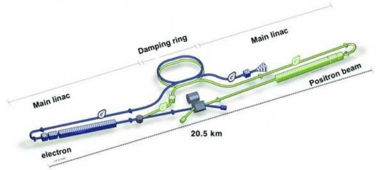
CPID: A Comprehensive Particle Identification Framework for Future e^+e^- Colliders

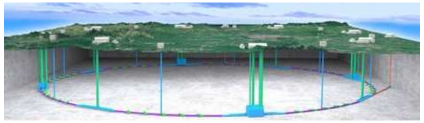
Uli Einhaus
DPG Frühjahrstagung
21.03.2023 Dresden
ulrich.einhaus@desy.de

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

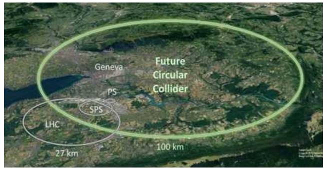
ILC



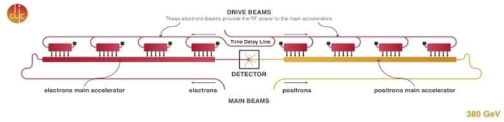
CEPC



FCC-ee

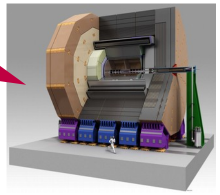


CLIC

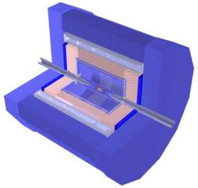


This talk uses ILD

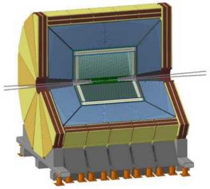
ILD



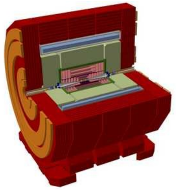
CEPC Baseline



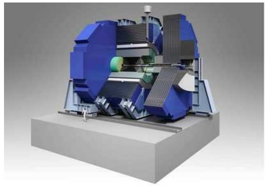
IDEA



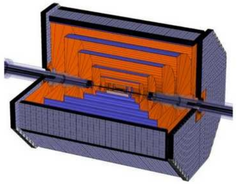
CLICdp



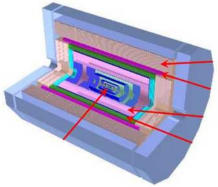
SiD



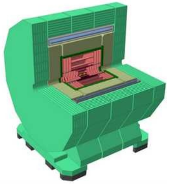
FST



CEPC 4th concept



CLD

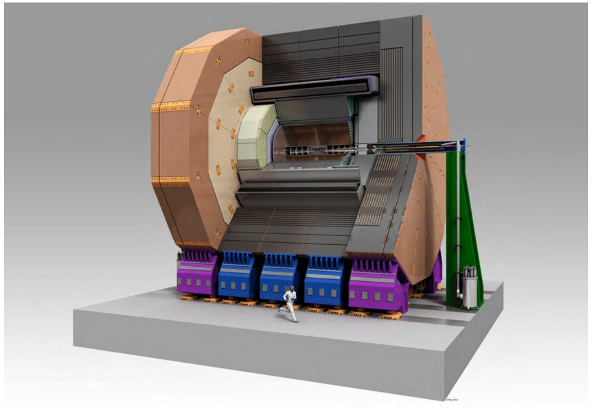


slide stolen from B. Dudar

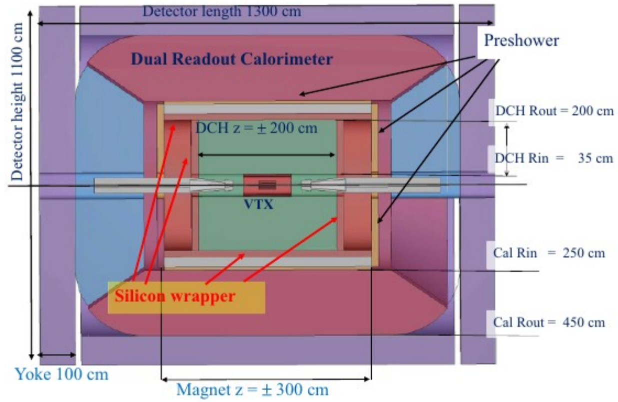
- Many proposals under consideration – common tools desired, in particular software!
  → key4HEP / EDM4HEP

PID at Future Higgs Factories

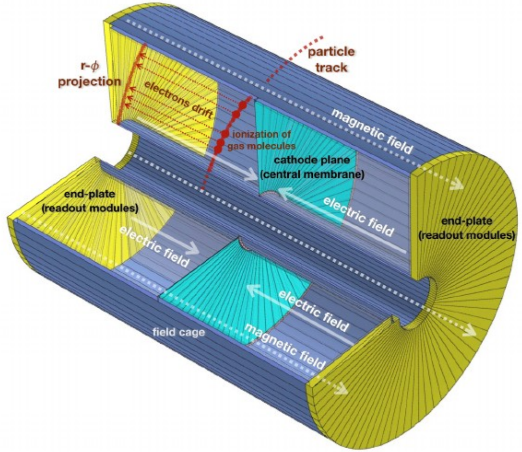
- Increasing understanding that particle identification (PID), in particular charged hadron PID, is a very valuable observable at a Future Higgs Factories
- Recent studies focus on 90-250 GeV and precision flavour physics instead of direct (BSM) detection at TeV range → PID is more effective and more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



ILD

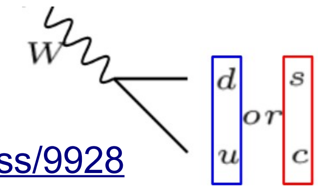


IDEA



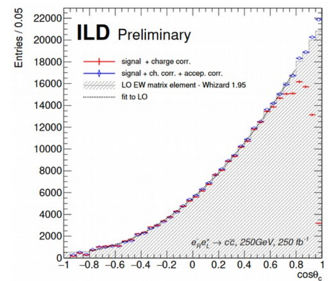
CEPC-det

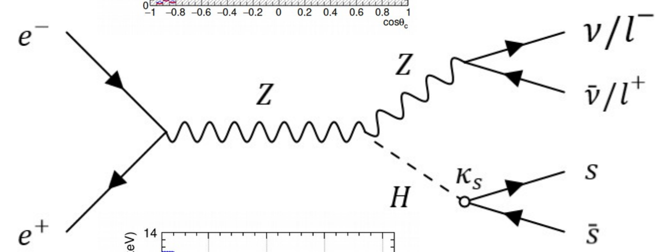
Examples for PID Applications at ILD



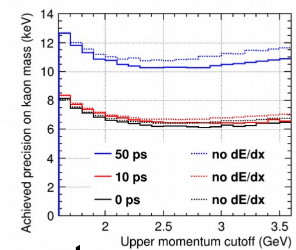
- Z and W hadronic decay branching fractions via flavour tagging
  → make connection between quark flavour and jet composition
  https://ediss.sub.uni-hamburg.de/handle/ediss/9634 , https://ediss.sub.uni-hamburg.de/handle/ediss/9928

- Forward-backward asymmetry in $e^+e^- \to q\bar{q}$
  → study asymmetry in each flavour channel exclusively
  overview: https://tel.archives-ouvertes.fr/tel-01826535
  $e^+e^- \to$ tt, bb: https://agenda.linearcollider.org/event/8147
  $e^+e^- \to$ bb/cc: https://arxiv.org/abs/2002.05805 ,
  https://agenda.linearcollider.org/event/9211/contributions/49358/
  $e^+e^- \to$ bb/cc, ss: https://agenda.linearcollider.org/event/9440 ,
  https://agenda.linearcollider.org/event/9285





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



- 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/

PID Technology

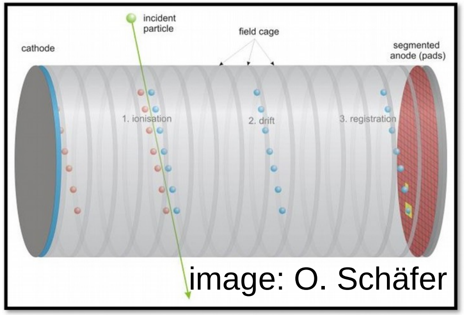
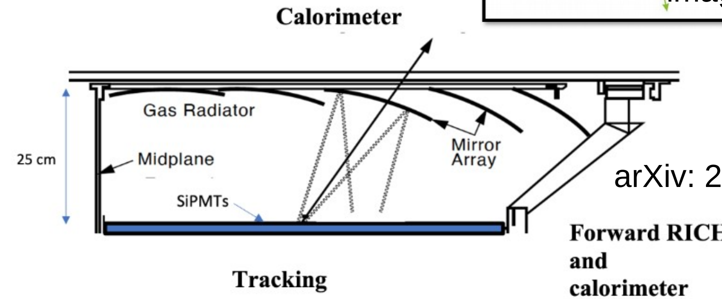


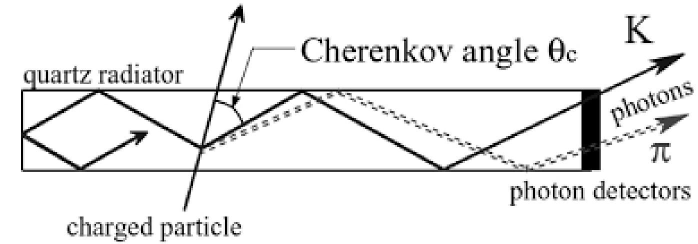
image: O. Schäfer

- Gaseous trackers (Time Projection Chamber, Drift Chamber): specific energy loss dE/dx, via gas ionisation, up to 20 GeV



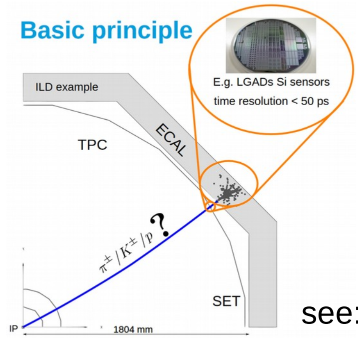
arXiv: 2203:07535

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



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

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



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

see: T 48.5 B. Dudar

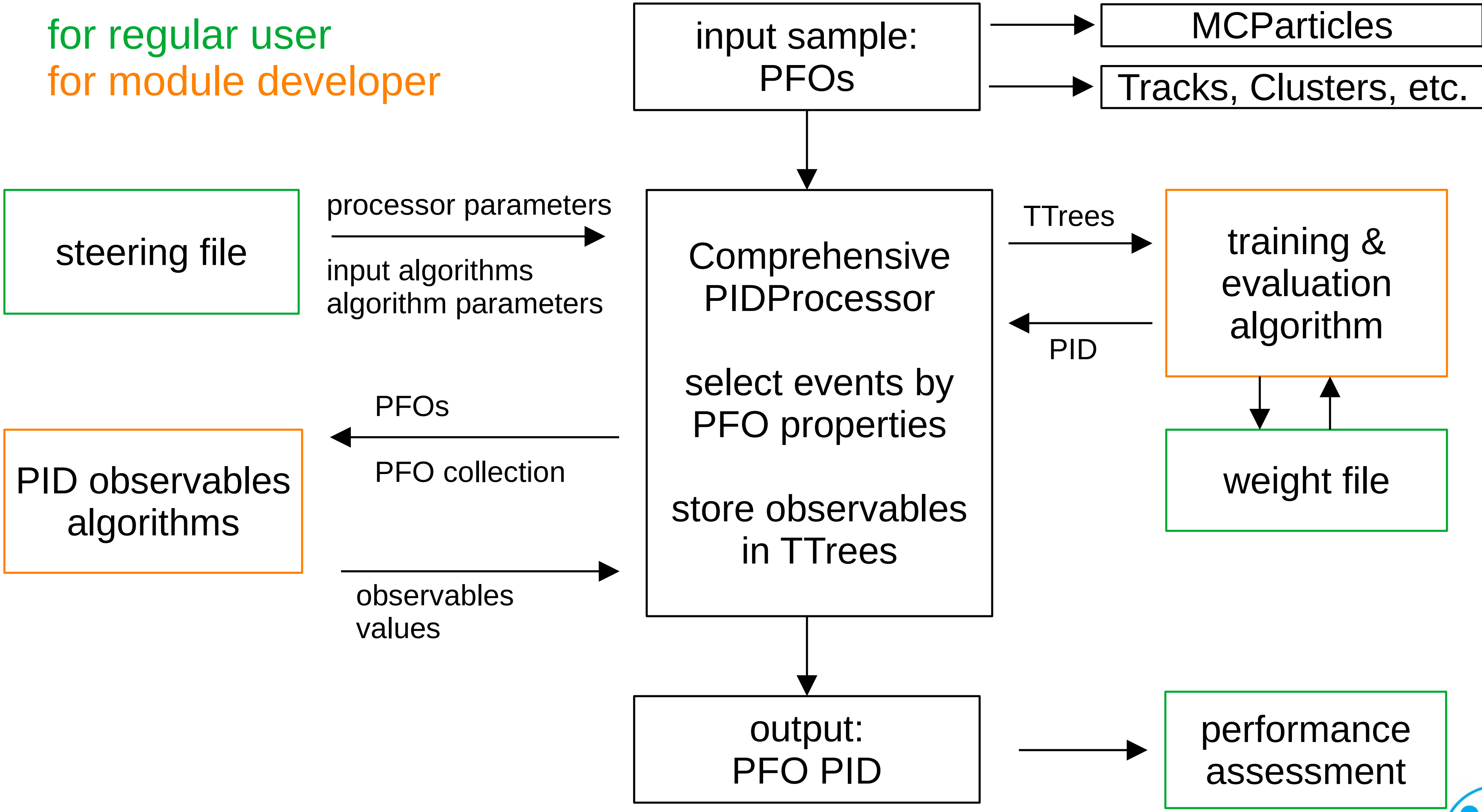
Central Questions

- 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 result depend on the dE/dx resolution?
  - What if we add a RICH to SiD?

New Framework: Comprehensive Particle Identification (CPID)

- Modularity as core philosophy:
  - observables algorithms
  - training methods / evaluation algorithms
- 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, somewhat inflexible algorithm

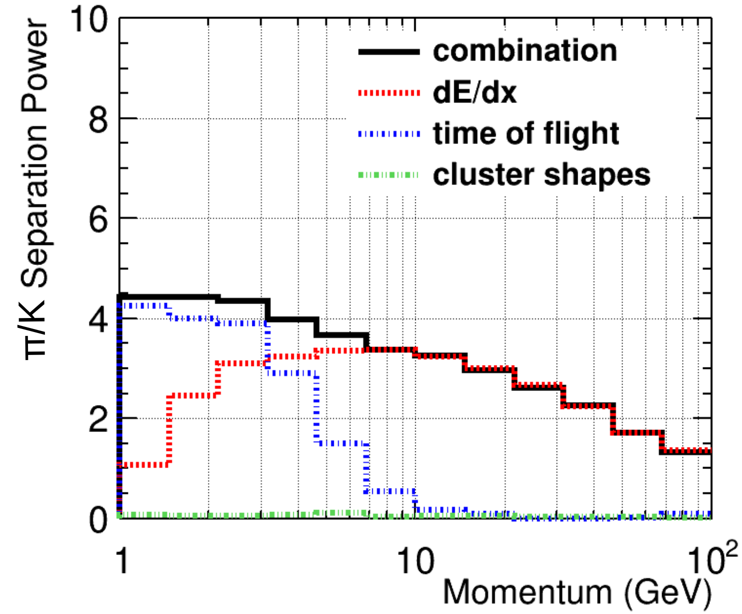
General Structure



Example 1: π/K Separation with Combined Observables

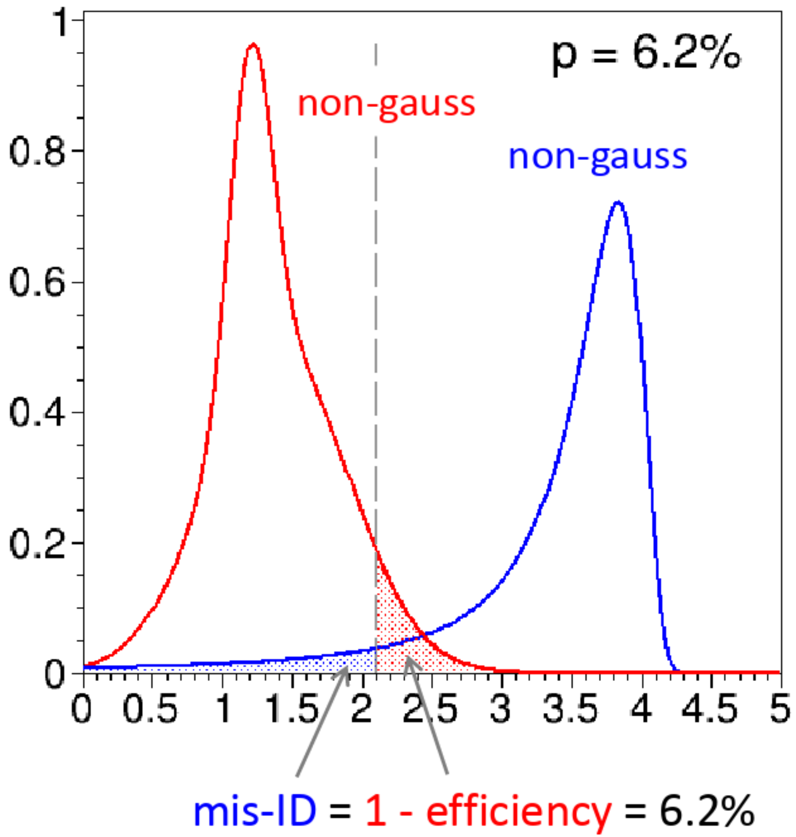
- dE/dx + TOF
- Single particles ‘calibration’ events, flat in log(p) and cos(θ)
- BDT with sig = K, bkg = π; train & eval per 12 mom bins and per used observable(s)

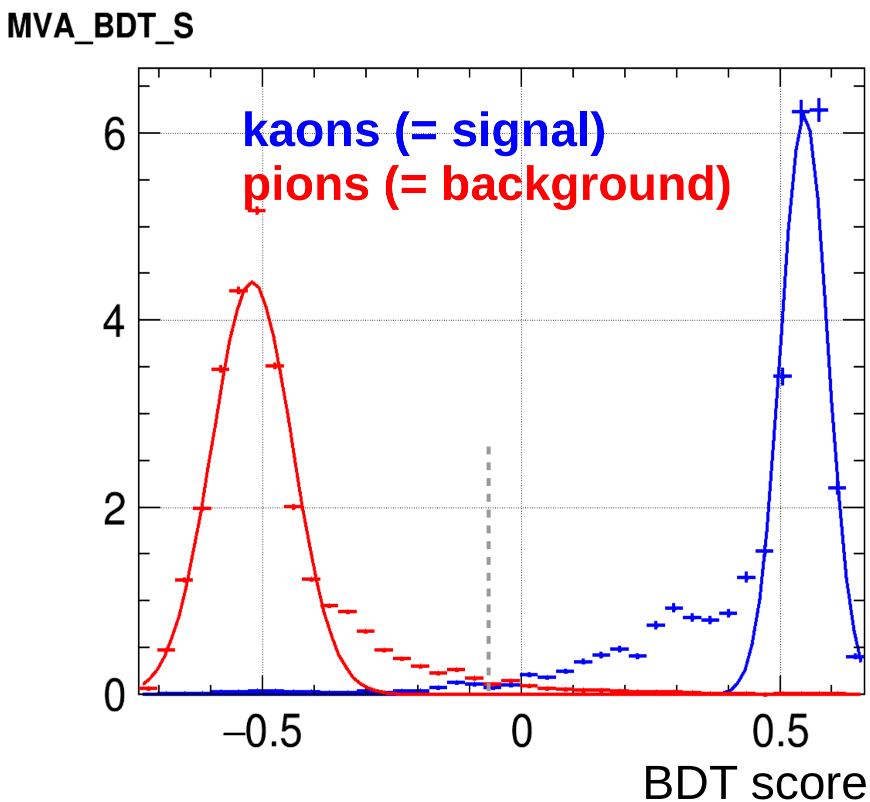
  → How do we calculate a separation power from a BDT score?



p-value Assessment

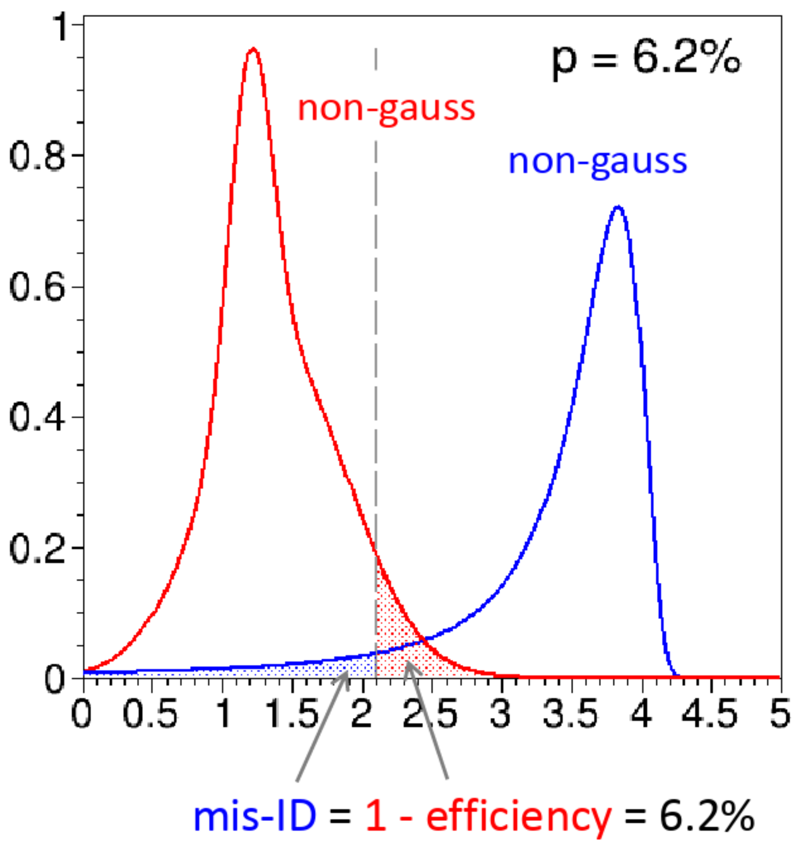
- Find cut with mis-ID = 1 - efficiency = p-value → find Gaussian quantile → compute Z = 2 · quantile of standard Gauss

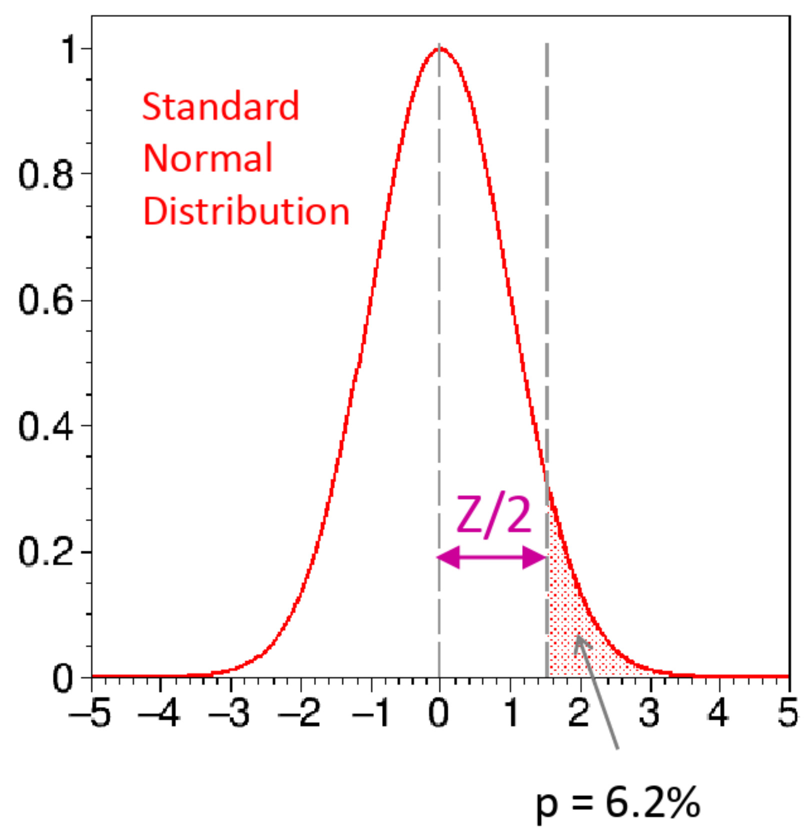




K. Götzen, PID WS GSI 2017:
PANDA Quality Measures for PID Classification Problems

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

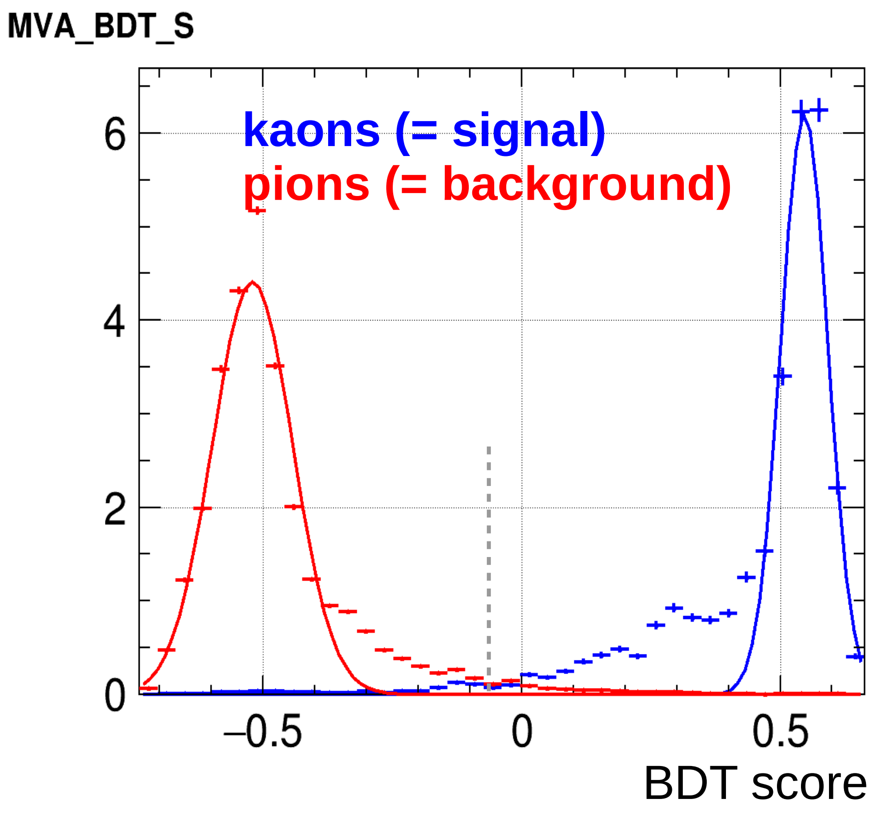


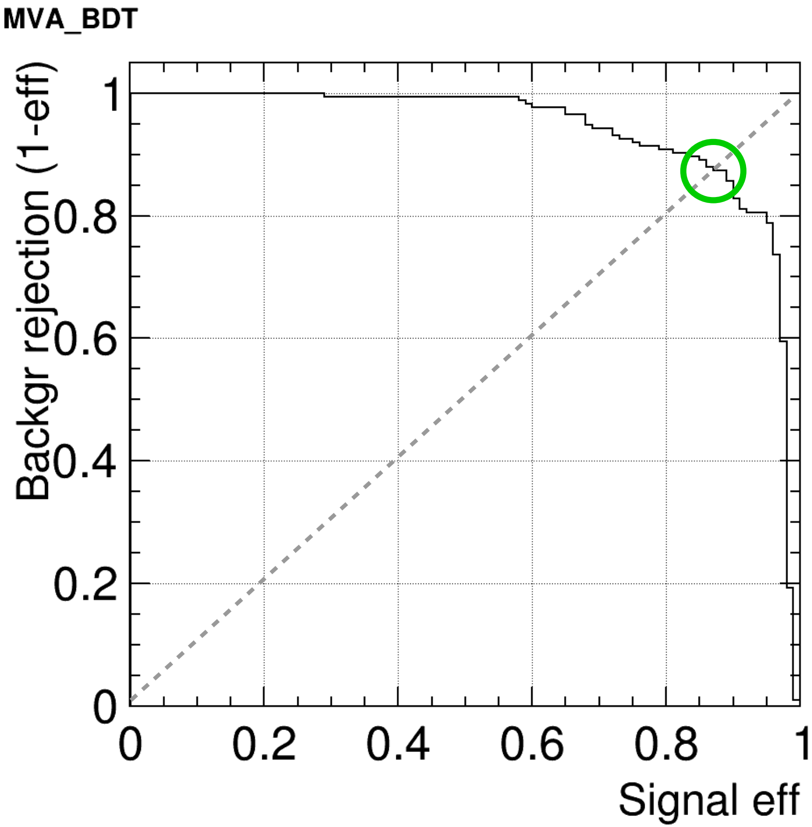


K. Götzen, PID WS GSI 2017:
PANDA Quality Measures for PID Classification Problems

p-value Assessment

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

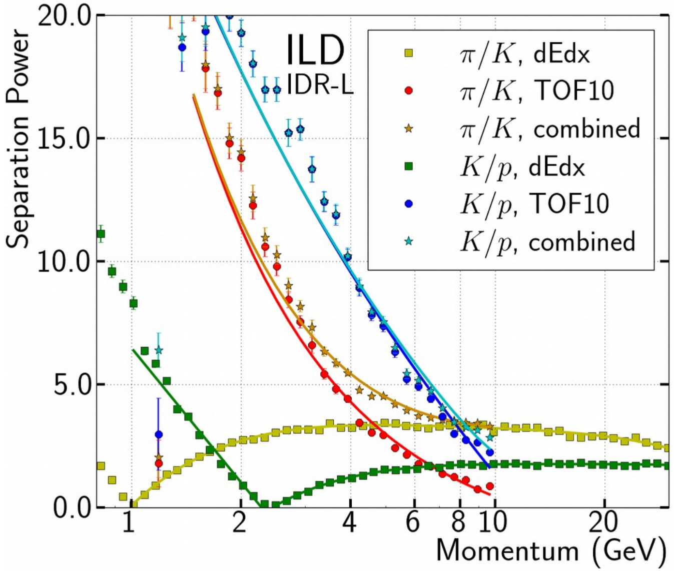




Example 1: π/K Separation with Combined Observables

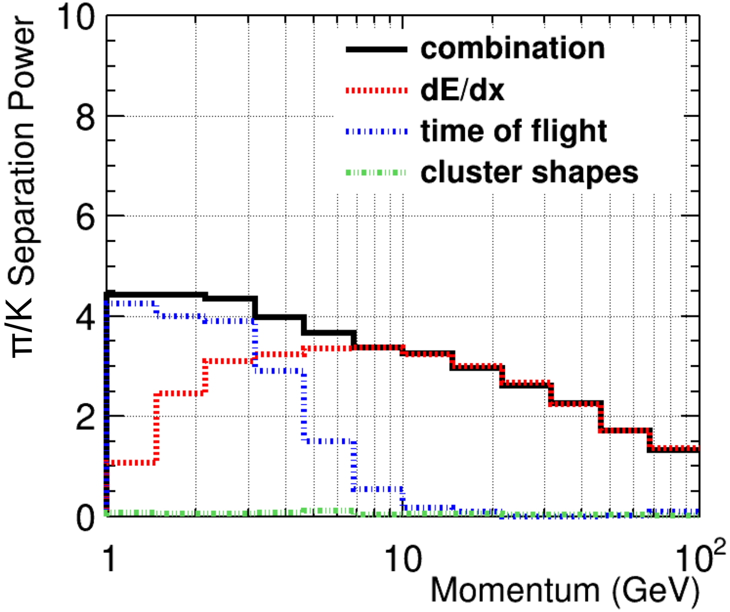
- dE/dx + TOF
- Single particles ‘calibration’ events, flat in log(p) and cos(θ)
- BDT with sig = K, bkg = π; train & eval per 12 mom bins and per used observable(s)

ILD Interim Design Report



https://arxiv.org/abs/2003.01116

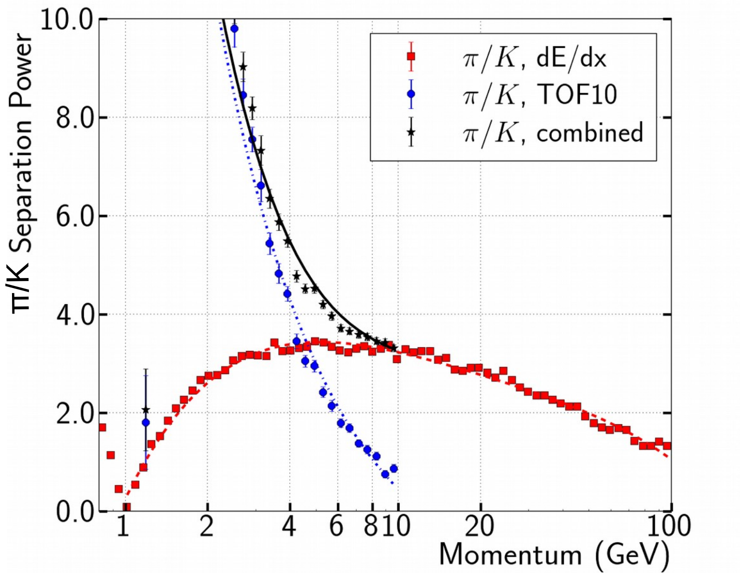
CPID, BDT result



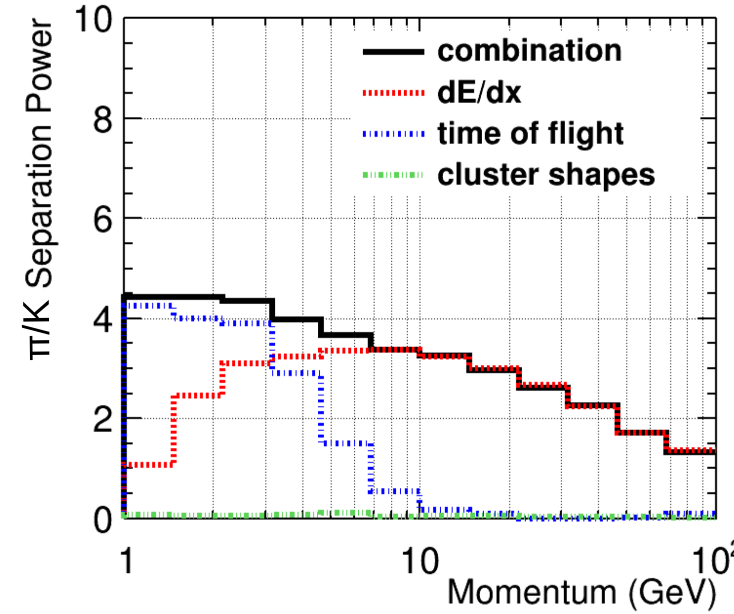
Example 1: π/K Separation with Combined Observables

- dE/dx + TOF
- Single particles ‘calibration’ events, flat in log(p) and cos(θ)
- BDT with sig = K, bkg = π; train & eval per 12 mom bins and per used observable(s)
- dE/dx very similar, TOF levels out due to badly reconstructed events (→ see next Talk!)

analogue to ILD Interim Design Report



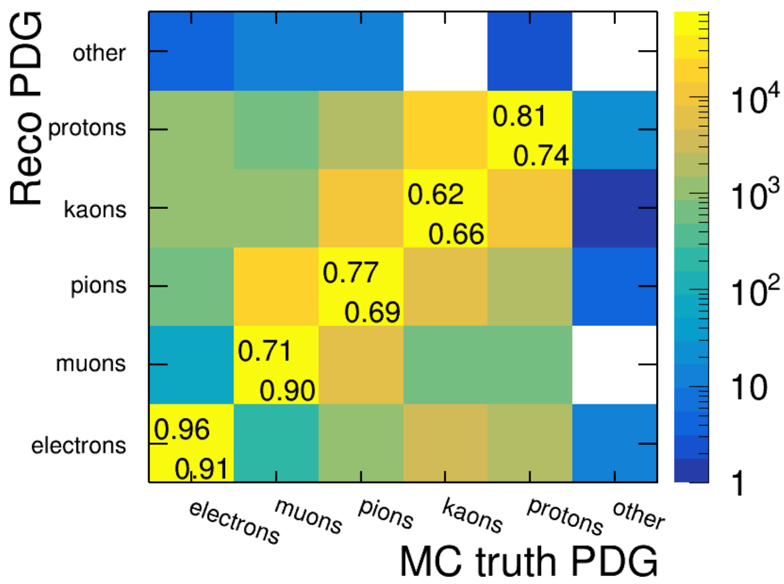
CPID, BDT result



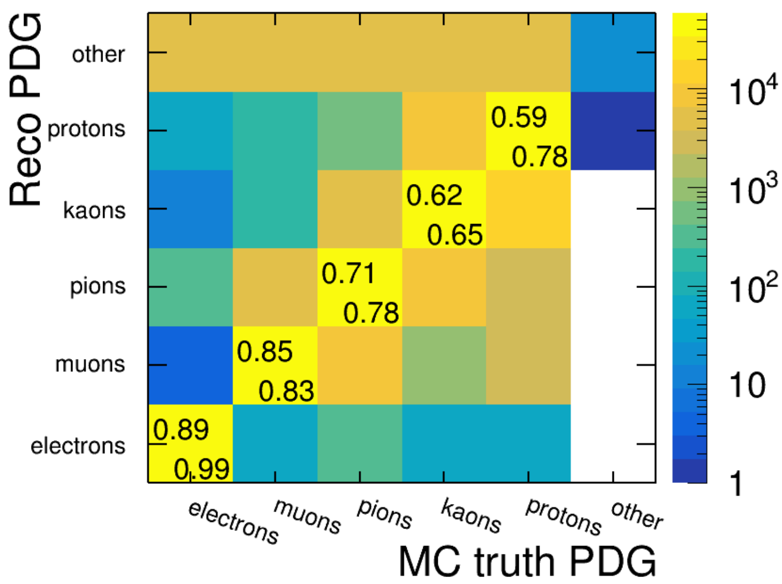
Example 2: Multiclass Assignment Matrix

- dE/dx + calorimeter cluster shapes
- Single particle 'calibration' events, flat in log(p) and cos(θ)
- e, μ, π, K, p; multiclass BDT; assignment matrix with $^{\text{eff}}/_{\text{pur}}$ on diagonal
- Simple BDT has issue with misassignment, but already generates similar reco purity

'Old' PID

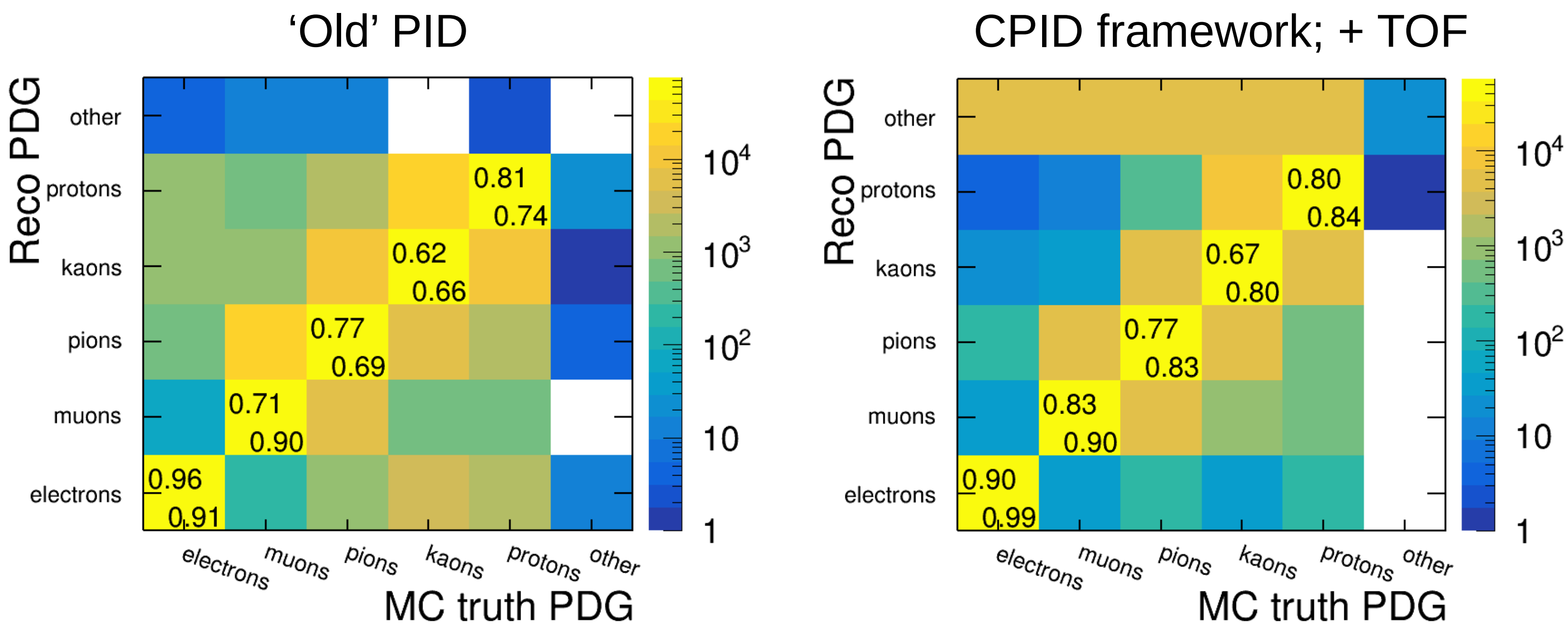


CPID framework



Example 2: Multiclass Assignment Matrix

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



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
- Much more to come!

- Your feedback and input are welcome!

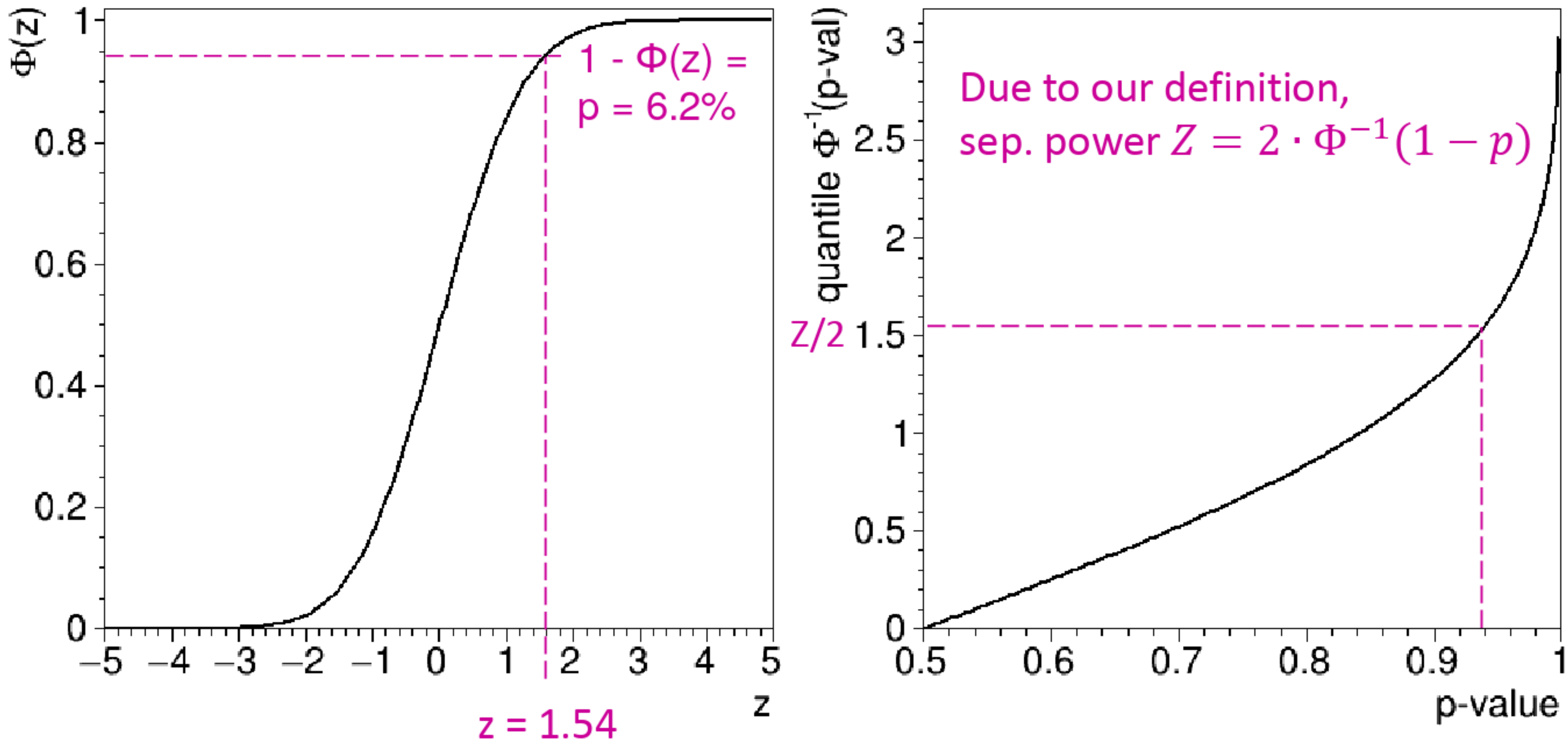
What is particle identification / PID

- Identification of the species of high energy particles
- E.g. e, μ, γ, π, K, p, Λ, n, *[whatever is detector-stable]*
- Origin: collider interaction point, fixed target, annihilating DM, active galactic nucleus
- Average over large statistics, or event-by-event identification of individual particles

  → improve precision physics via event-by-event PID!

p-value assessment

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



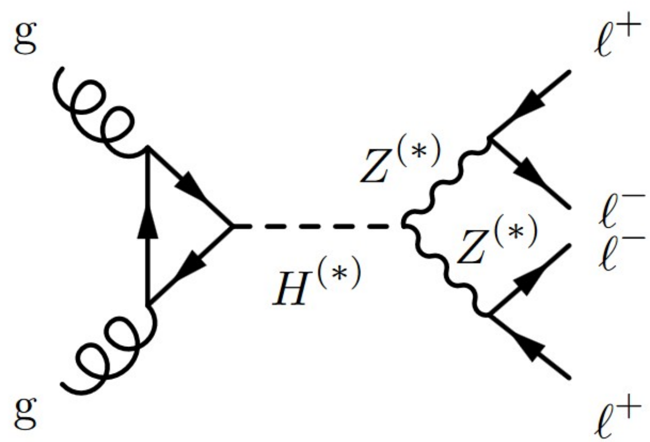
`ROOT::Math::gaussian_cdf(z)`

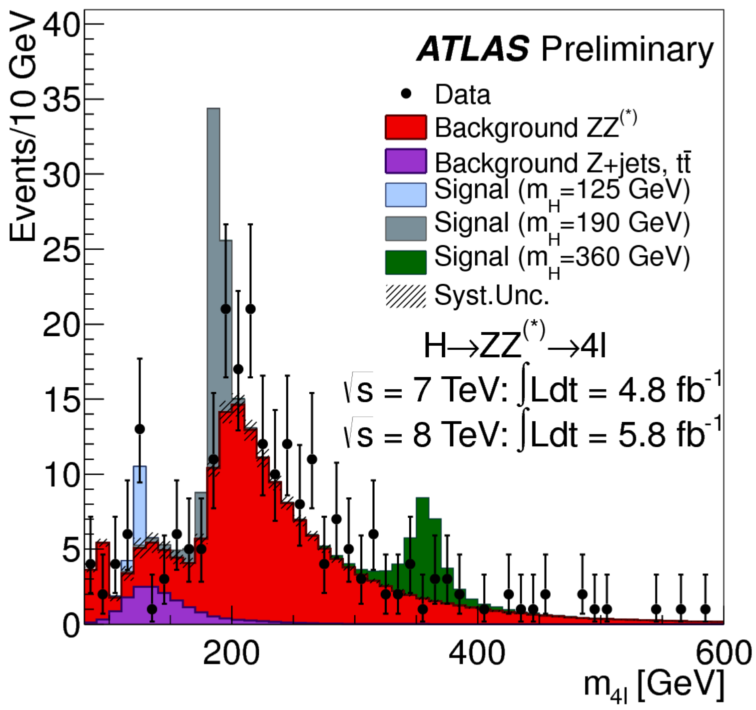
`ROOT::Math::gaussian_quantile_c(p,1)`

Talk by K. Götzen, PANDA, 2017

maybe e/μ ID at the LHC

- H → ZZ* → 4l (e/μ)





- easily identifiable via muon chambers and ECal

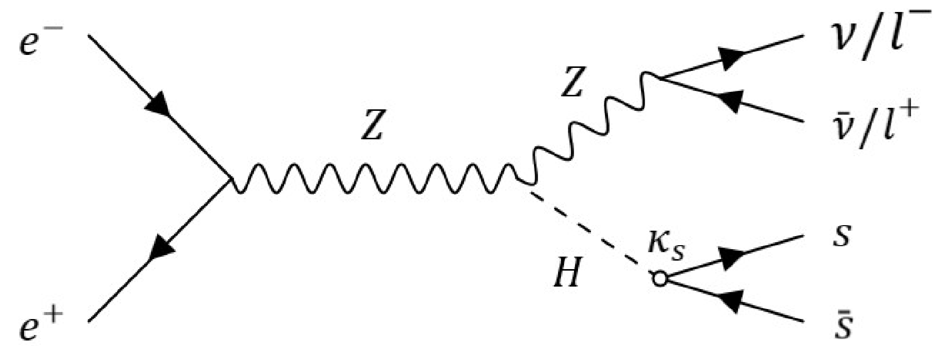
- more difficult: e, μ at low momenta, π^+ vs. K^+ vs. p^+, K^0_S and Λ^0

Higgs to strange

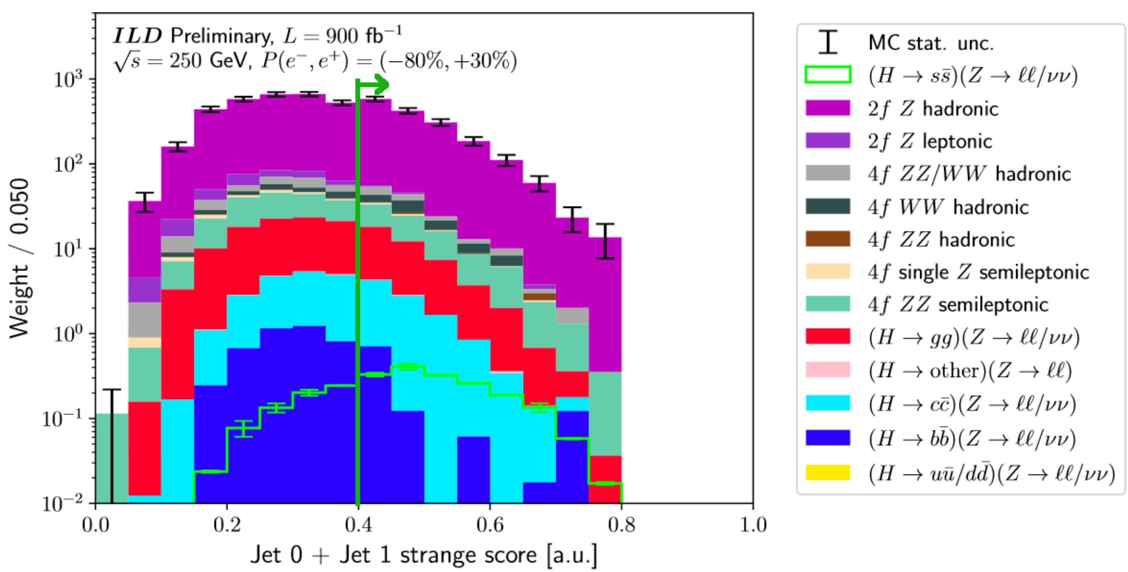
- Study Higgs to strange coupling
- Cute-based analysis, final cut:

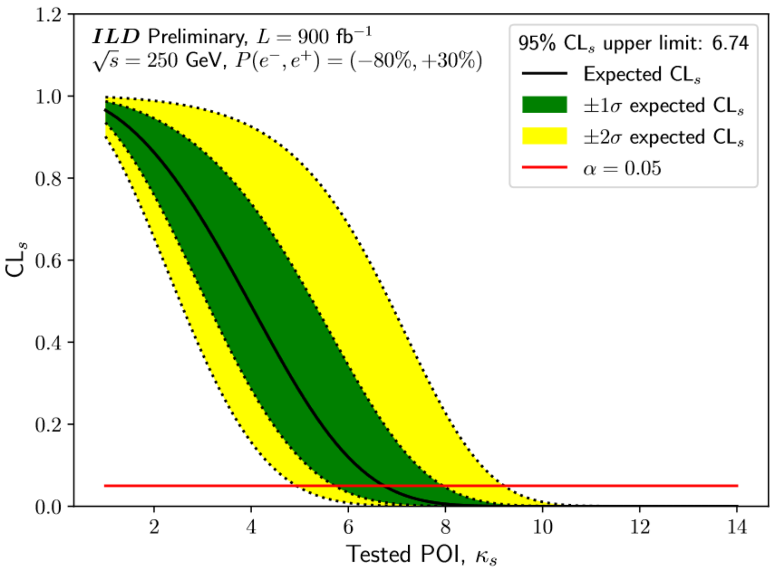
  developed strange tagger using $K^{\pm}$, K^0_S, Λ^0

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



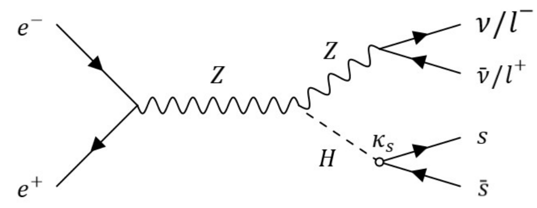
[https://arxiv.org/abs/2203.07535]



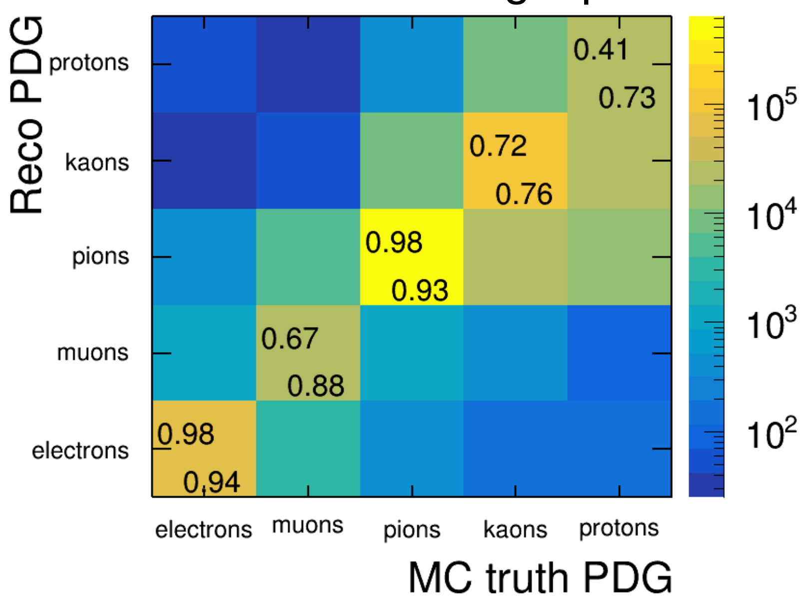


Example 3

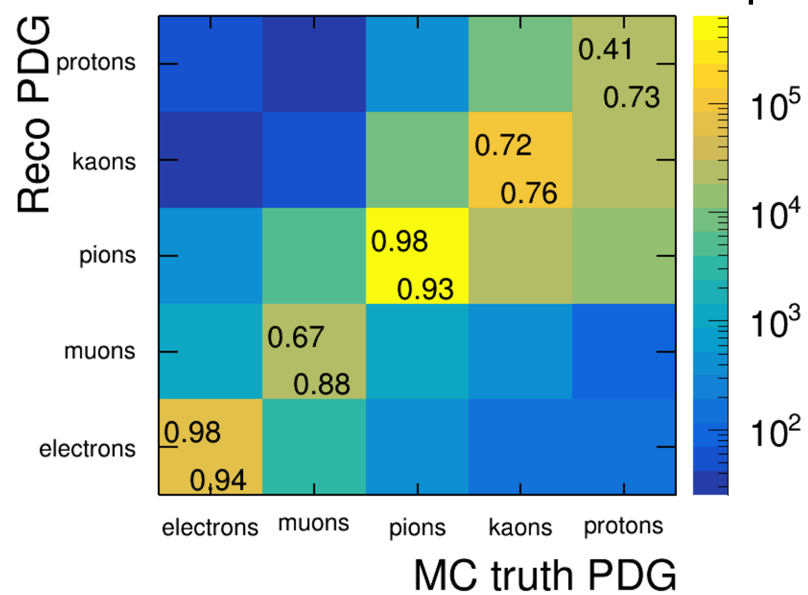
- dE/dx, TOF, cluster shapes
- e+e- → ZH → $l\bar{l}$ $s\bar{s}$
- Kaon ID vs. all others, assignment matrix
- Kaons well identifiable; calibration source not very relevant



calibrated with single particles



calibrated with with the $s\bar{s}$ sample



View of the steering file

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

```xml
<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>
```