dE/dx at ILD

Implementation and Applications

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LCTPC Collaboration Meeting

13.01.2022

I. Implementation of dE/dx in ILD reconstruction

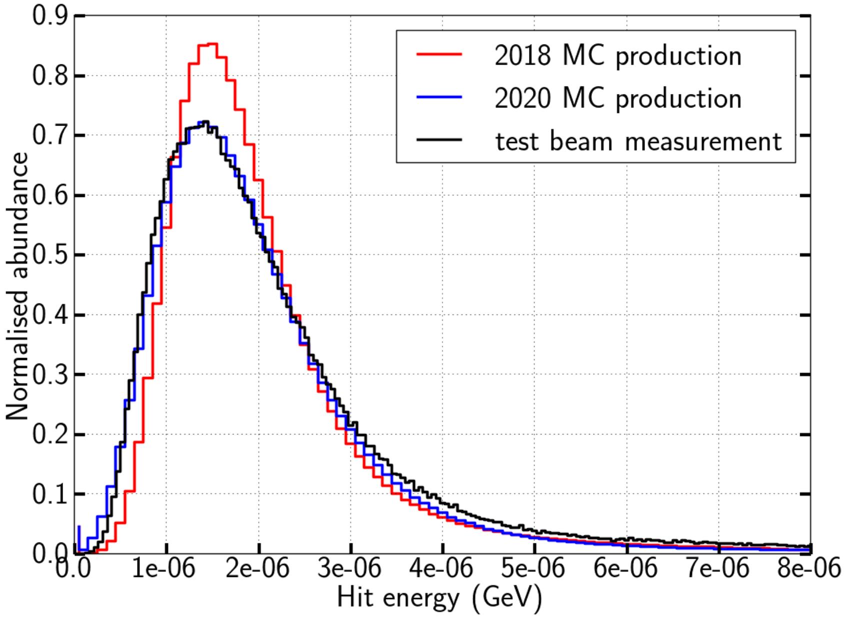
dE/dx implementation

- In iLCSoft, dE/dx is computed at the end of track reconstruction based on tracker hit information with energy deposited by Geant4 $\rightarrow$ Compute_dEdxProcessor
- Trimmed truncated mean: Reject 8% hits with smallest dE/dx and 30% with largest dE/dx
- After averaging, smearing factor adjusts track dE/dx value to achieve a dE/dx resolution in a given test sample similar to test beam results, necessary because Geant4 generates a too small width

Recalibration 2020

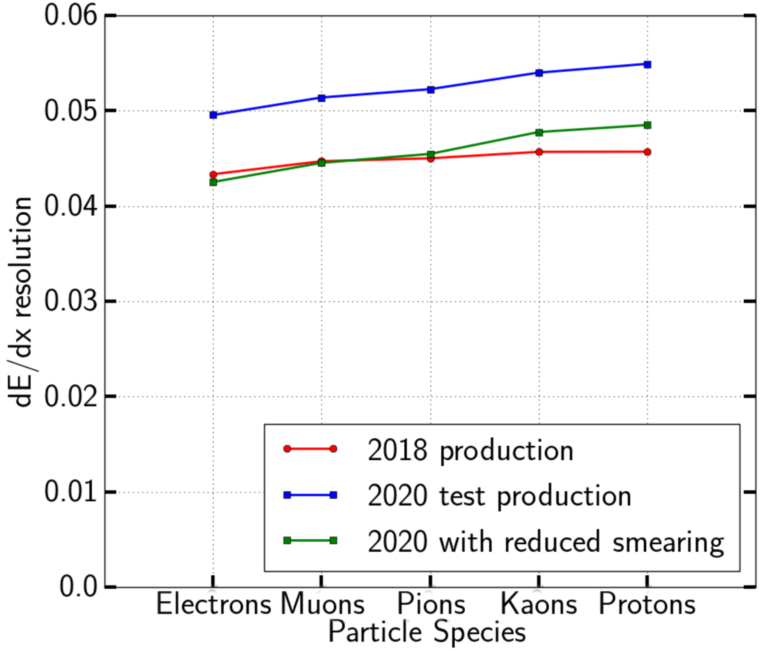
- 2018 MC production (“IDR production” with 500 GeV and iLCSoft v02-00-01) was the first large production to include dE/dx
- For the 2020 MC production (250 GeV, iLCSoft v02-02), a new Geant4 version (v10.04) was used with an ionisation closer to test beam observations (by P. Malek)
- Larger width, smaller dE/dx value

  → Needed recalibration



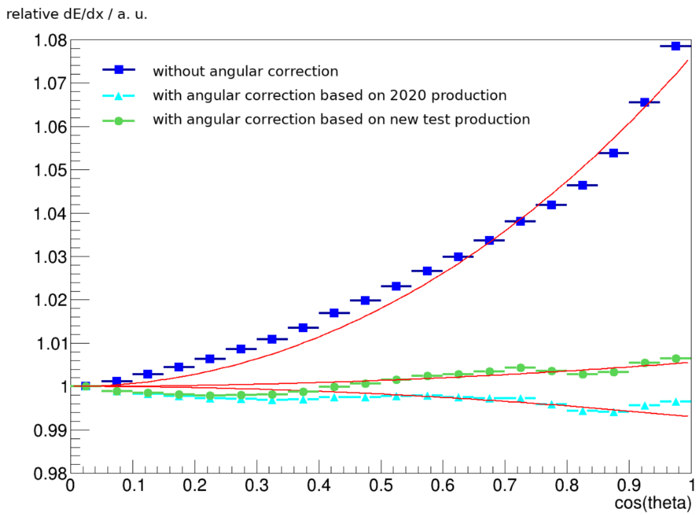
Recalibration 2020

- Reduction of smearing factor revealed intrinsic dependence on species
- Introduction of ‘fiducial electrons’ to compare to test beam conditions
- Other species a bit worse now, probably overestimated a bit in the past



Angular correction

- Unfortunately, also the (polar) angular dependence changed, which was overlooked
- Very forward particles have dE/dx value up to 7% too large, which causing wrong species assignment
- A. Irles provided AngularCorrection_dEdxProcessor, which uses only track information (on DST level) and overwrites dE/dx value
- Only used individually for analyses, production was not redone/adjusted as a whole
- See also https://agenda.linearcollider.org/event/9197/



PID extraction

- Tool for PID extraction out of observables like dE/dx: LikelihoodPIDProcessor
- Takes observables, uses trained MVA to generate best-guess PID tag incl. likelihood
- Unfortunately, there is no documentation, complicated code, difficult to train on new sample, and recent dE/dx reference parametrisation was incorrect

  → output currently questionable or wrong (dE/dx)
- For now, there is a work-around recipe to re-run it with correct dE/dx parameters
- Mid term, I plan to provide a new flexible PID tool
- Recently, I started to first combine dE/dx and TOF, then head to ‘general case’

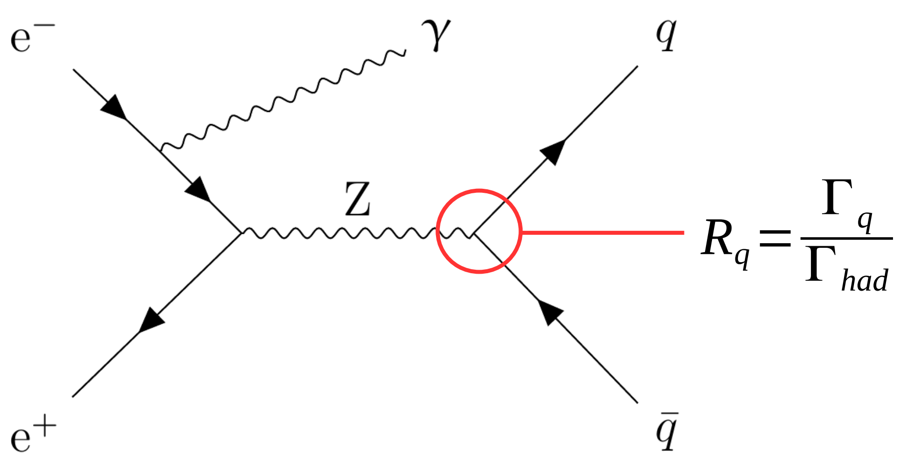
II. Application of dE/dx in ILD analyses

ILD analyses/techniques using dE/dx

- Z and W hadronic decay branching fractions via flavour tagging: Paul Malek, UE
- H → ss with s-tagging: Matthew Basso
- Forward-backward asymmetry in $e^+e^- \rightarrow$ qq: Roman Pöschl, Francois Richard, Sviatoslav Bilokin, Adrian Irles, Yuichi Okugawa, Jesus Marquez, e.a.
- Kaon mass with TOF: UE
- Track refit with correct particle mass: Yasser Radkhorrami, Bohdan Dudar

Determination of the light hadron flavour branching fractions of the Z boson

by Paul Malek, thesis publication in prep.



- Test flavour universality of Z decay branching fractions
- R_c and R_b can be determined individually
- Task: determine $R_{u,d,s}$!
- Particle composition of outgoing jets contains information of $R_{u,d,s}$, but needs to be identified and disentangled

Determination of the light hadron flavour branching fractions of the Z boson

$$\frac{N_h}{N_{\text{had}}} = 2 \cdot \sum_q \eta_q^h R_q$$

$$\frac{N_{hk}}{N_{\text{had}}} = (2 - \delta_{hk}) \cdot \sum_q \rho \cdot \eta_q^h \eta_q^k R_q$$

- Identify detector-stable hadrons h: $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$, K^{0}, Λ^{0}
- N_h: single-tagged hadrons h
- N_{hk}: double-tagged hadrons h and k
- → Tagging order is irrelevant, so 5 + 15 = 20 observables
- η^h_q: probability to generate hadron h from quark q ε {u, d, s}
- 3 R_q, 15 η^h_q, ρ to be determined
- → need additional contraints!

Determination of the light hadron flavour branching fractions of the Z boson

- Additional constraints:

$$R_\mathrm{d} + R_\mathrm{u} + R_\mathrm{s} = 1 - R_\mathrm{c} - R_\mathrm{b}$$
$$R_\mathrm{d} = R_\mathrm{s}$$

$$\eta_\mathrm{d}^{\pi^\pm} = \eta_\mathrm{u}^{\pi^\pm}$$
$$\eta_\mathrm{d}^{\mathrm{K}^0(\bar{\mathrm{K}}^0)} = \eta_\mathrm{u}^{\mathrm{K}^\pm}$$
$$\eta_\mathrm{u}^{\mathrm{K}^0(\bar{\mathrm{K}}^0)} = \eta_\mathrm{d}^{\mathrm{K}^\pm}$$
$$\eta_\mathrm{s}^{\mathrm{K}^0(\bar{\mathrm{K}}^0)} = \eta_\mathrm{s}^{\mathrm{K}^\pm}$$
$$\eta_\mathrm{u}^{\Lambda(\bar{\Lambda})} = \eta_\mathrm{d}^{\Lambda(\bar{\Lambda})}$$

- Reduces parameters to 12:

ρ, $R_{d,s}$, 10 η^h_q

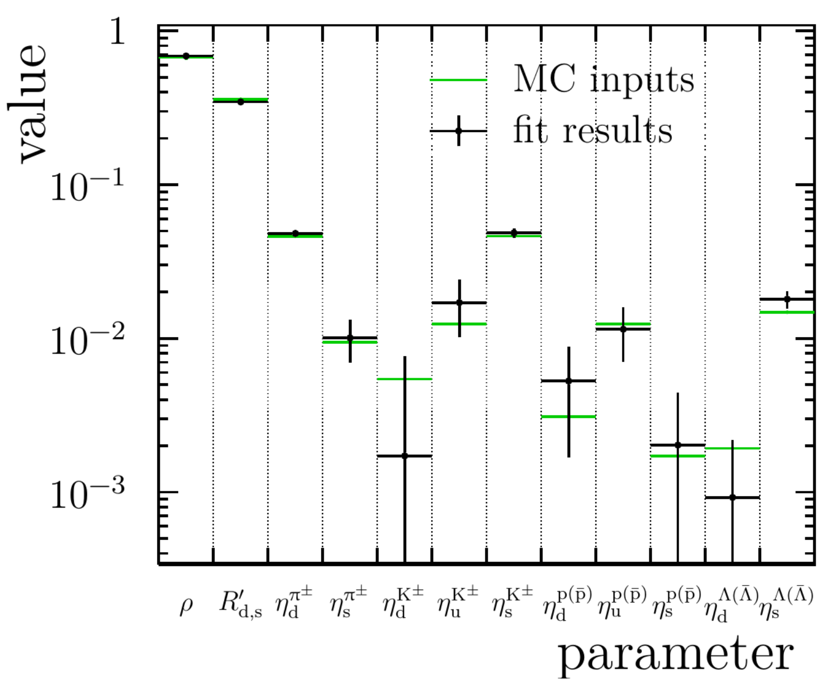
Determination of the light hadron flavour branching fractions of the Z boson

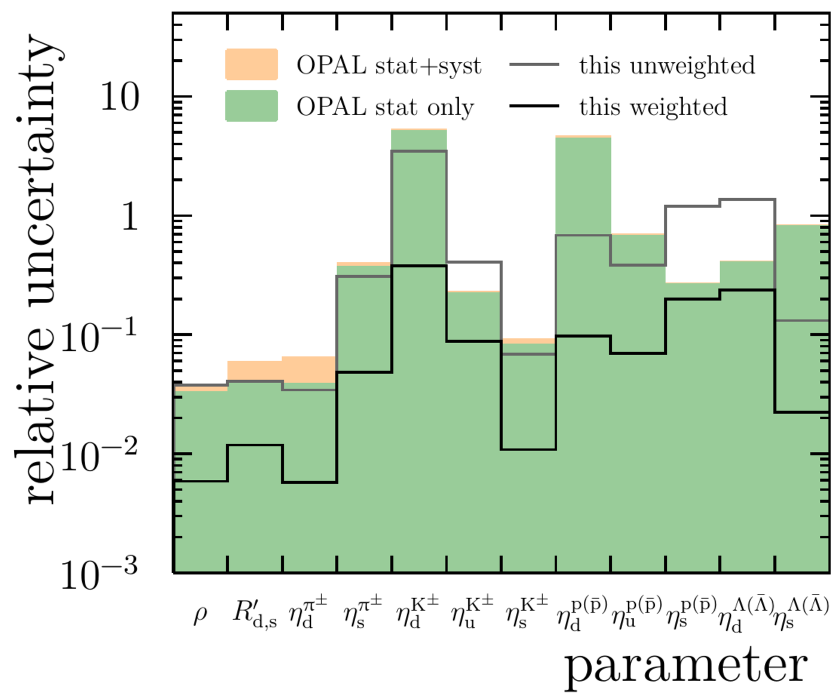
- Particle ID:
- $\pi^\pm$, $K^\pm$, $p^\pm$ are identified via dE/dx – but with the DBD data set (v01-16-04), so dE/dx was added via toy MC based on the performance in v02-00-02
- Toy MC works on track level with a rel. resolution of 4.7% for 220 hits, and dependences on number of hits N and polar angle θ of: $\sigma_{dE/dx} \propto N^{-0.47} \cdot (\sin\theta)^{0.34}$
- K^0, Λ^0 are identified via V0Finder, i.e. finding offset vertex of 2 tracks and fitting invariant mass
- Resulting purities and efficiencies: (rows normalised to 1 → diagonal is purity)

Assigned tag	True tag $\pi^\pm$	$K^\pm$	$p(\bar{p})$	K^0_S	$\Lambda(\bar{\Lambda})$	other
$\pi^\pm$	0.845(2)	0.053(1)	0.000(0)	0.002(0)	0.000(0)	0.099(2)
$K^\pm$	0.134(3)	0.735(3)	0.045(2)	0.000(0)	0.001(0)	0.085(2)
$p(\bar{p})$	0.008(1)	0.414(5)	0.441(6)	0.000(0)	0.011(1)	0.125(4)
K^0_S	0.000(0)	0.000(0)	0.000(0)	0.904(4)	0.009(1)	0.086(4)
$\Lambda(\bar{\Lambda})$	0.000(0)	0.000(0)	0.000(0)	0.083(6)	0.809(9)	0.108(6)
efficiency	0.763(2)	0.546(3)	0.678(6)	0.334(4)	0.261(5)	—

Determination of the light hadron flavour branching fractions of the Z boson

- Result of the fit:
- Agrees with MC input within uncertainties
- Significant improvement of (statistical) uncertainties compared to OPAL

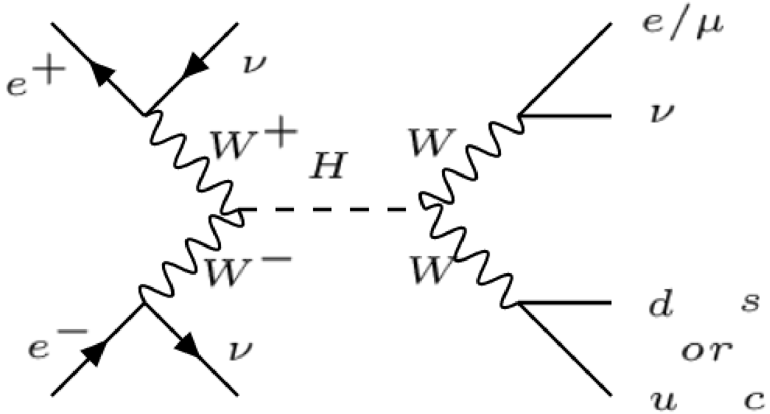




Hadronic W decay

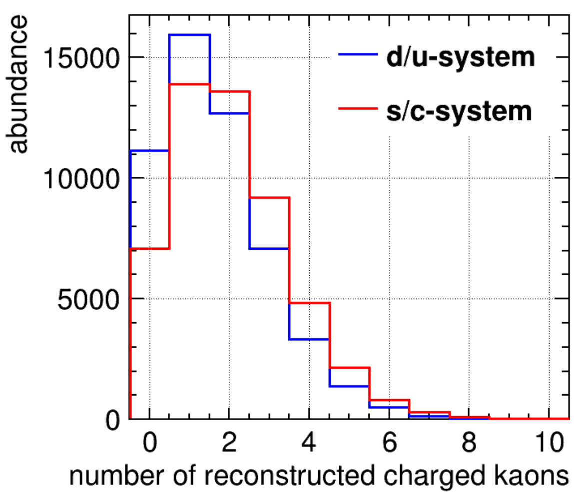
by UE, thesis publication in prep.

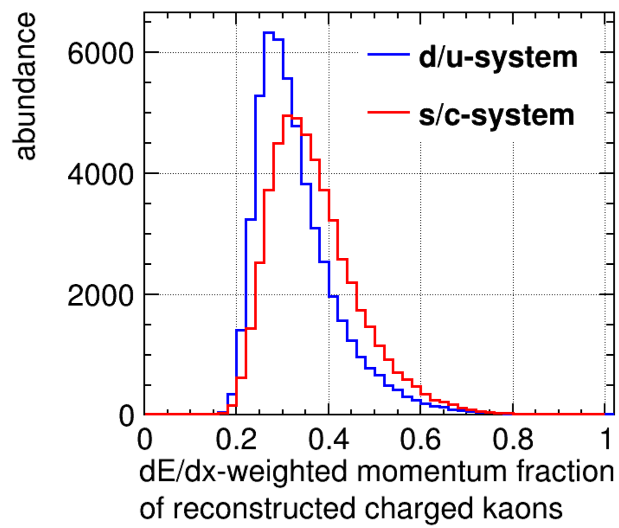
- Hadronic decay coefficients of W (analogue to R_q of Z): CKM matrix
- Least known one: V_{cs}, can be extracted via direct measurement of W → cs decays
- Need to differentiate between W → du and W → cs
- c and s produce strange particles, used PID to identify, compare to existing vertex-based flavour tag
- Sample used: H → WW → lν qq at 500 GeV from IDR production
- Re-reconstructed dE/dx with different effective resolutions to check impact

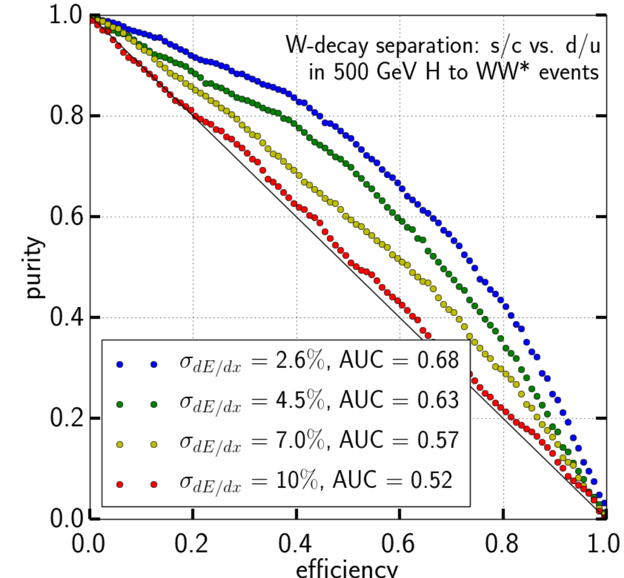


Hadronic W decay

- Reconstruct 2-jet decay system
- Identify $\pi^{\pm}$, $K^{\pm}$ (dE/dx), K^0, Λ^0 (V0Finder)
- Extract 20 observables based on number and momentum of particles and if they are the leading particle
- Use in boosted decision tree (BDT) MVA, use area-under-curve of resulting purity/efficiency curve as measure

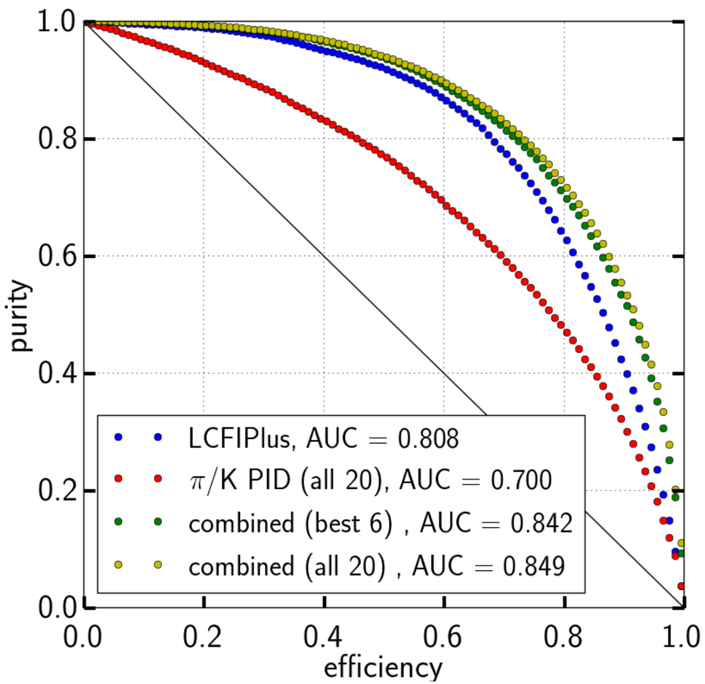


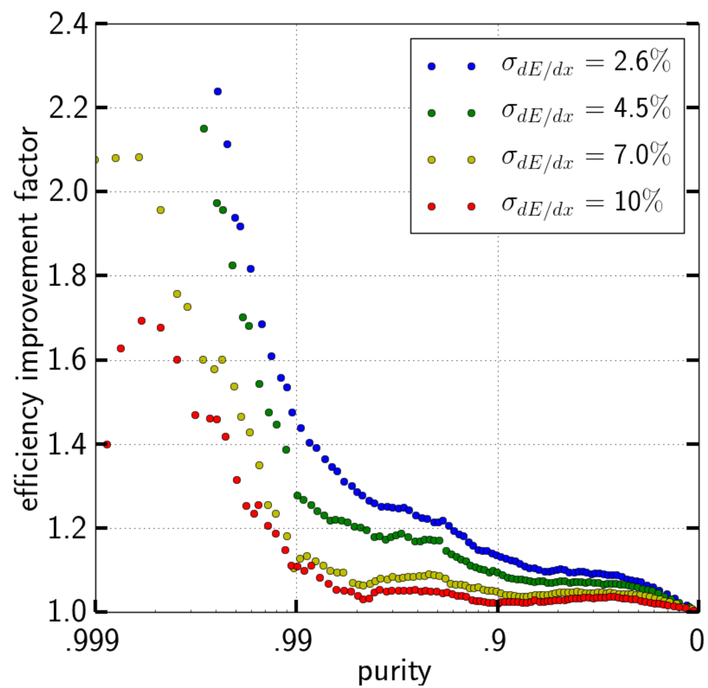




Hadronic W decay

-
- Compare to existing vertex-based flavour tag by LCFIPlus
- Adds independent information, allows significant increase of statistics at high requested purities





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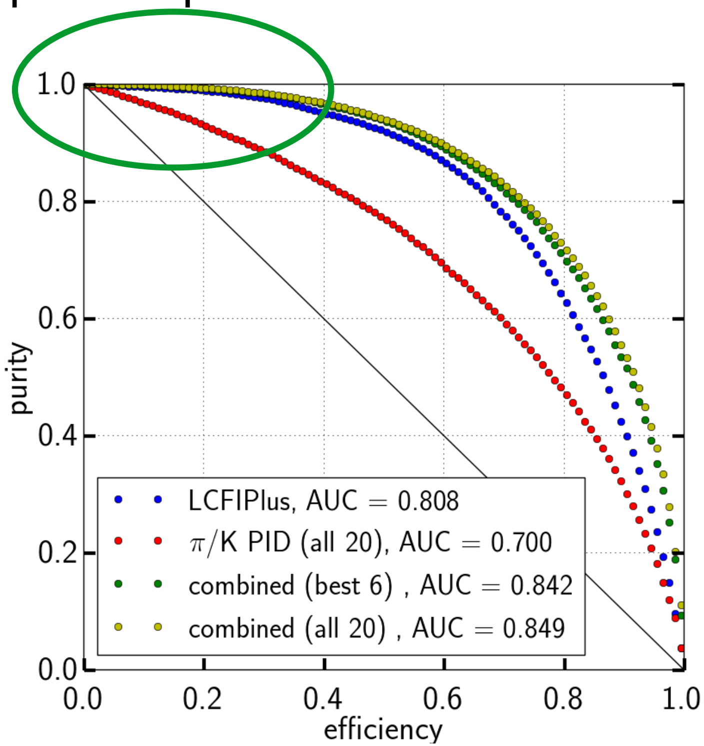
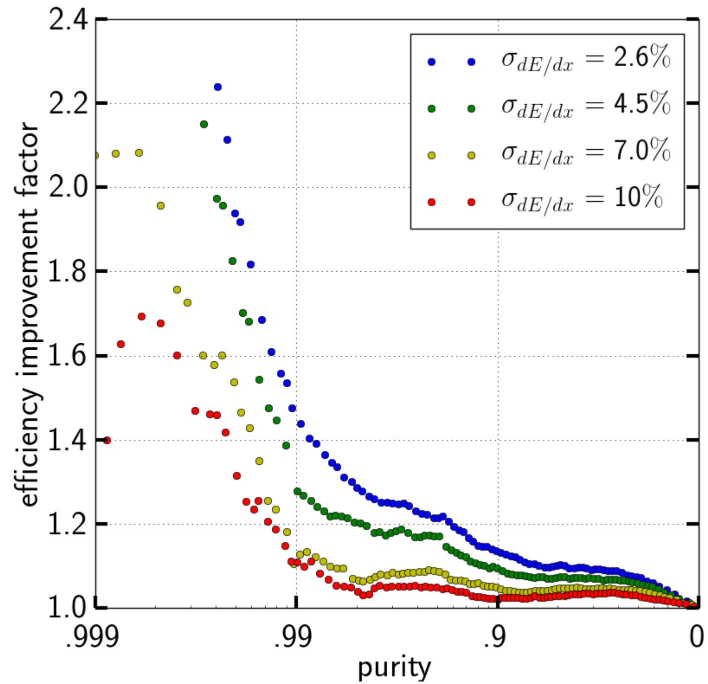




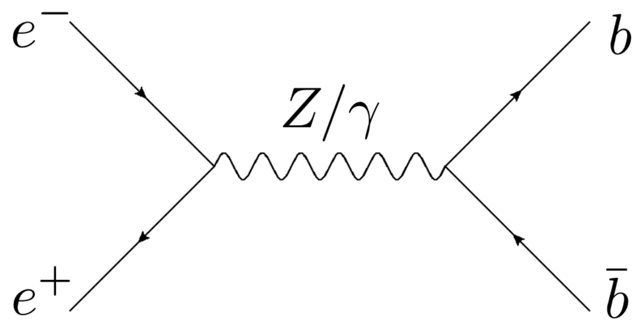
Z → qq forward/backward asymmetry

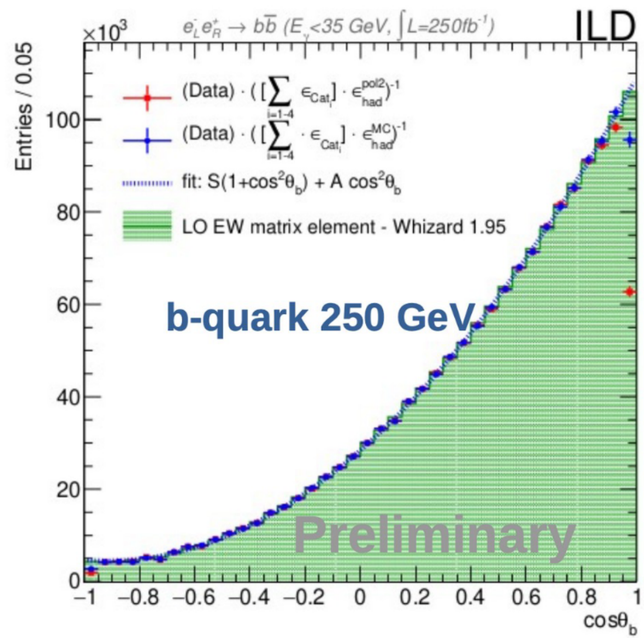
- Forward/backward asymmetry A_{FB} of s-channel exchange sensitive to new physics

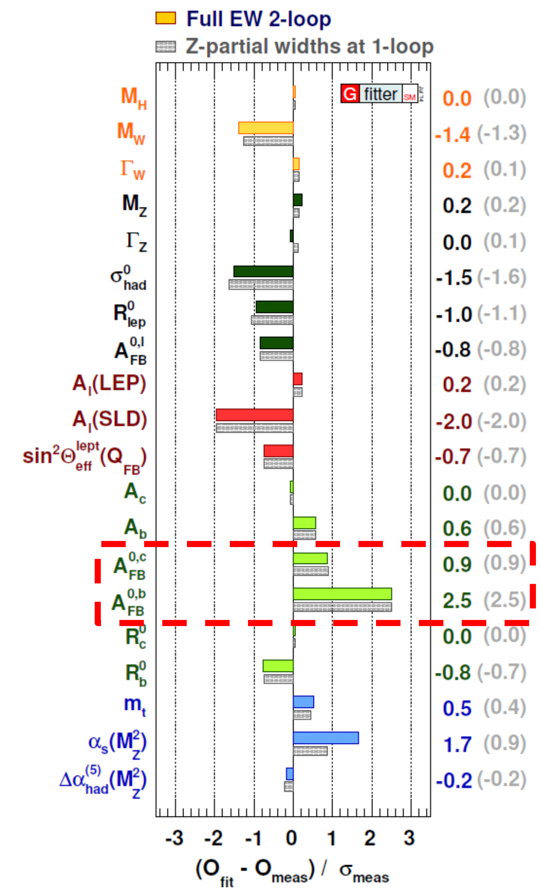
$$A_{FB}^{q\bar{q}} = \frac{\sigma_F^{q\bar{q}} - \sigma_B^{q\bar{q}}}{\sigma_F^{q\bar{q}} + \sigma_B^{q\bar{q}}}$$

- Heavy flavour group has been studying these processes for some years, with $e^+e^- \rightarrow$ tt, bb, cc, ss

- A_{FB} measured at LEP to percent level, can be measured with ILD to permille level

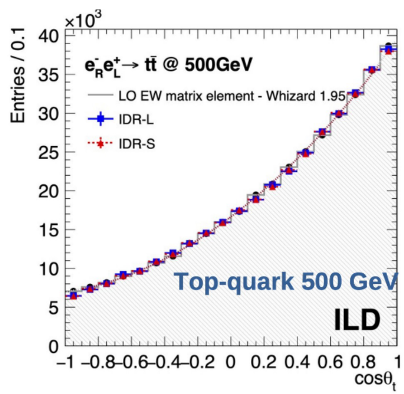


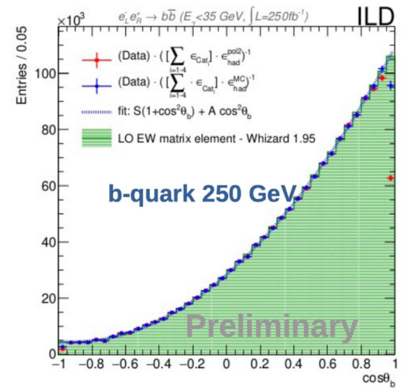


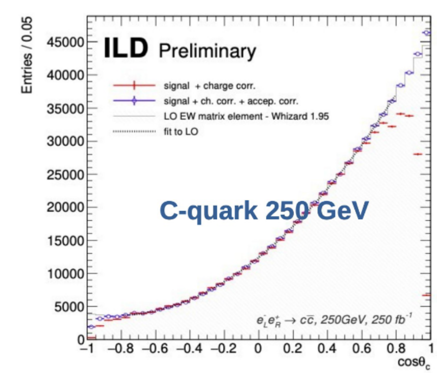


Z → qq forward/backward asymmetry

- References:
- S. Bilokin's PhD thesis https://tel.archives-ouvertes.fr/tel-01826535
- $e^+e^- \rightarrow$ bb, 2019 https://agenda.linearcollider.org/event/8147
- $e^+e^- \rightarrow$ tt, bb 2019 https://confluence.desy.de/download/attachments/42357928/ILD-PHYS-PUB-2019-007.pdf
- $e^+e^- \rightarrow$ cc, 2020 https://arxiv.org/abs/2002.05805
- $e^+e^- \rightarrow$ bb/cc, ss 2021 https://agenda.linearcollider.org/event/9440, https://agenda.linearcollider.org/event/9285
- $e^+e^- \rightarrow$ bb/cc 2021 https://agenda.linearcollider.org/event/9211/contributions/49358/

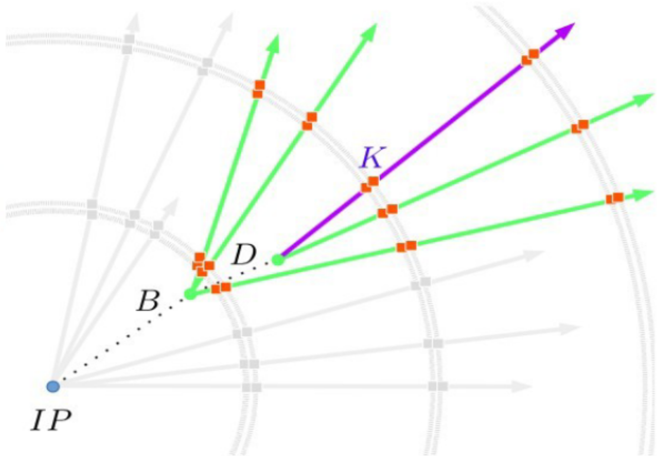


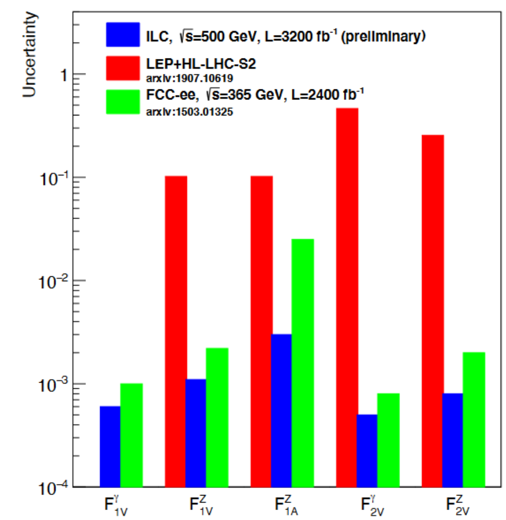




Z → qq forward/backward asymmetry

- Crucial: assign correct vertex charge to jets
- Either by summing over all PFO charges or by reconstructing secondary/tertiary vertices with known decay products → kaons
- Started with DBD samples and using toy MC, now using 2018 and 2020 productions and full dE/dx information including angular correction
- Result examples:
  - LEP: A_{FB} ~ 4%,
    ILD: $$\Delta A_{FB}^{c\bar{c}}(e_L p_R) = 0.16\%(stat.) + 0.09\%(syst.)$$ $$\Delta A_{FB}^{c\bar{c}}(e_R p_L) = 0.20\%(stat.) + 0.10\%(syst.)$$
  - top form factors improve 2 orders of magnitude compared to LEP

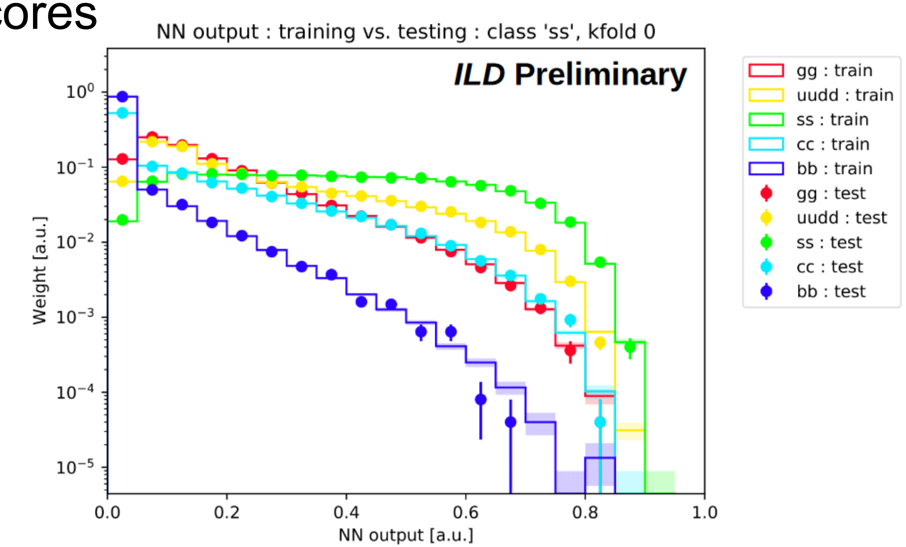




H → ss with s-tagging

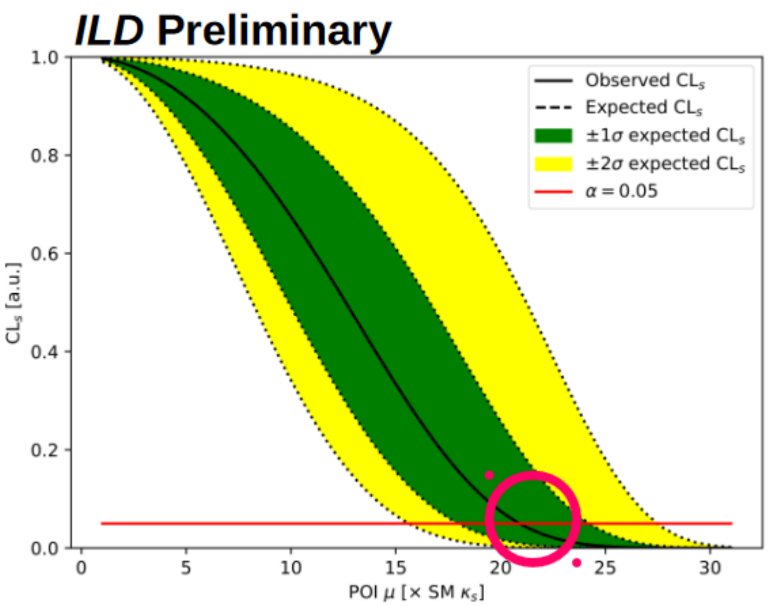
by Matthew Basso, https://indico.cern.ch/event/1030068/contributions/4471014/

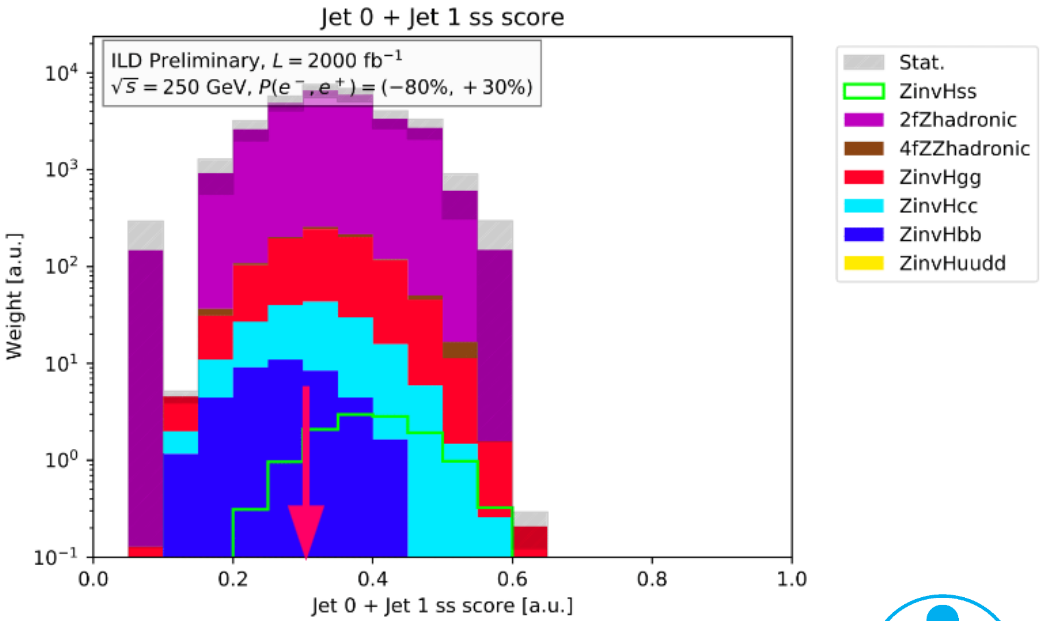
- Part of Snowmass: access H to strange coupling, develop a strange tagger
- Uses mini-DST samples of 250 GeV production
- Find H → ss in background of H → qq/gg and Z → qq, Z → qqqq
- Kinematic selection using jet momenta, energy and mass, missing mass and angular separation, number of PFO and flavour tag scores
- Flavour tag by neural network using 9 jet properties including LCFIPlus flavour tag scores (b/c/o), and 12 individual properties of the 10 leading particles in each jet including the **truth** PID of e, μ, π, K, p, K^0, Λ^0



H → ss with s-tagging

- Result:
- 29% signal eff., 0.016% background eff.
- No discovery, but 95% upper limit of 21 SM κ_s

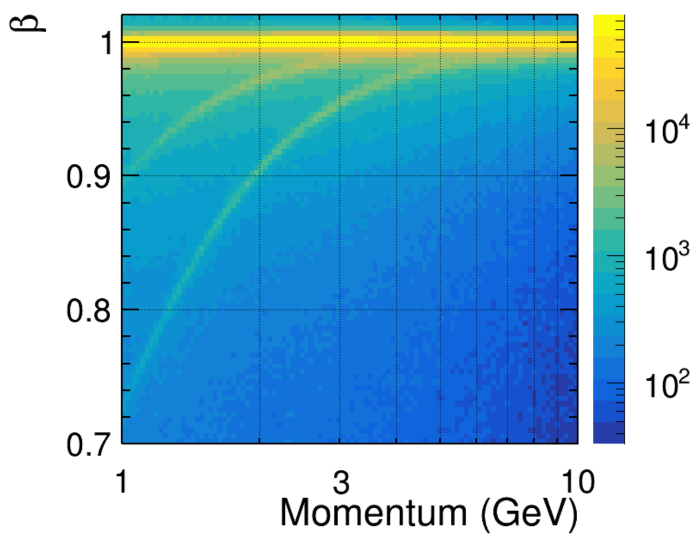


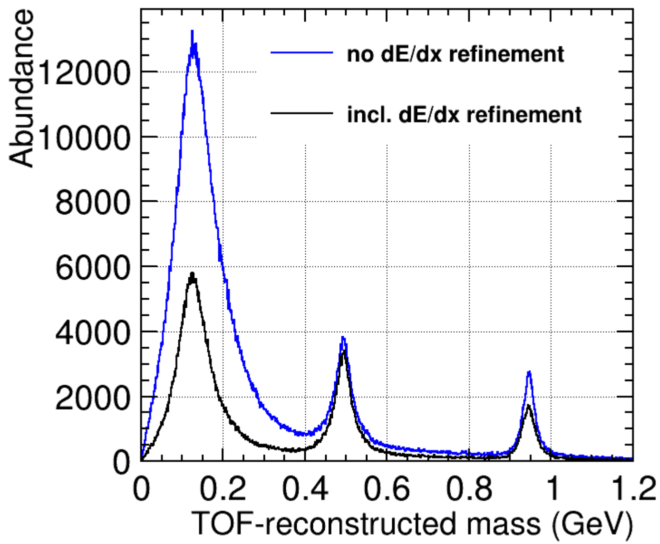


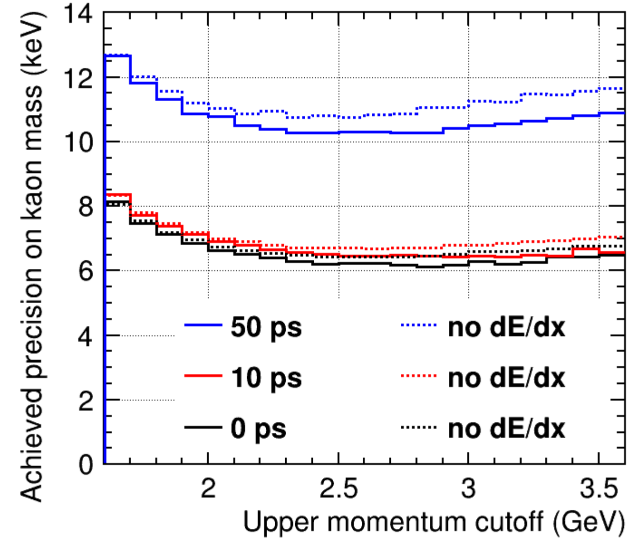
Kaon mass with TOF PID

by UE, https://agenda.linearcollider.org/event/8649

- Side note: In this analysis, the charged kaon mass is extracted using TOF PID, and a bit of dE/dx for refinement and background suppression (only use particles consistent within 2.5 σ with being a kaon)



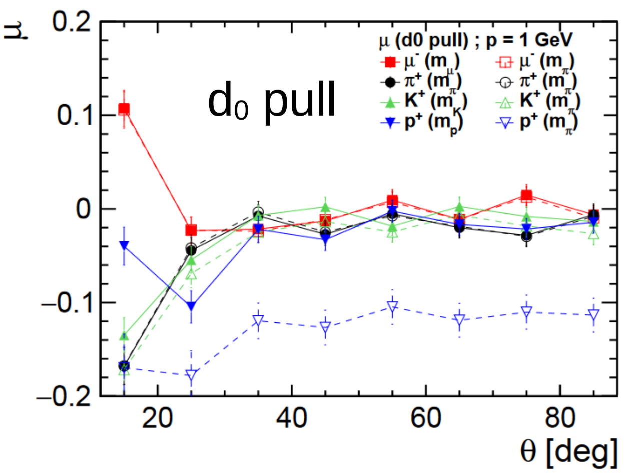


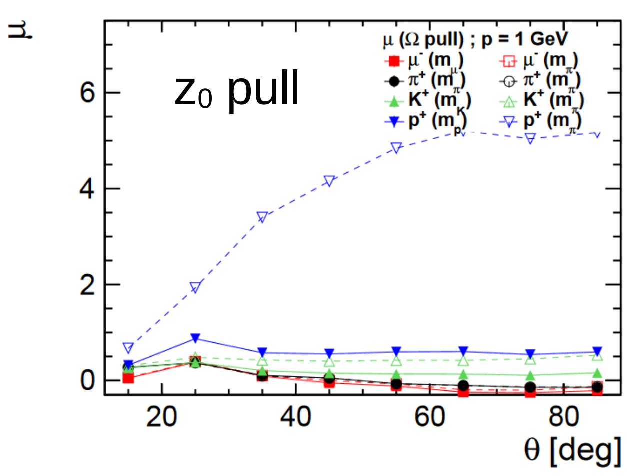


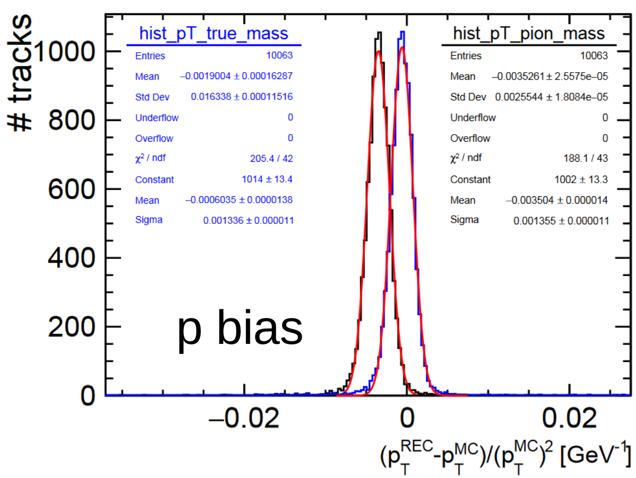
Track refitting with PID mass

by Yasser Radkhorrami, https://agenda.linearcollider.org/event/8498, and Bohdan Dudar

- All tracks are fitted assuming pion mass
- Yasser studied fitting with correct mass, which gives
  - better estimates of track parameters
  - better estimates of momentum and impact prameters
- Bohdan just started to study improved vertexing from track refit and consequently improved vertex-based flavour tag, using TOF PID







Summary

- dE/dx established in reconstruction
- More analyses using this information, some dedicatedly, some more as “added bonus”
- Implementation needs reliable calibration and easy-access PID extraction

Questions?