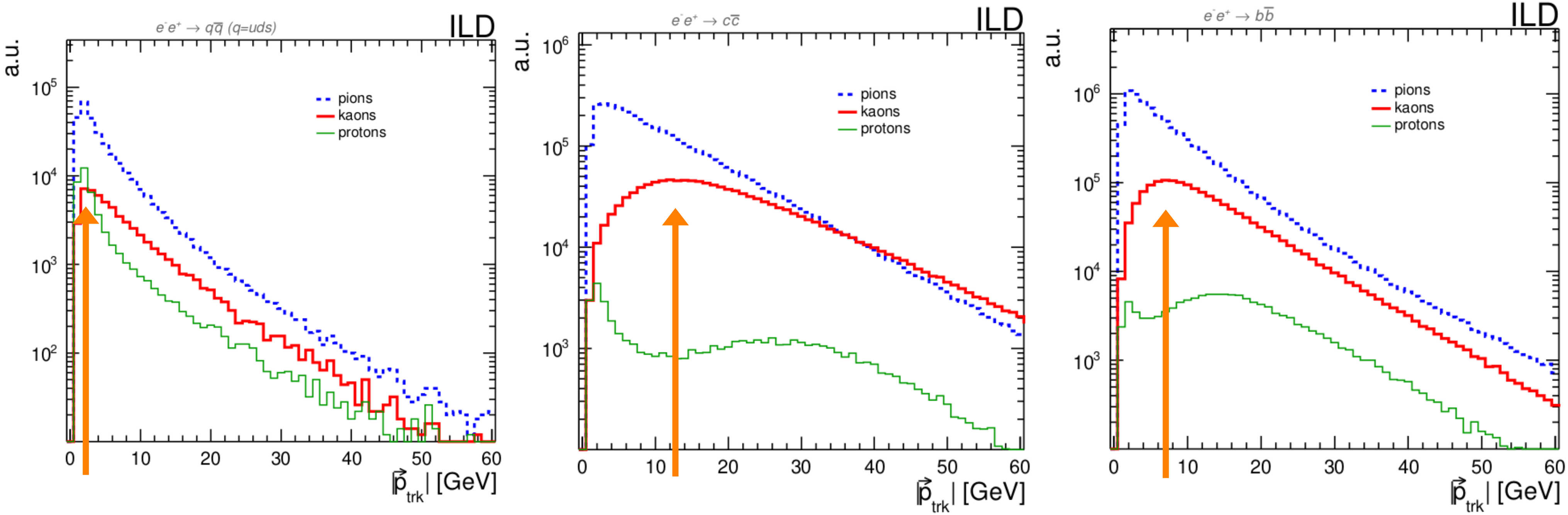


Figure 2: Distribution of reconstructed secondary vertices per jet (left) and a total number of secondary tracks per reconstructed vertex (right) for different quark flavours. In both cases, the plot includes the pseudo-vertices made of only one track, as described in the text and in [31].



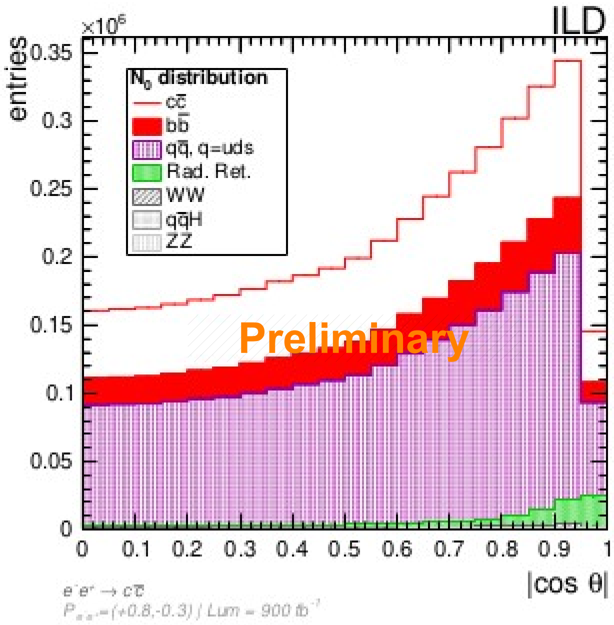
$e^-e^+ \to q\bar{q}$ (q=uds)
ILD
a.u.
pions
kaons
protons
$|\vec{p}_{trk}|$ [GeV]
$e^-e^+ \to c\bar{c}$
ILD
a.u.
pions
kaons
protons
$|\vec{p}_{trk}|$ [GeV]
$e^-e^+ \to b\bar{b}$
ILD
a.u.
pions
kaons
protons
$|\vec{p}_{trk}|$ [GeV]

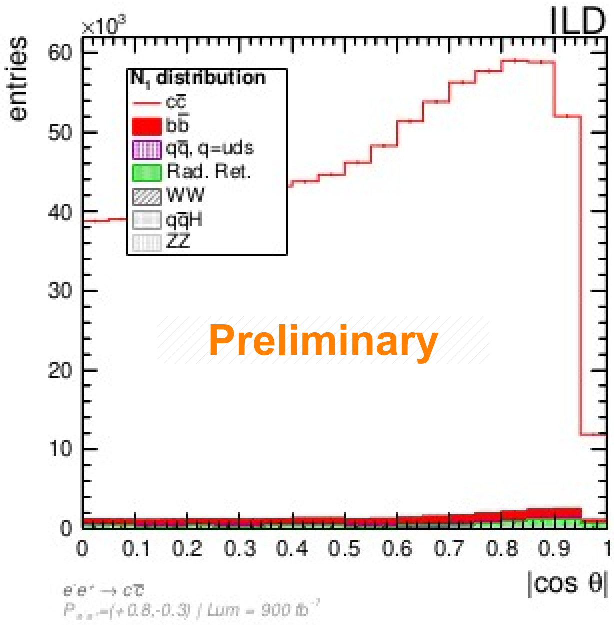
Double Tag Method

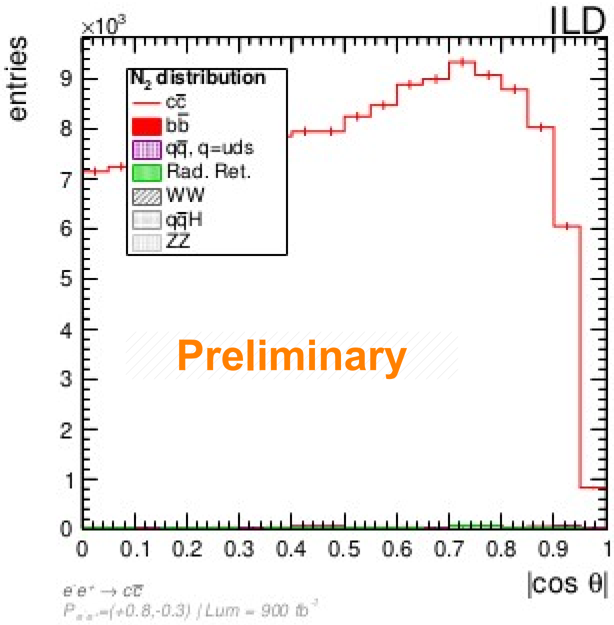
N0, N1, N2 for e+e- → $c\bar{c}$

Minimal contribution from the backgrounds

green and gray histograms







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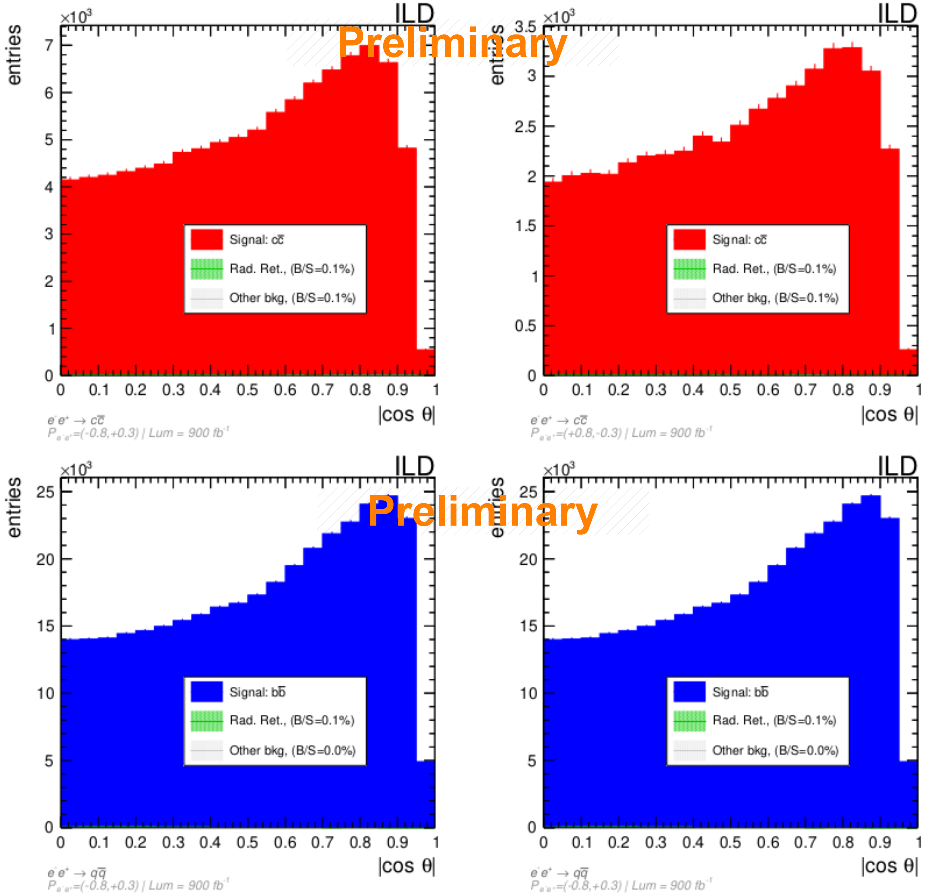
AFB- preselection



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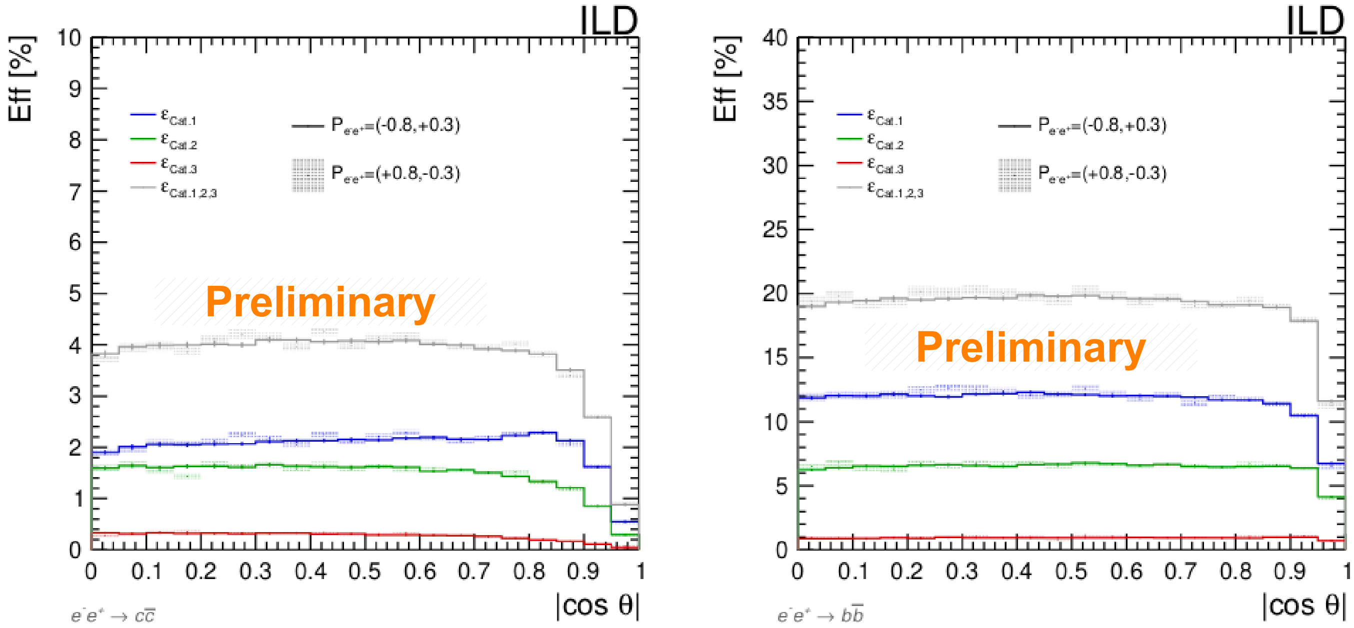
Efficiency/Acceptance corrections

- We define different categories with different priority depending of how the charge was measured in each jet. For example:
  - Cat1 Vtx-Vtx (for b-quark, and K-K for c-quark)
  - Cat 2 K-Vtx or Vtx-K
  - Cat 3 K-K
- Since we start from a pure qq-bar sample, we are able to measure the efficiency/acceptance of each method.



Double charge measurements

▶ 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

Unc.

Preliminary

Source	$e^-e^+ \to c\bar{c}$				$e^-e^+ \to b\bar{b}$			
	$P_{e^-e^+}(-0.8,+0.3)$		$P_{e^-e^+}(+0.8,-0.3)$		$P_{e^-e^+}(-0.8,+0.3)$		$P_{e^-e^+}(+0.8,-0.3)$	
	R_c	$A_{FB}^{c\bar{c}}$	R_c	$A_{FB}^{c\bar{c}}$	R_b	$A_{FB}^{b\bar{b}}$	R_b	$A_{FB}^{b\bar{b}}$
Statistics	**0.18%**	**0.38%**	**0.27%**	**0.52%**	**0.12%**	**0.24%**	**0.23%**	**0.70%**
Preselection eff.	<0.01%	0.12%	0.02%	0.16%	<0.01%	0.08%	0.06%	0.12%
Background	0.01%	0.01%	0.02%	0.02%	0.01%	0.01%	0.06%	<0.01%
heavy quark mistag	0.11%	<0.01%	0.06%	<0.01%	0.12%	<0.01%	0.22%	<0.01%
uds mistag	0.03%	<0.01%	0.02%	<0.01%	0.08%	<0.01%	0.14%	<0.01%
Angular correlations	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%
Beam Polarisation	<0.01%	<0.01%	0.02%	0.01%	<0.01%	0.01%	0.03%	0.15%
Systematics	**0.15%**	**0.16%**	**0.12%**	**0.19%**	**0.18%**	**0.13%**	**0.29%**	**0.22%**
Total	**0.24%**	**0.41%**	**0.30%**	**0.55%**	**0.21%**	**0.27%**	**0.37%**	**0.73%**

Table 5: Breakdown of statistical and systematic uncertainties for the different experimental observables.

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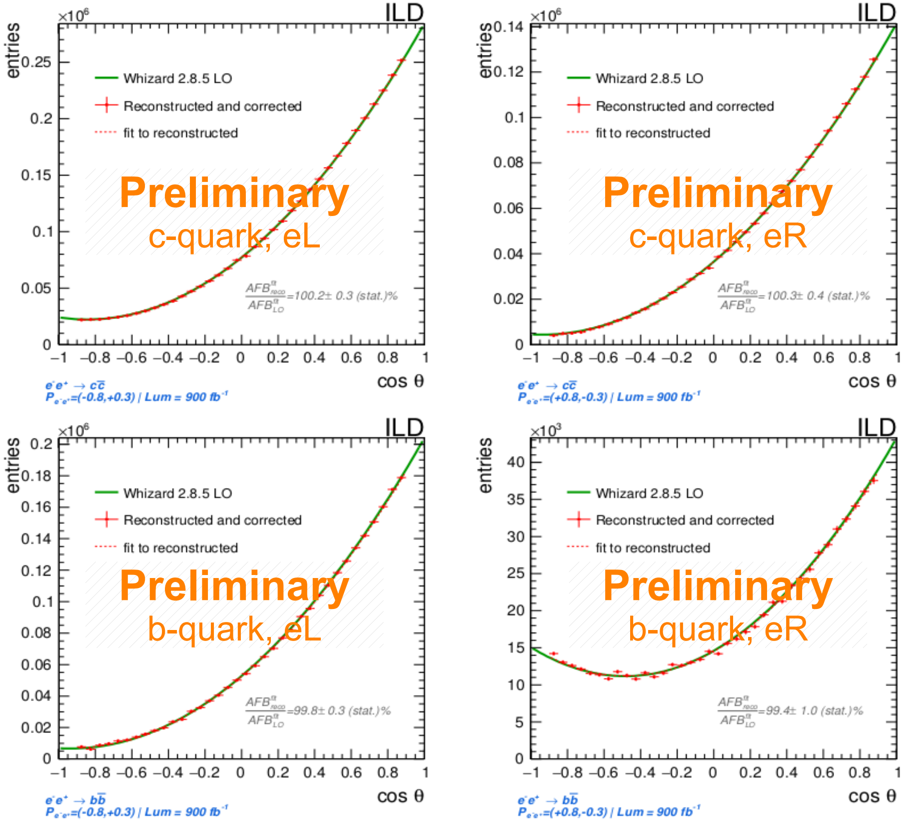
Beam polarisation uncertainty

Beam polarisation uncertainty			
$\Delta P^{-}_{e^-}$ [%]	$\Delta P^{+}_{e^-}$ [%]	$\Delta P^{+}_{e^-}$ [%]	$\Delta P^{-}_{e^+}$ [%]
0.1	0.04	0.1	0.14

R. Karl
10.3204/PUBDB-2019-03013.

- ▶ Reduced impact on the shape of the differential cross section
  - except for the case with eR where the eL events may contaminate the sample (larger cross section and different asymmetry)



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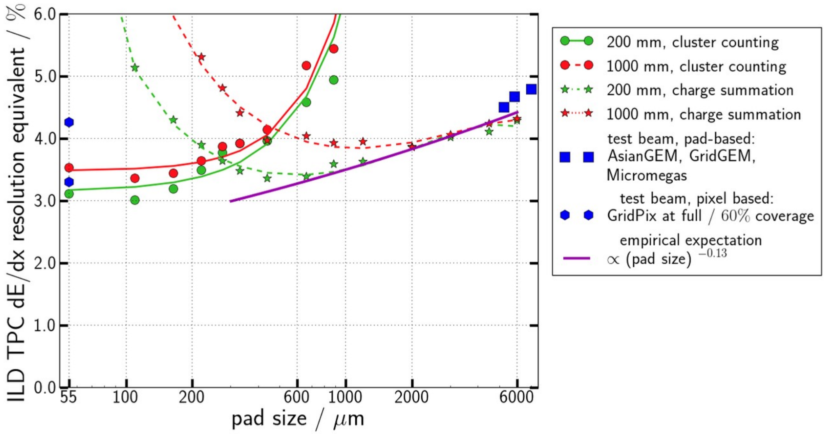
Better dE/dx particle Identification ?

▶ **Conventional dE/dx method: sum of all charge of a track**

- Landau shaped, large RMS... compensated with truncated mean algorithms

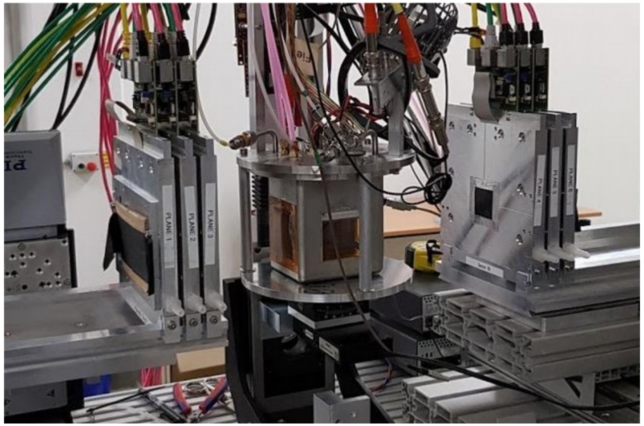
▶ **Alternative approach: cluster counting**

- Count number of ionising interactions (Poisson shaped)
- Allows for better particle separation but depends on counting efficiency.
- Can improve the separation power by a factor ... 30-40%



Under study (dedicated simulations and TBs)

GridPix, beam test at ELSA test beam @Uni Bonn



Why this luxury?

Beam spot size

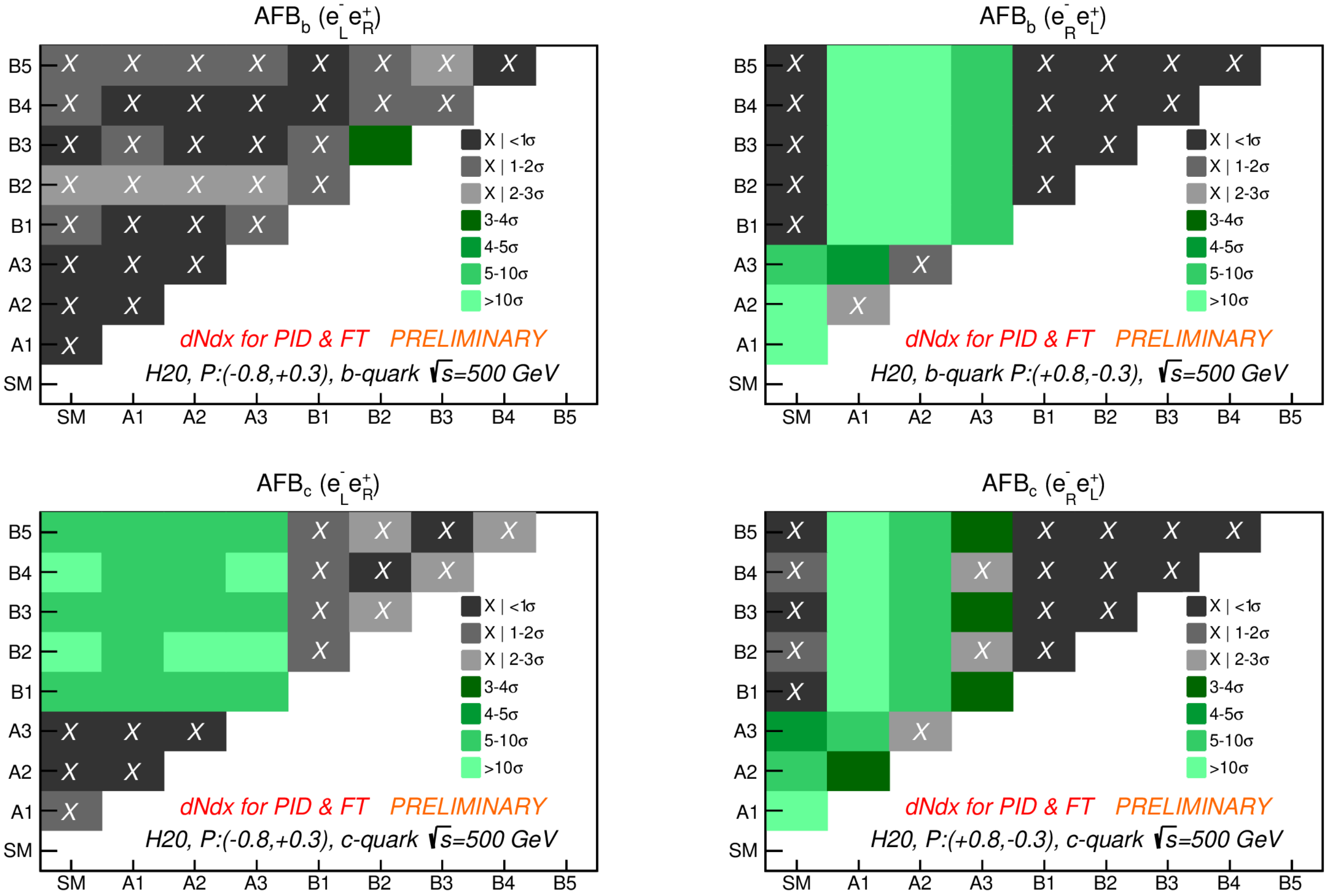
	FCCee	ILC	SLC	LEP
σ_x[nm]	13700	516	1500	200000
σ_y[nm]	36	7.7	500	2500

Source SLC, LEP, PDG

©R. Poeschl

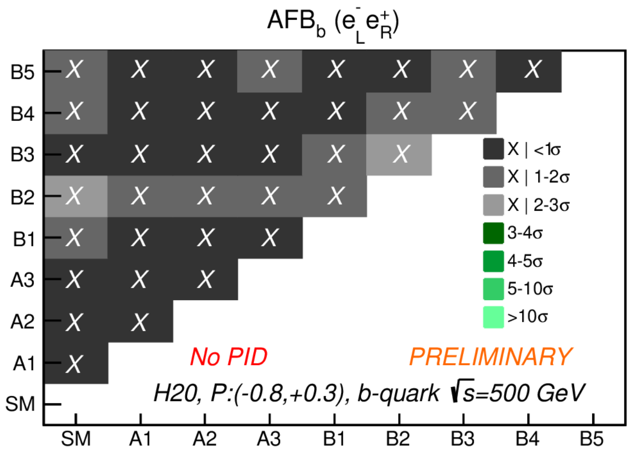
LEP >> SLC >> ILC

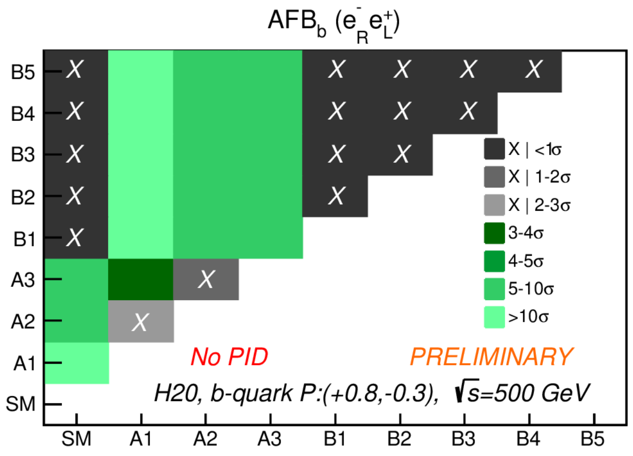
ILC500

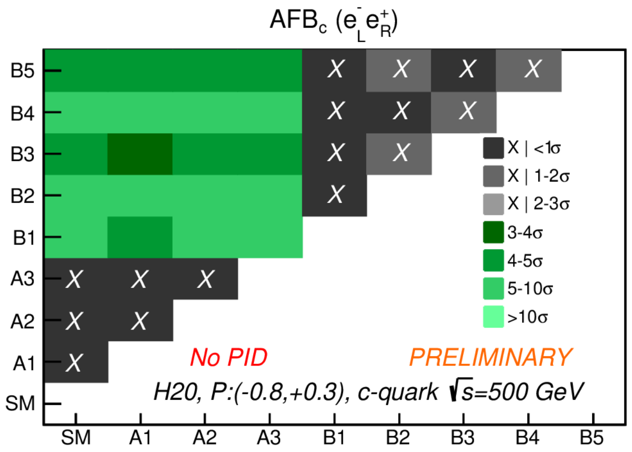


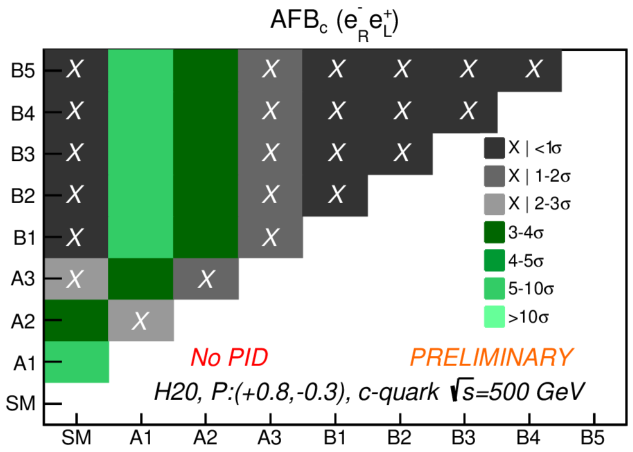
AFB$_b$ ($e^-_L e^+_R$)
dNdx for PID & FT PRELIMINARY
H20, P:(-0.8,+0.3), b-quark √s=500 GeV
AFB$_b$ ($e^-_R e^+_L$)
dNdx for PID & FT PRELIMINARY
H20, b-quark P:(+0.8,-0.3), √s=500 GeV
AFB$_c$ ($e^-_L e^+_R$)
dNdx for PID & FT PRELIMINARY
H20, P:(-0.8,+0.3), c-quark √s=500 GeV
AFB$_c$ ($e^-_R e^+_L$)
dNdx for PID & FT PRELIMINARY
H20, P:(+0.8,-0.3), c-quark √s=500 GeV
X | <1σ
X | 1-2σ
X | 2-3σ
3-4σ
4-5σ
5-10σ
>10σ
SM A1 A2 A3 B1 B2 B3 B4 B5

ILC500 no TPC

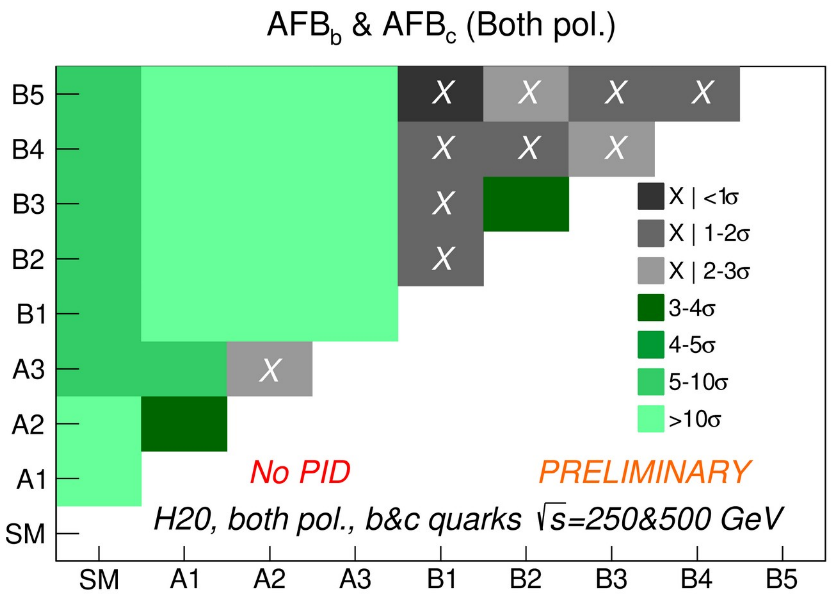




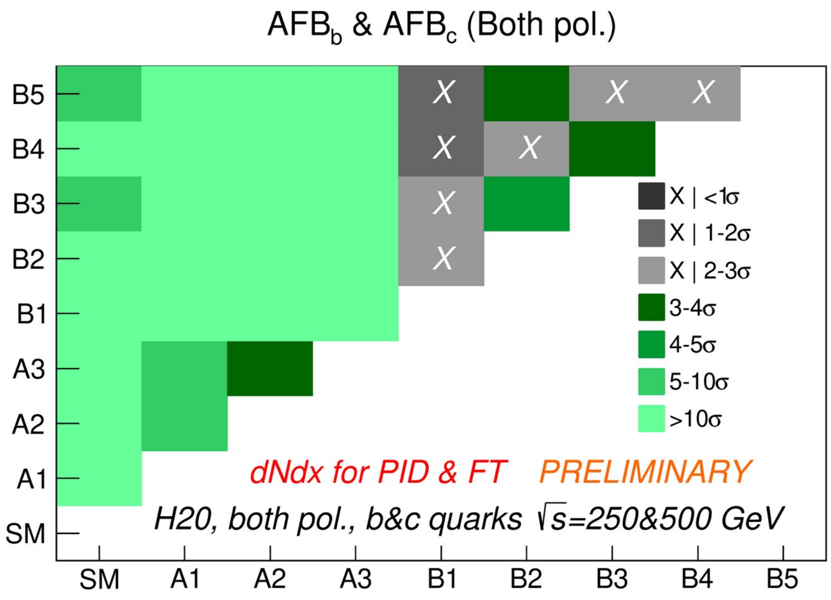




ILC250 & ILC500 (w/o TPC vs w/TPC)



ILC250&ILC500
noTPC



ILC250&ILC500