CPID: A Comprehensive Particle Identification Framework for Future e^+e^- Colliders

Uli Einhaus
International Workshop on Future Linear Colliders
16.05.2023, SLAC
ulrich.einhaus@desy.de

HELMHOLTZ

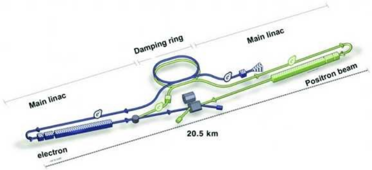
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

ILD

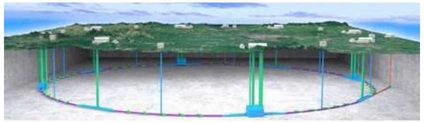
DESY.

The Landscape of Proposed Next-Gen Colliders / Future HTE Factories

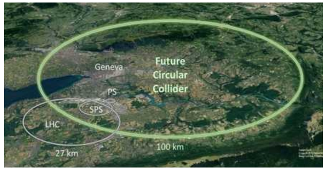
ILC



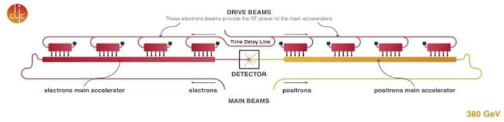
CEPC



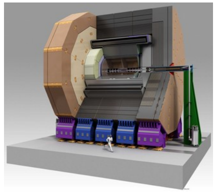
FCC-ee



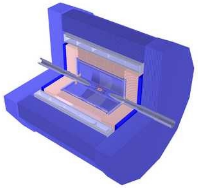
CLIC



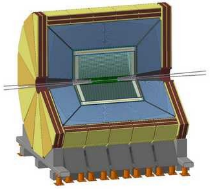
ILD



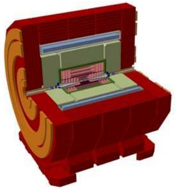
CEPC Baseline



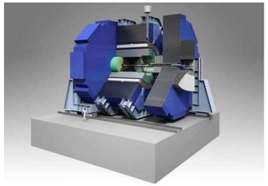
IDEA



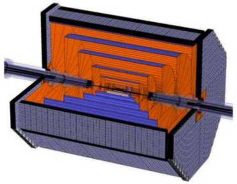
CLICdp



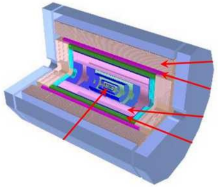
SiD



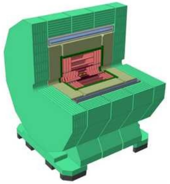
FST



CEPC 4th concept



CLD

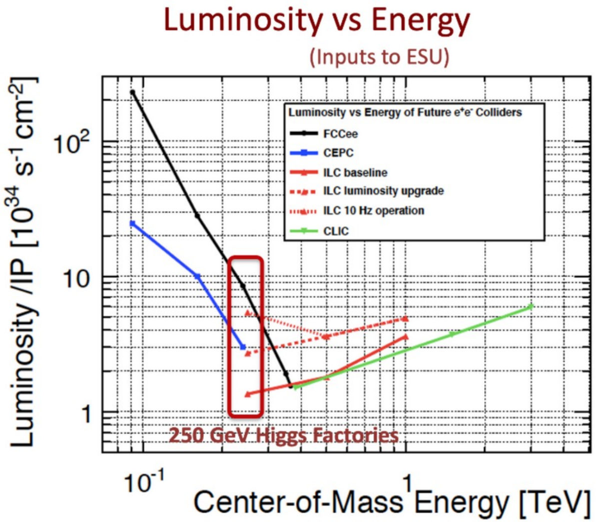


slide stolen from B. Dudar

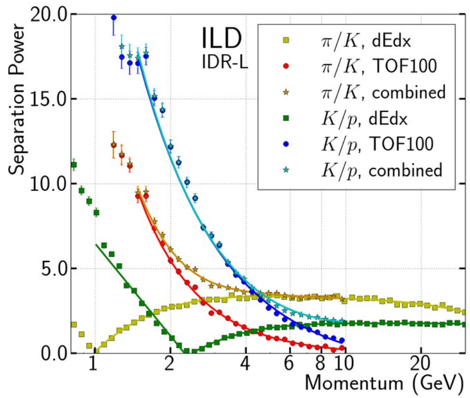
- Many proposals under consideration – common tools desired, in particular software!
  → key4HEP / EDM4HEP

PID at Future Higgs/Top/Electroweak Factories

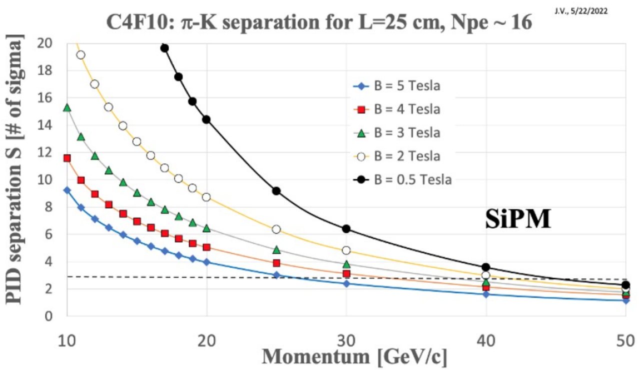
- Increasing understanding that particle identification (PID), in particular charged hadron ID, is a very valuable observable at a Future Higgs Factories
- Recent studies focus on 90-250 GeV and precision flavour physics instead of direct (BSM) detection at TeV range → PID is more effective and more relevant there
- This work: new software framework for comprehensive PID



https://arxiv.org/abs/1903.01629



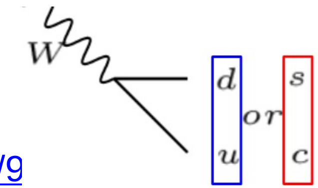
https://arxiv.org/abs/2003.01116

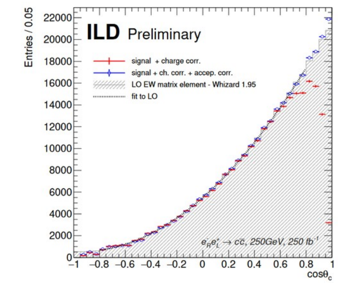


https://arxiv.org/abs/2203.07535

Examples for PID Applications

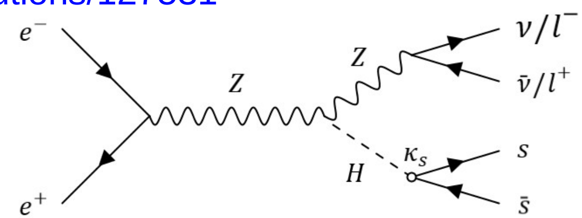
- Z and W hadronic decay branching fractions via flavour tagging
  → make connection between quark flavour and jet composition
  https://ediss.sub.uni-hamburg.de/handle/ediss/9634 , https://ediss.sub.uni-hamburg.de/handle/ediss/9



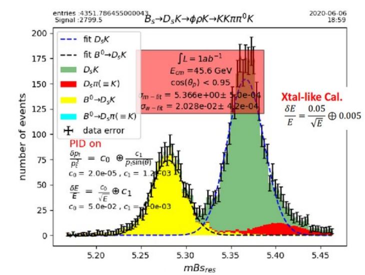


- Forward-backward asymmetry in $e^+e^- \rightarrow q\bar{q}$
  → study asymmetry in each flavour channel exclusively
  overview: https://indico.desy.de/event/33640/contributions/127531

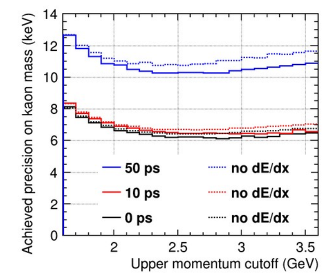
- H → $s\bar{s}$ with s-tagging → identify high-momentum kaons to tag $s\bar{s}$ events
  https://arxiv.org/abs/2203.07535



- B and tau physics rely on excellent PID, mostly relevant at Z pole e.g. https://indico.in2p3.fr/event/23012/contributions/89990



- Kaon mass with TOF
  https://pos.sissa.it/380/115/



- Track refit with correct particle mass for better momentum and vertex
  https://agenda.linearcollider.org/event/8498/

- Overview: https://indico.cern.ch/event/1256374/contributions/5338875/

Possible PID Technology

- Gaseous trackers (Time Projection Chamber, Drift Chamber): specific energy loss dE/dx, via gas ionisation, up to 30 GeV

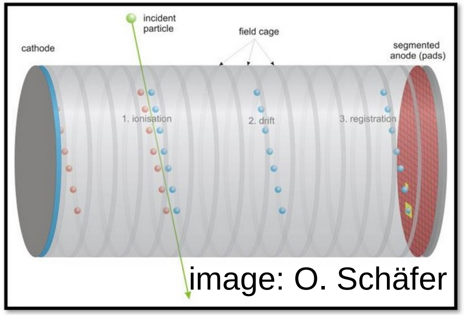
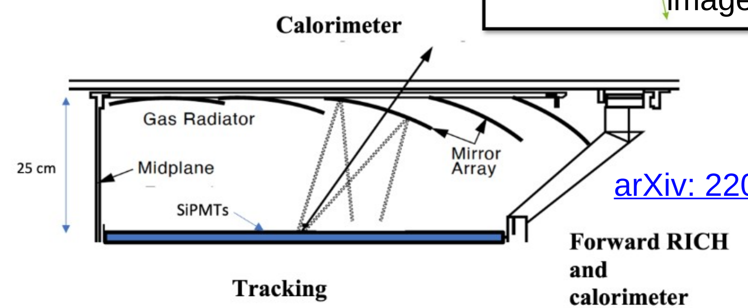


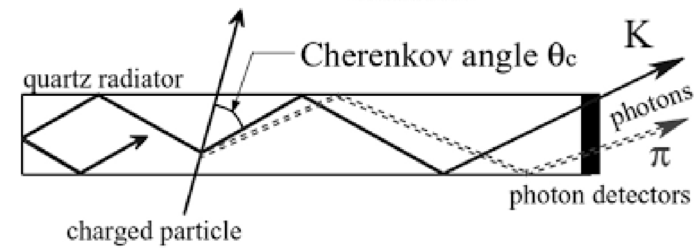
image: O. Schäfer

- Ring Imaging Cherenkov Detectors: Cherenkov angle, via imaging, 10 to 50 GeV



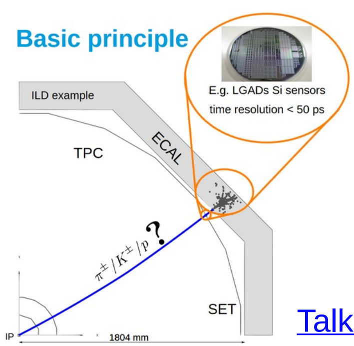
arXiv: 2203:07535

- Time of Propagation Counter: Cherenkov angle, via timing, up to 10 GeV



https://doi.org/10.1016/j.nima.2017.02.045

- Time of Flight: time, via Silicon timing, up to 5 GeV



Talk by Bohdan

Central Questions

- How do we combine the different technologies best?
- How can we create a general assessment of PID performance valid for all of them?
- Can we use machine learning to extract the best performance from the PID observables?
- Optimise detectors and compare them
  - At what timing resolution starts TOF to be relevant for flavour tagging?
  - How does **my** physics channel depend on the dE/dx (dN/dx) resolution?
  - What if we use a silicon tracker + RICH instead of a TPC in ILD?

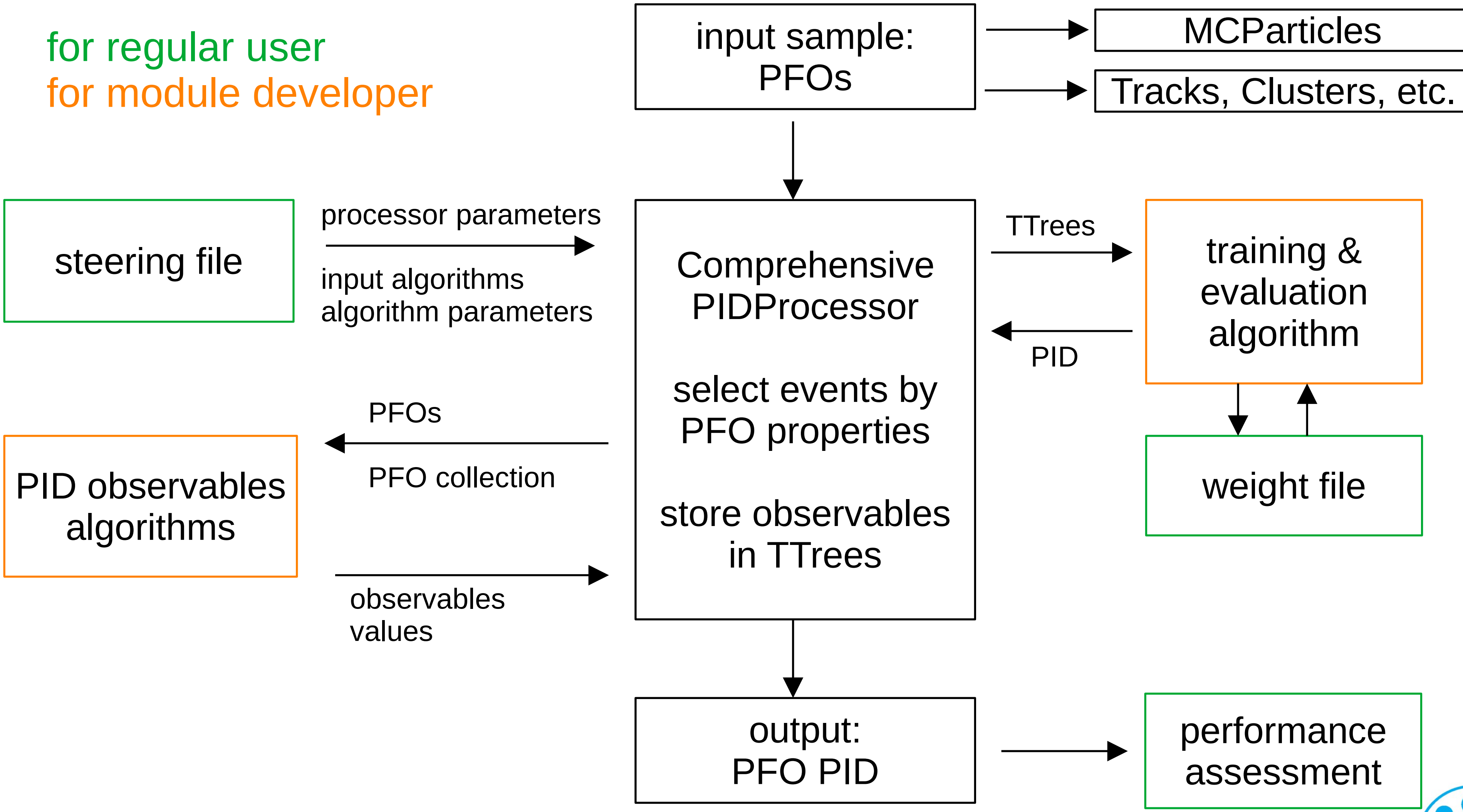
New Framework: Comprehensive Particle Identification (CPID)

- Modularity as core philosophy:
  - observables algorithms
  - training methods (MVAs / NNs / etc.)
- Core code takes care of book keeping
  - simple, well defined data structures for storage (TTree) and interfaces (std::vector)

- For now, being implemented in LCIO / Marlin in iLCSoft
  - immediately usable in Key4HEP via ‘Marlin wrapper’
  - target: implement in EDM4HEP, make available to whole future colliders community
- In ILD: goal to replace current LikelihoodPIDProcessor

General Structure

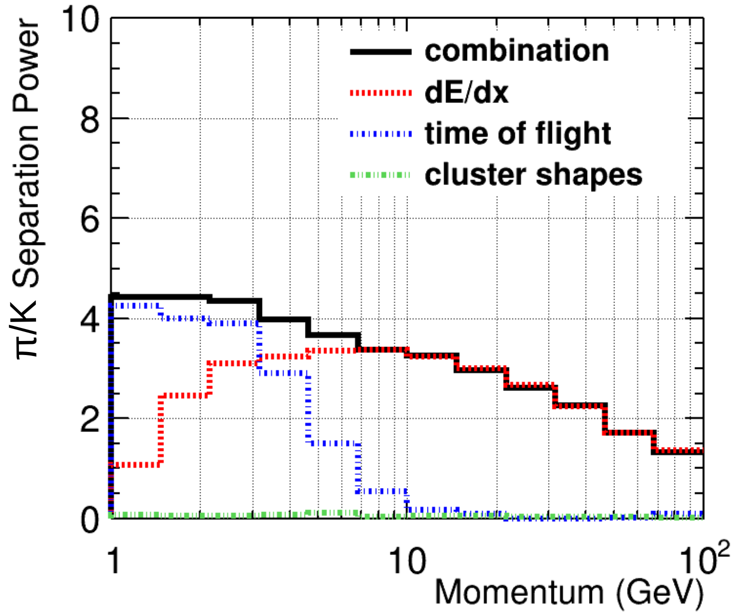
for regular user
for module developer



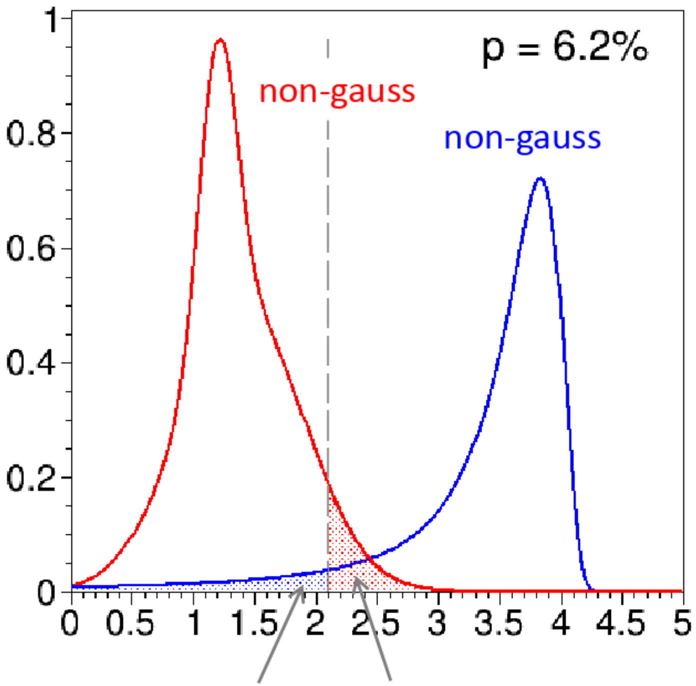
Example 1: π/K Separation with Combined Observables

- dE/dx + TOF
- Single particles ‘calibration’ events, flat in log(p) and cos(θ)
- BDT with sig = K, bkg = π; train & infer per 12 mom bins and per used observable(s)

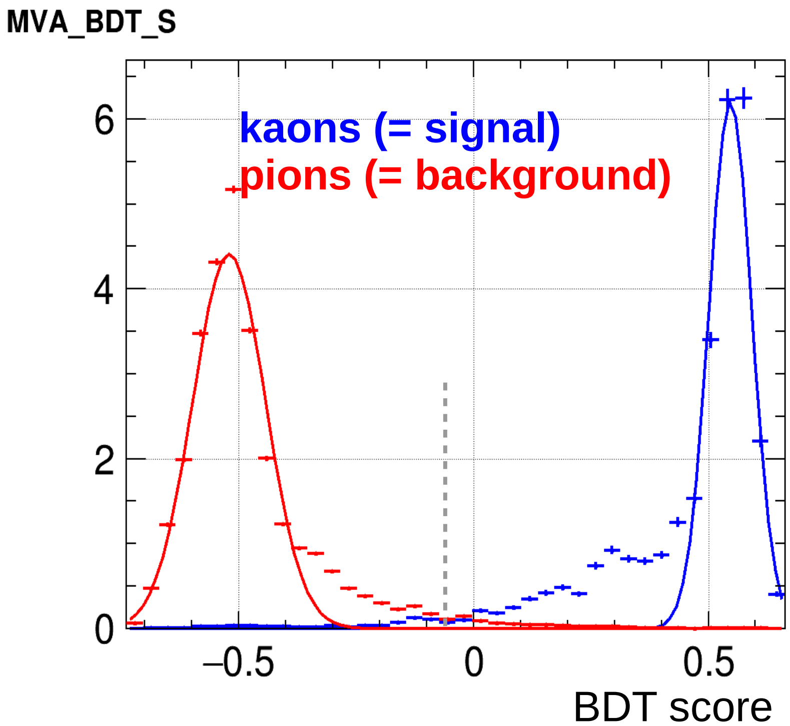
  → How do we calculate a separation power from a BDT score?



- Find cut with mis-ID = 1 - efficiency = p-value → find Gaussian quantile → compute Z = 2 · quantile of standard Gauss



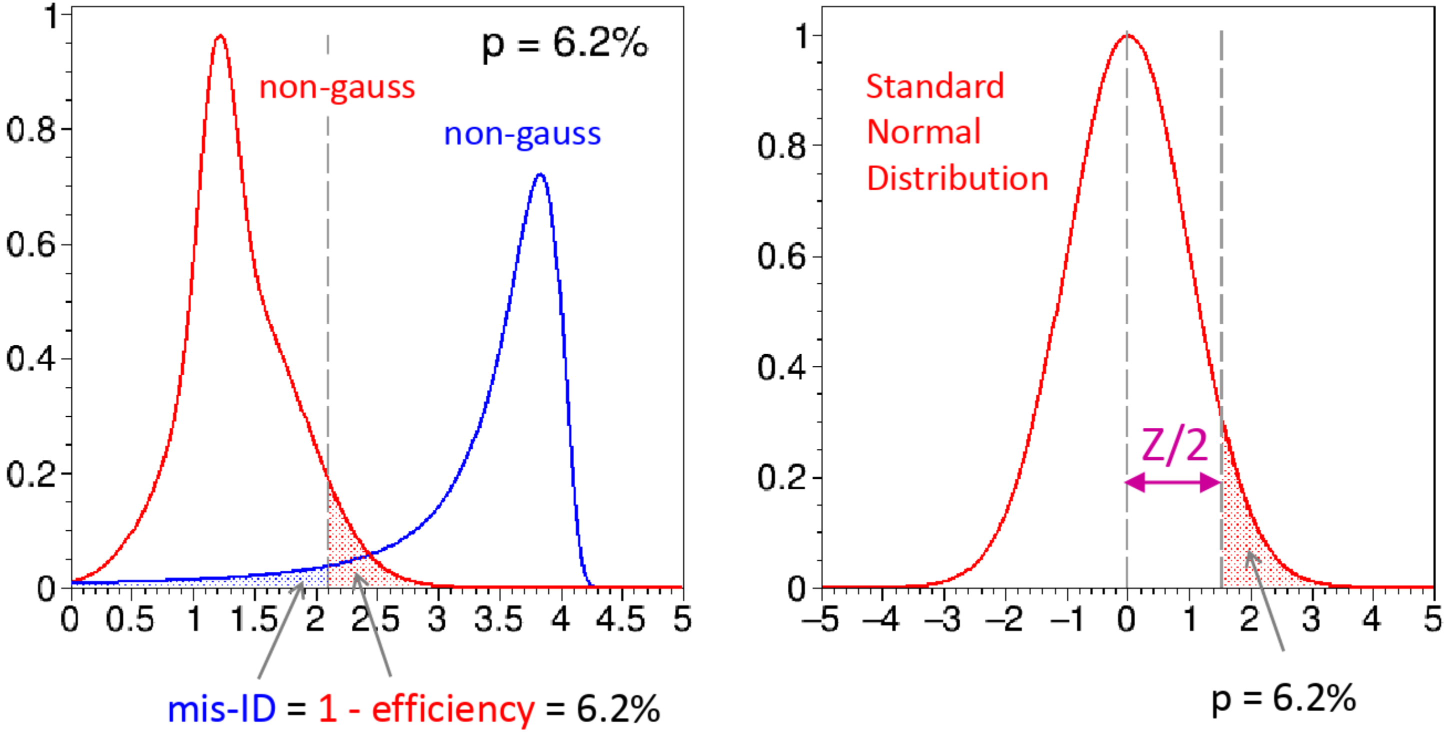
mis-ID = 1 - efficiency = 6.2%



K. Götzen: https://indico.gsi.de/event/7080/contributions/31950/attachments/22952/28789/pid_kgoetzen_separationpower.pdf

p-value Assessment

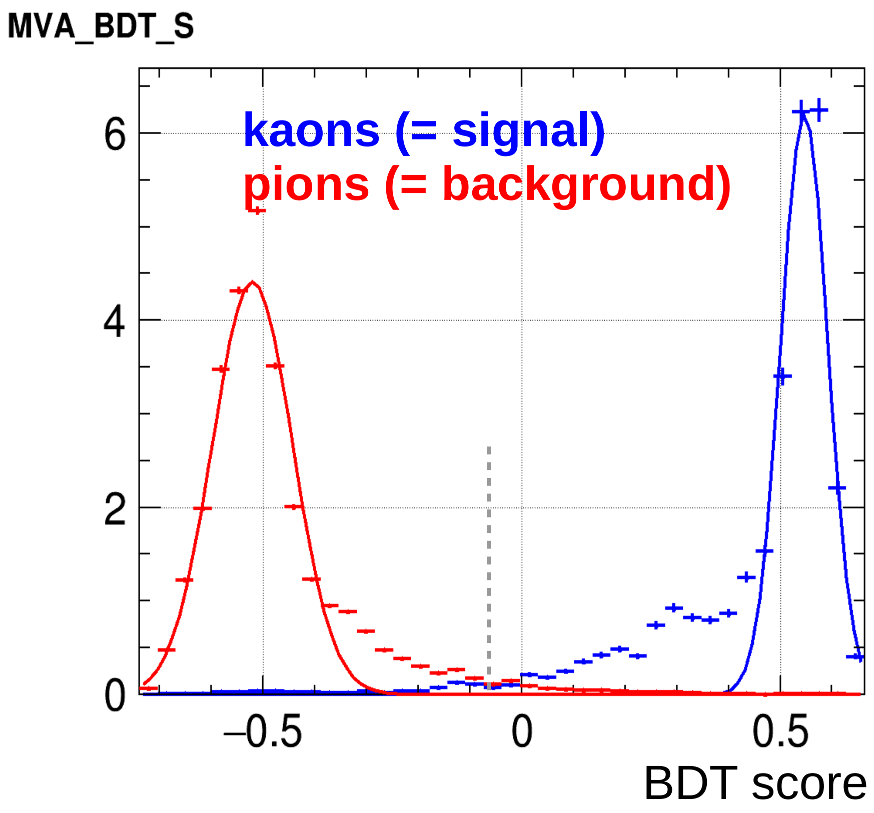
- Find cut with mis-ID = 1 - efficiency = p-value → find Gaussian quantile
  → compute $Z = 2 \cdot$ quantile of standard Gauss

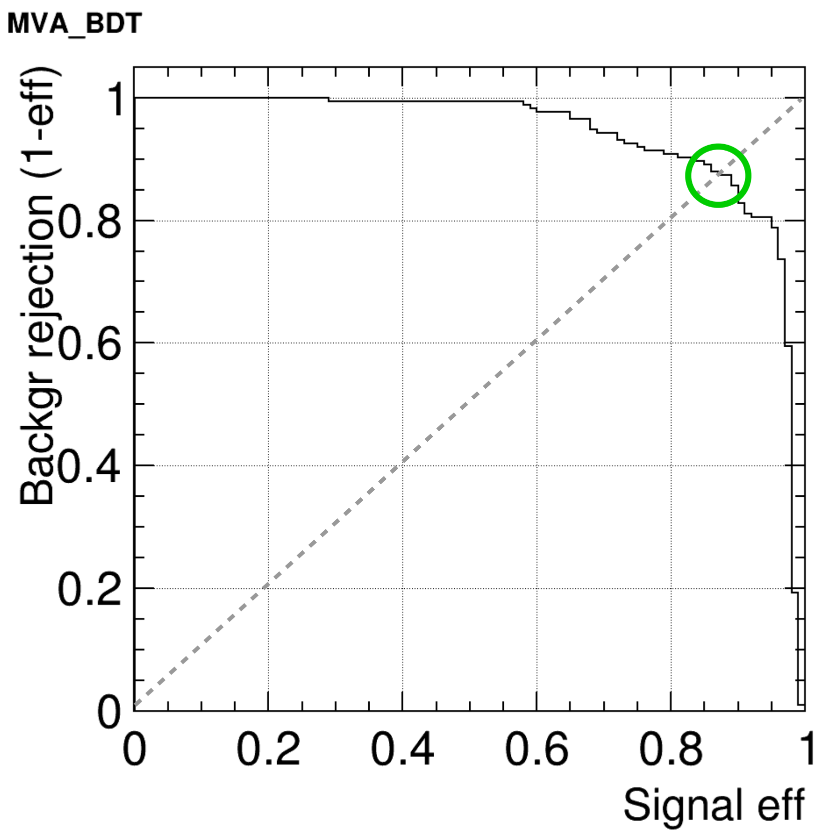


K. Götzen: https://indico.gsi.de/event/7080/contributions/31950/attachments/22952/28789/pid_kgoetzen_separationpower.pdf

p-value Assessment

- ‘Central tail split’ of BDT score is equivalent to crossing point of ROC curve with x=y line

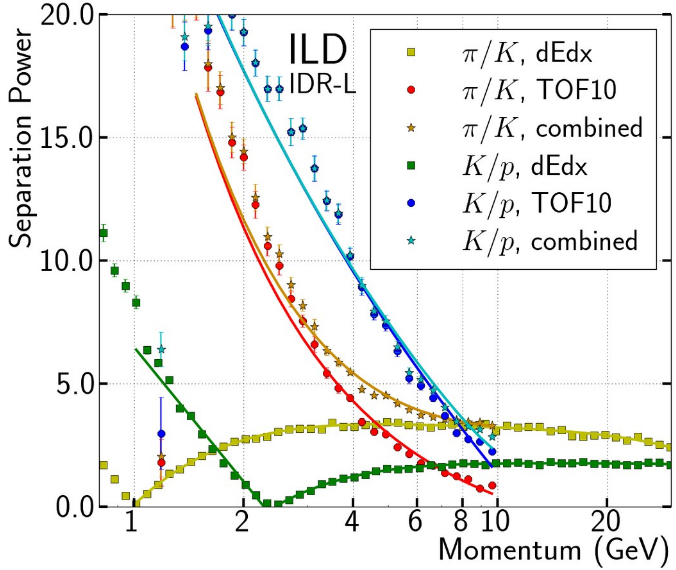




Example 1: π/K Separation with Combined Observables

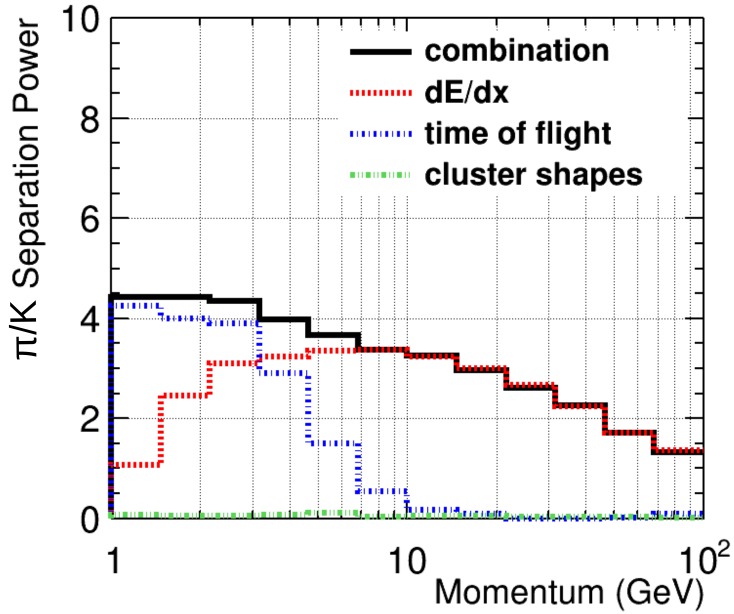
- dE/dx + TOF
- Single particles ‘calibration’ events, flat in log(p) and cos(θ)
- BDT with sig = K, bkg = π; train & infer per 12 mom bins and per used observable(s)

ILD Interim Design Report



https://arxiv.org/abs/2003.01116

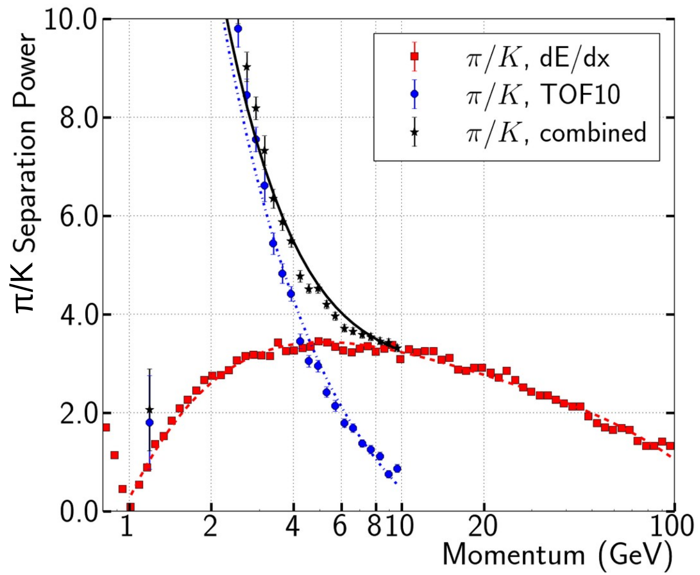
CPID, BDT result



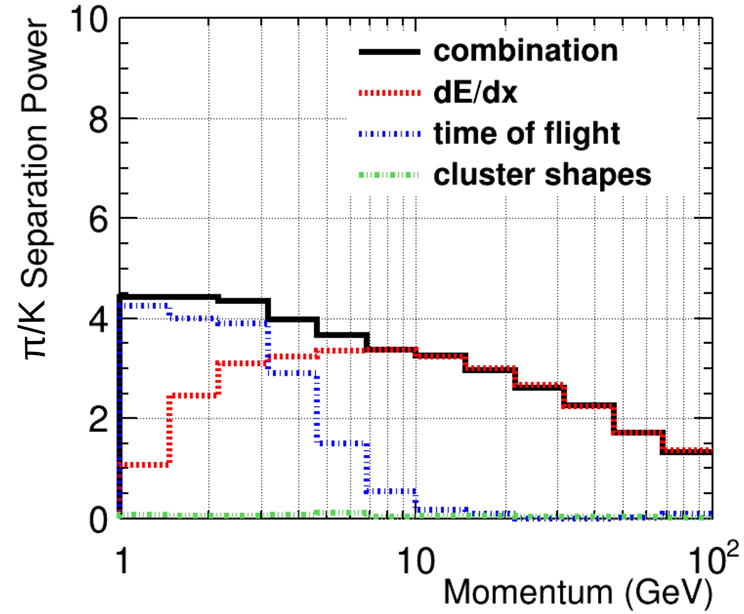
Example 1: π/K Separation with Combined Observables

- dE/dx very similar
- TOF levels out at low momenta due to misreconstructed events, which cause a constant finite background in the p-value assessment
  → still covers dE/dx blind spot, S > 4 still good enough!
  → same performance, less ‘fancy’ way to show it, but more honest

analogue to ILD Interim Design Report

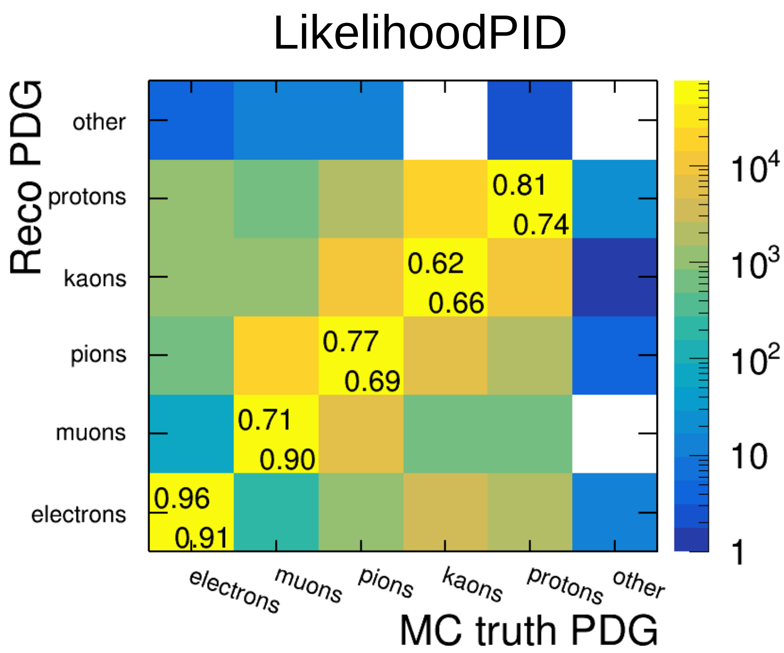


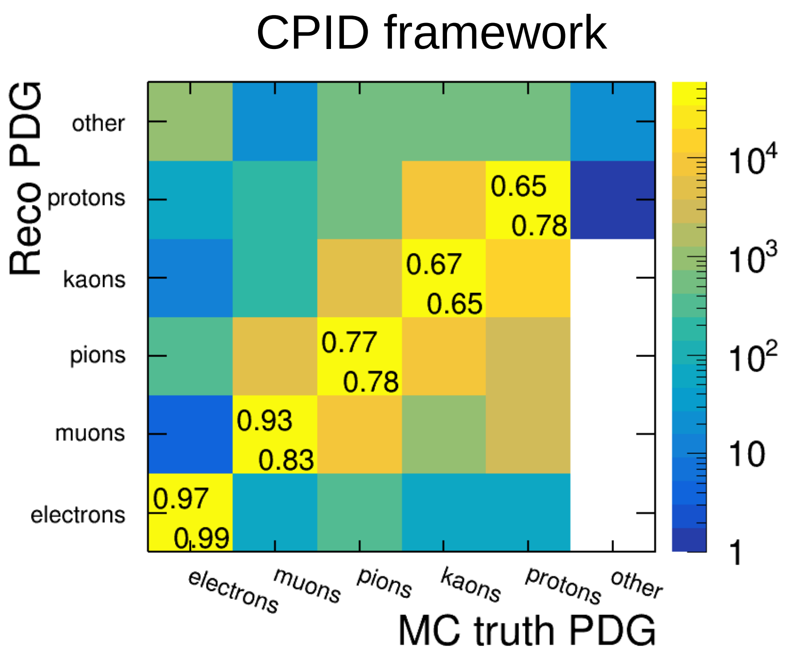
CPID, BDT result



Example 2: Multiclass Confusion Matrix

- dE/dx + calorimeter cluster shapes
- Single particle 'calibration' events, flat in log(p) and cos(θ)
- e, μ, π, K, p; multiclass BDT; confusion matrix with eff/pur on diagonal
- CPID with simple BDT already competitive to LikelihoodPID

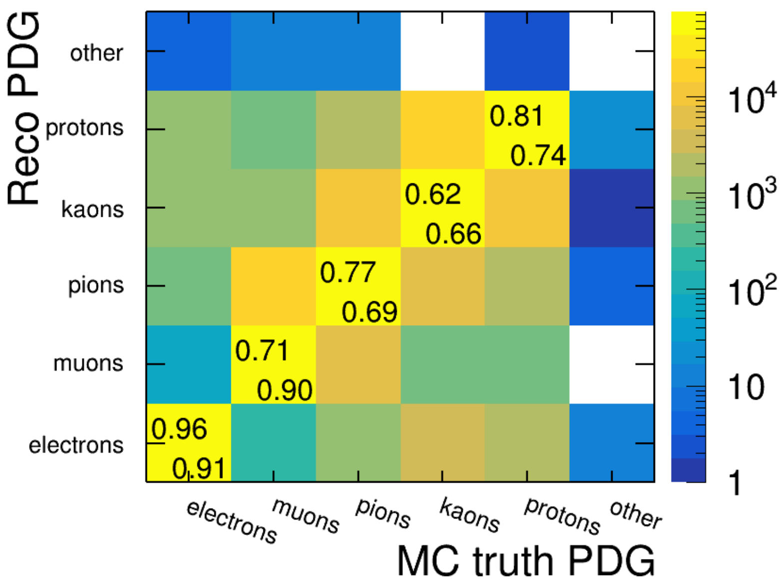




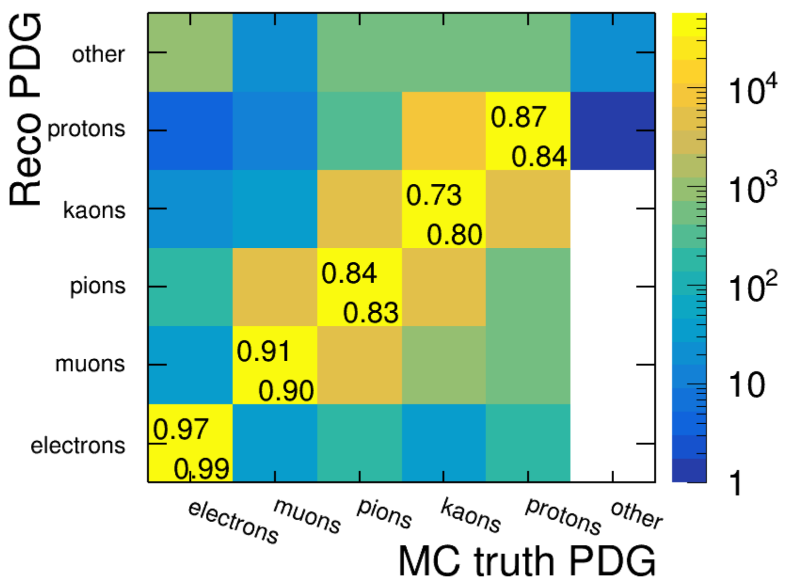
Example 2: Multiclass Confusion Matrix

- dE/dx + calorimeter cluster shapes
- Single particle ‘calibration’ events, flat in log(p) and cos(θ)
- e, μ, π, K, p; multiclass BDT; confusion matrix with eff/pur on diagonal
- Addition of TOF gives immediately better result – previously hard, easy in CPID

LikelihoodPID



CPID framework; + TOF



Summary

- New Comprehensive PID framework under development
- Aims to provide common platform for future e+e- Higgs factories
- Allow for
  - combining and comparing PID techonologies
  - assessing on full detector level with robust performance quantities
  - easy-to-use retraining and flexible adaptation
- First performance indicators already comparable to state-of-the-art
- Application to ongoing ILD physics analyses under discussion

- Your feedback and input are welcome!

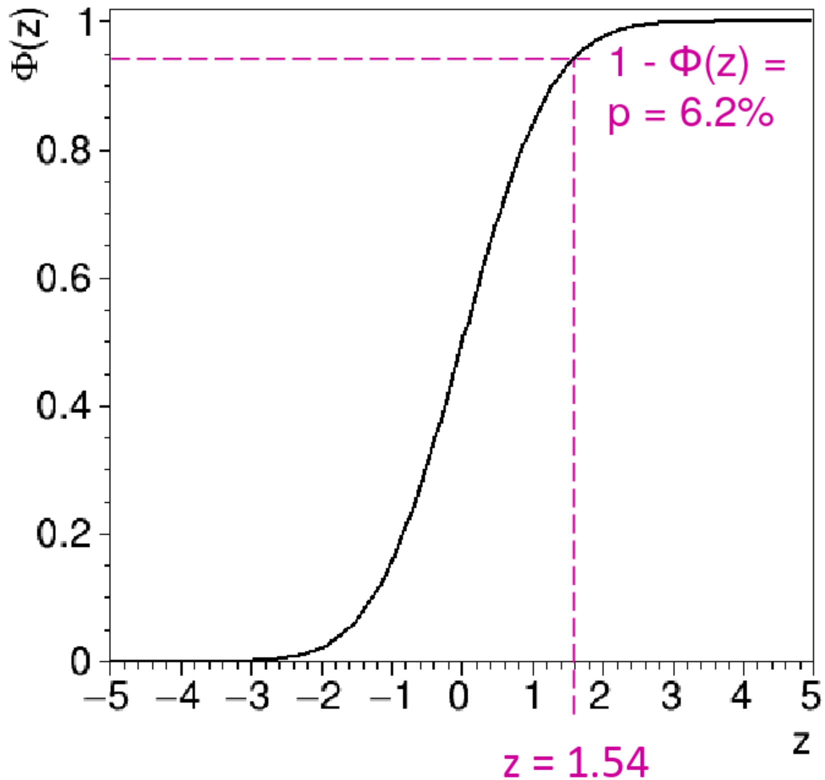
What is particle identification / PID

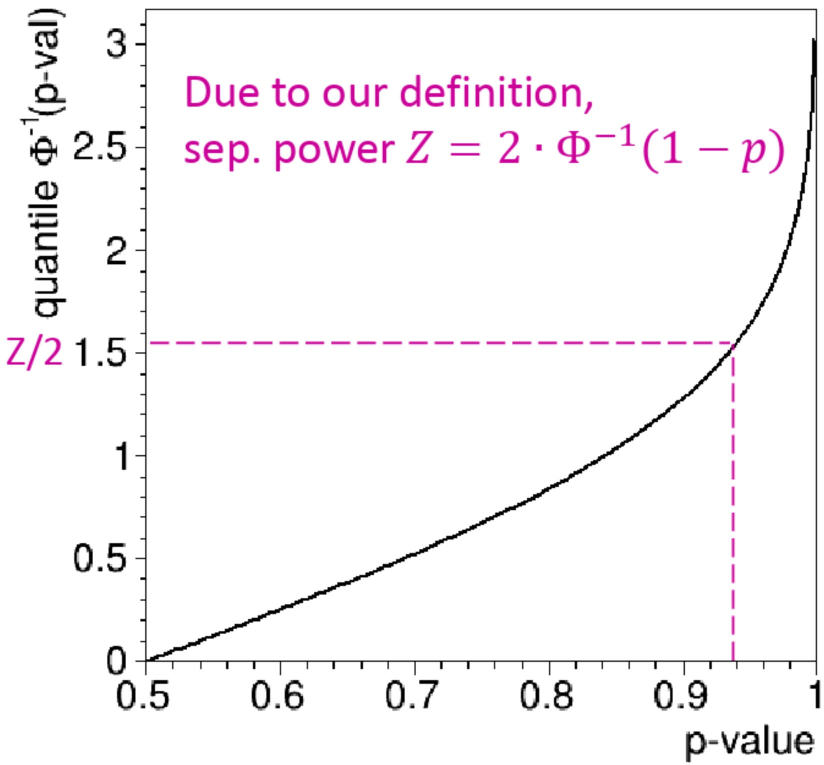
- Identification of the species of high energy particles

  → e.g. e, μ, γ, π, K, p, Λ, n, *[whatever is detector-stable]*
- Focus of dedicated PID systems is on charged hadron separation, specifically kaon ID
- Dedicated electron and muon ID relevant at lower momenta
- Also don't forget V0s: K^0_S, Λ

p-value assessment

Gaussian quantile is inverse of distribution function $\Phi(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Z} e^{-z^2/2}\, dz$






```
ROOT::Math::gaussian_cdf(z)
```

```
ROOT::Math::gaussian_quantile_c(p,1)
```

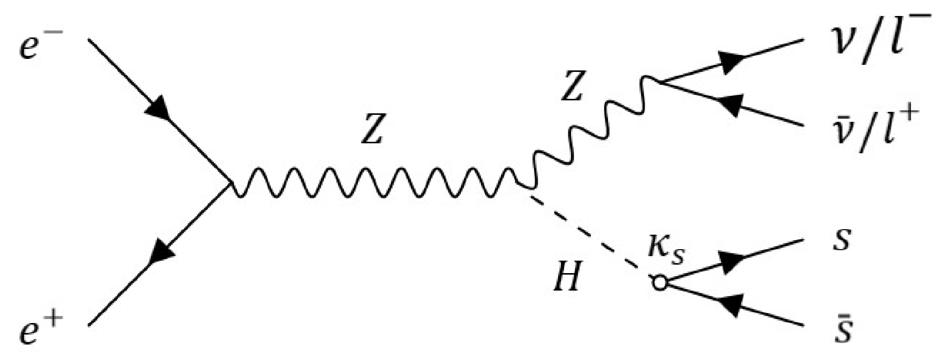
K. Götzen: https://indico.gsi.de/event/7080/contributions/31950/attachments/22952/28789/pid_kgoetzen_separationpower.pdf

Higgs to strange

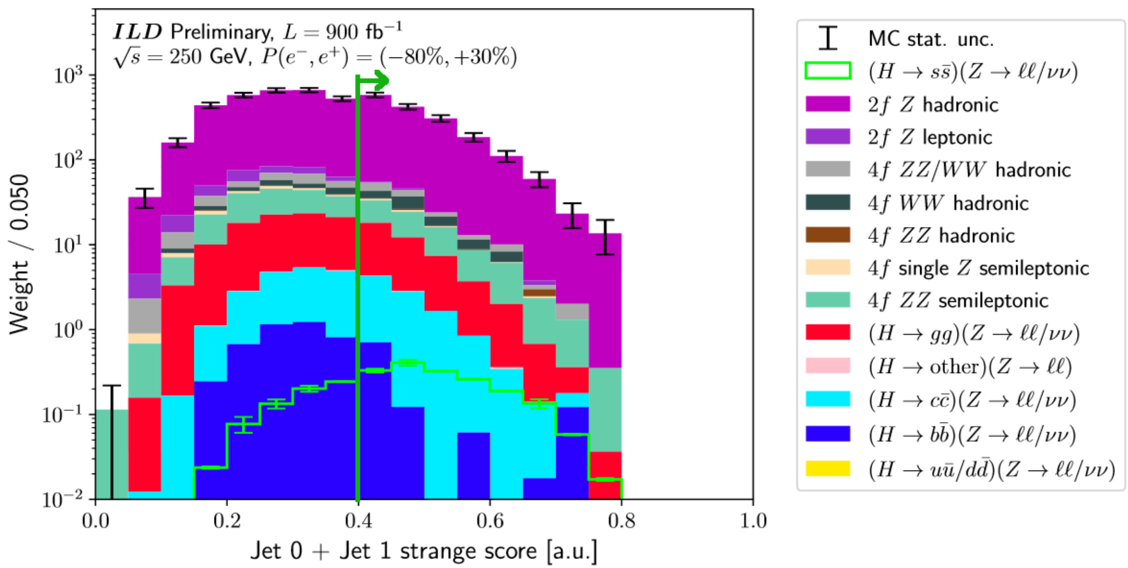
- Study Higgs to strange coupling
- Cute-based analysis, final cut:

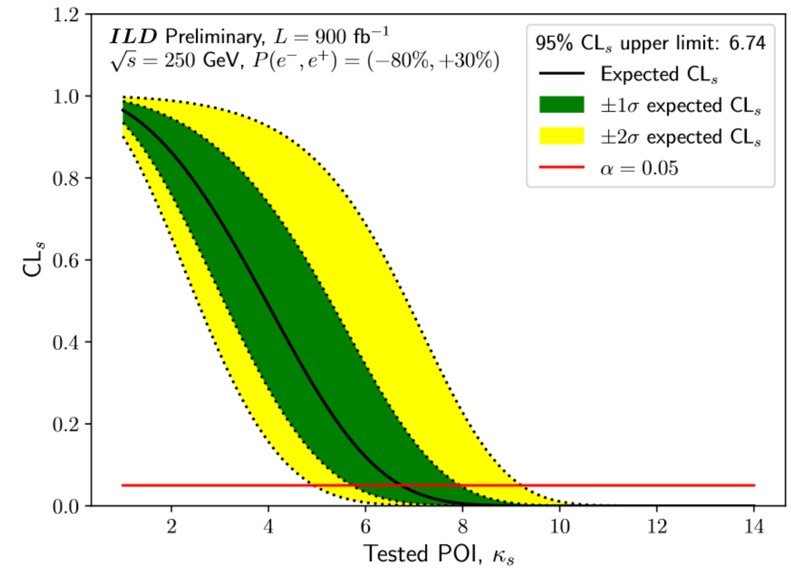
  developed strange tagger using $K^{\pm}$, K^0_S, Λ^0

  → allows to cut background by factor 3
- Results in upper limit on $\kappa_s < 6.7$



https://arxiv.org/abs/2203.07535





View of the steering file

- Steering file
  - input sample
  - observables algorithms
  - signal categories PDGs
  - evaluation algorithm
  - weight file
  - sample cuts etc.

```
<processor name="MyComprehensivePIDProcessor" type="ComprehensivePIDProcessor">

  <parameter name="PFOCollection" type="string" value="PandoraPFOs"/>

  <parameter name="inputAlgoSpecs" type="StringVec">
    dEdx
    TOF:TOF0
    TOF:TOF10
    TOF:TOF50
    dEdx_RCD:dEdx_RCD
  </parameter>

  <parameter name="dEdx.F" type="FloatVec"  value="1 2 3"/>
  <parameter name="dEdx.S" type="StringVec" value="a b c"/>

  <parameter name= "TOF0.S" type="StringVec" value="TOFEstimators0ps" />
  <parameter name="TOF10.S" type="StringVec" value="TOFEstimators10ps"/>
  <parameter name="TOF50.S" type="StringVec" value="TOFEstimators50ps"/>

  <parameter name="dEdx_RCD.F" type="FloatVec">
    -1.28883368e-02   2.72959919e+01   1.10560871e+01 -1.74534200e+00  -9.84887586e-07
     6.49143971e-02   1.55775592e+03   9.31848047e+08  2.32201725e-01   2.50492066e-04
     6.54955215e-02   8.26239081e+04   1.92933904e+07  2.52743206e-01   2.26657525e-04
     7.52235689e-02   1.59710415e+04   1.79625604e+06  3.15315795e-01   2.30414997e-04
     7.92251260e-02   6.38129720e+04   3.82995071e+04  2.80793601e-01   7.14371743e-04
  </parameter>

</processor>
```