PID Potential with a TPC

Recent Developments and Prospects

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The 2022 Int. WS on the HE CEPC
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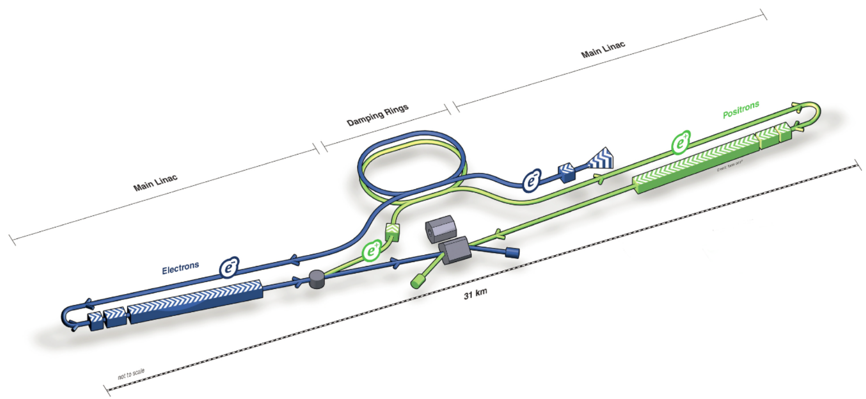
Context

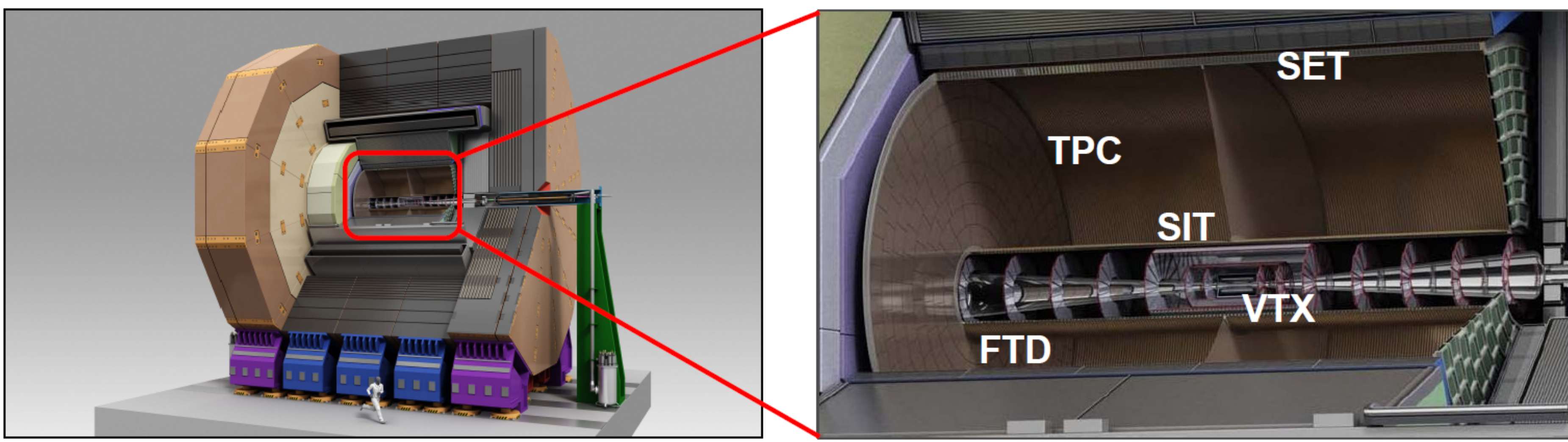
- The Linear Collider TPC Collaboration (LCTPC) develops readout options for TPCs for Linear Collider application, including high granularity opportunities.
  - Several readout options developed
  - Large prototype TPC + infrastructure at DESY II Test Beam Facility
- The proposed International Linear Collider (ILC) forsees 2 detectors, one of which, the International Large Detector (ILD), has a TPC as central tracker.
- ILC:
  - e^+-e^- collider
  - 250-500 GeV, upgrade: 1 TeV
  - Polarised beams (80% e^-, 30% e^+)
  - Under political consideration in Japan



ILC Scheme | © www.form-one.de

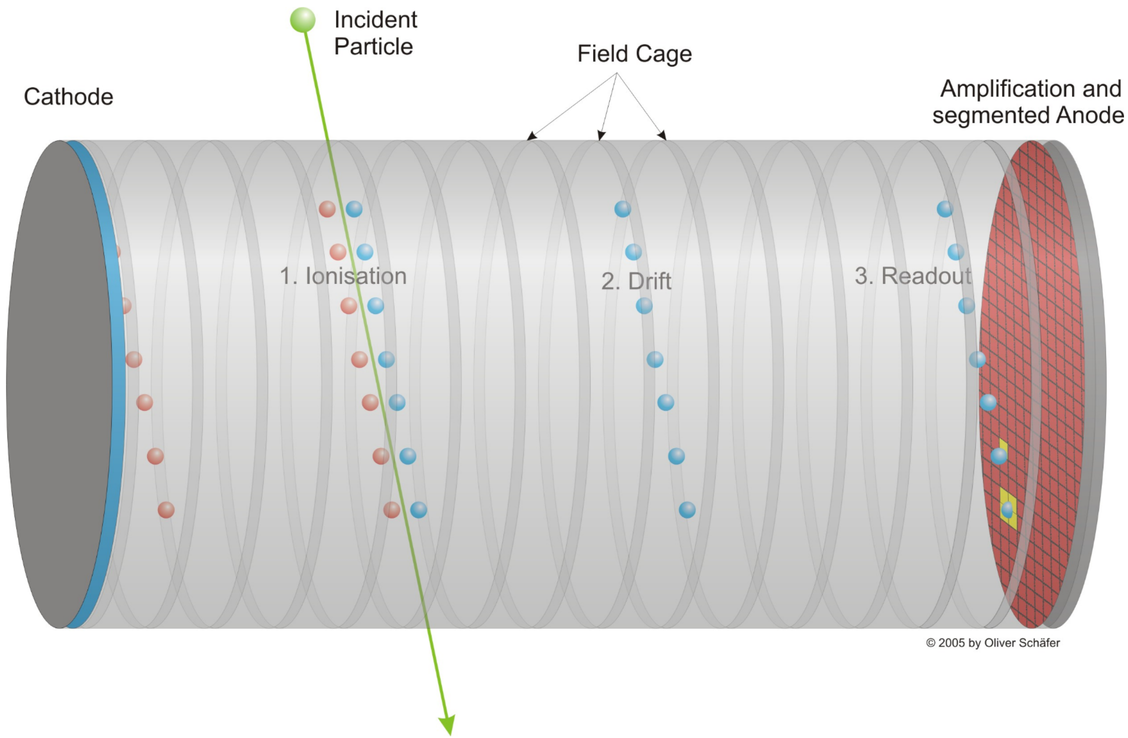
Context

- ILD:
  - Multi-purpose detector optimised for Particle Flow and ILC environment
  - 3.5 T solenoid surrounding continuous tracker & highly granular calorimeter
  - $\sigma_{1/pt} = 2 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$ (TPC alone: $10^{-4}\ \mathrm{GeV}^{-1}$)



The Time Projection Chamber

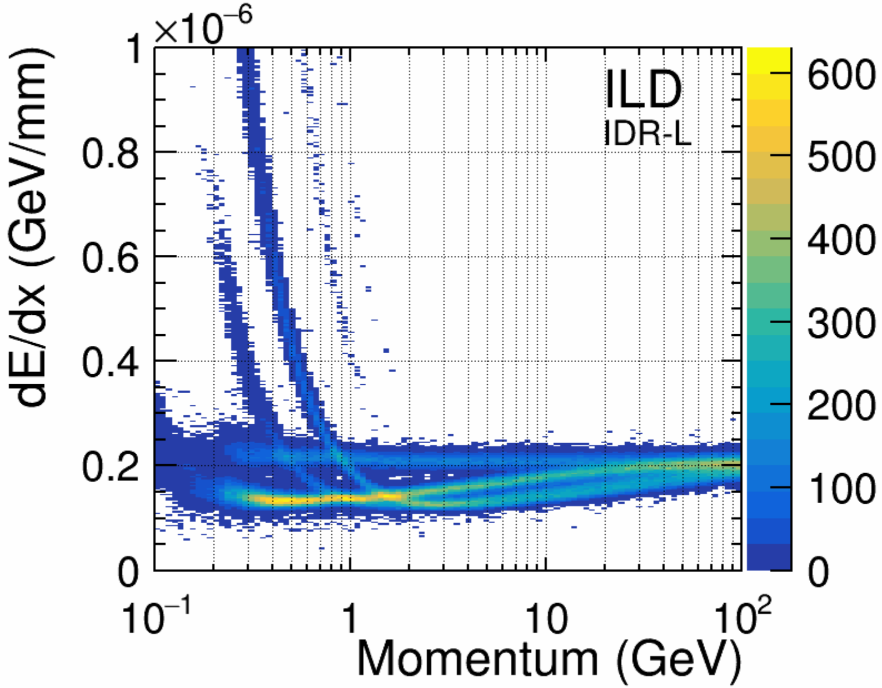
- ILD TPC:
  - 330 mm < r < 1770 mm with 6 mm readout granularity (default); |z| < 2350 mm
  - 220 hits along track, excellent tracking efficiency down to low p
  - Continuous tracking allows to find kinks, V0s, etc.
  - Momentum resolution determines point resolution goal: $\sigma_{r/\varphi} = 100\ \mu m$
  - 5 % X_0 in barrel, 25 % X_0 in end cap
  - Gaseous tracker with T2K gas (95 % Ar, 3 % CF_4, 2 % iC_4H_{10}) measures specific energy loss dE/dx; resolution aim: 5 %



dE/dx and Cluster Counting

- Conventional dE/dx method: sum of all charge of a track
- Landau shaped → large RMS → mediocre correlation with the average energy loss
- Partly compensated by applying truncated mean etc.
- Empirical dependence of dE/dx resolution on track length L and readout granularity G:
  $\sigma_{dE/dx} \sim L^{-0.47} \times G^{-0.13}$

Blum, Riegler, Rolandi: Particle Detection with Drift Chambers

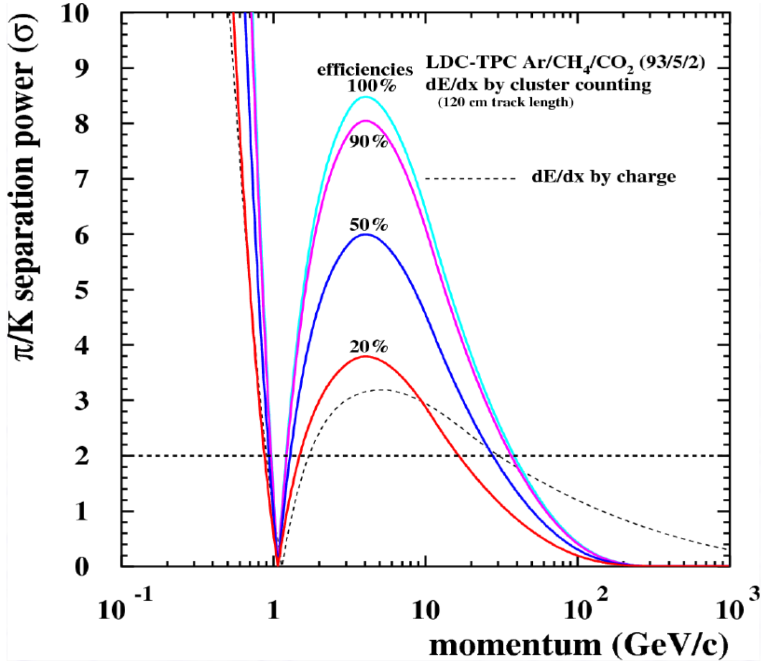


The ILD Concept Group: Interim Design Report
https://arxiv.org/abs/2003.01116

dE/dx and Cluster Counting

- Alternative approach: cluster counting
  → count number of ionising interactions
- Poisson shaped → better correlation with average energy loss
- Allows for better particle separation, but depends on counting efficiency
- Requires granularity similar to cluster distances O(300µm)
- Number of reconstructed cluster is in general not proportional to average energy loss, so resolution is not a good measure instead use separation power:

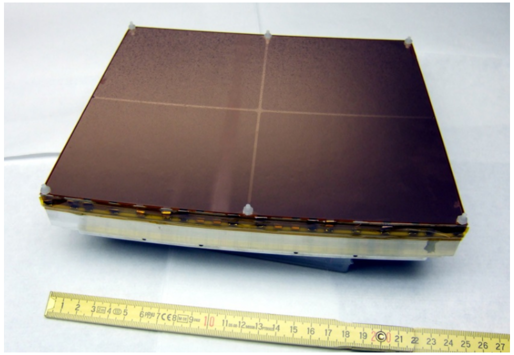
$$S = \frac{|\mu_A - \mu_B|}{\sqrt{\frac{1}{2}(\sigma_A^2 + \sigma_B^2)}}$$

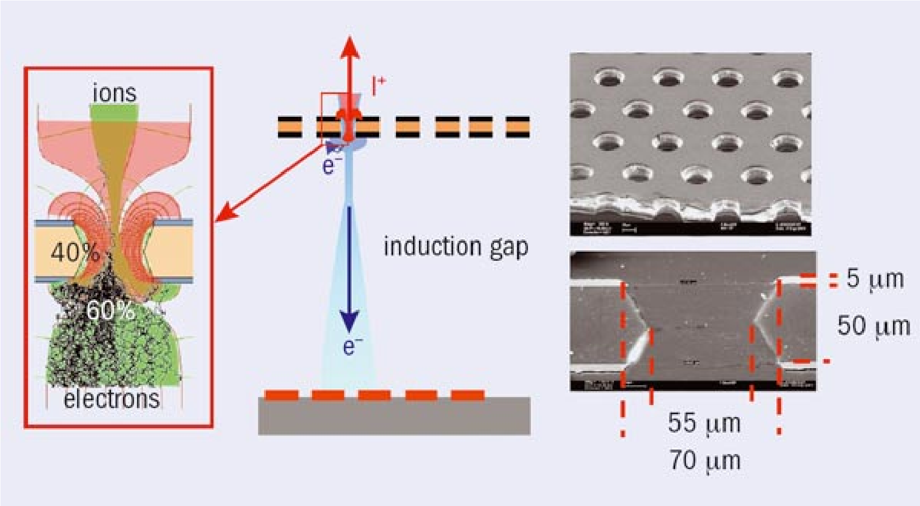


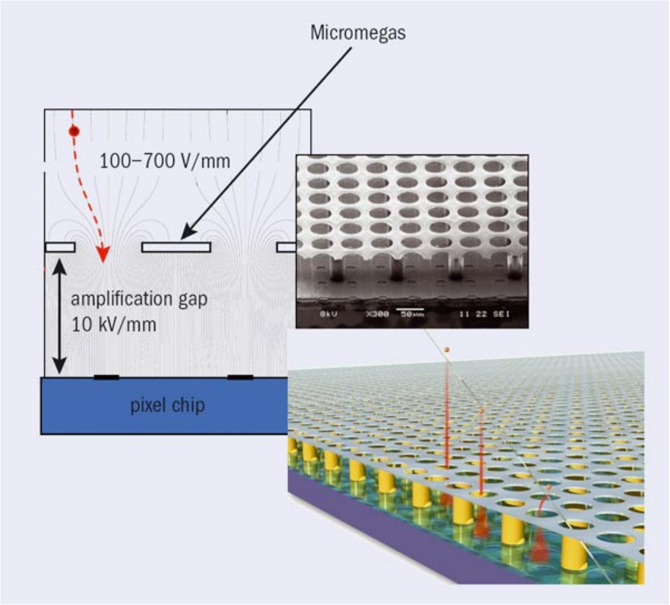
M. Hauschild: dE/dx and Particle ID Performance with Cluster Counting; at ILC Ws. Valencia 2006

TPC Readout Technologies

- MPGD-based amplification; default pads of ~ 6 mm in r
- Pad-based readout with GEMs, by DESY, by KEK
- Pad-based readout with Micromegas, by CEA Saclay
- Modules have been developed and successfully tested in test beam campaigns



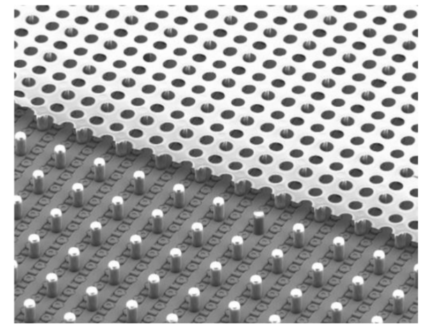


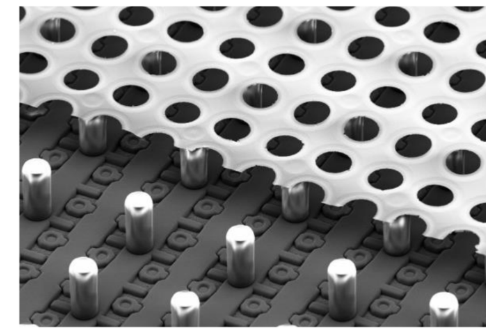


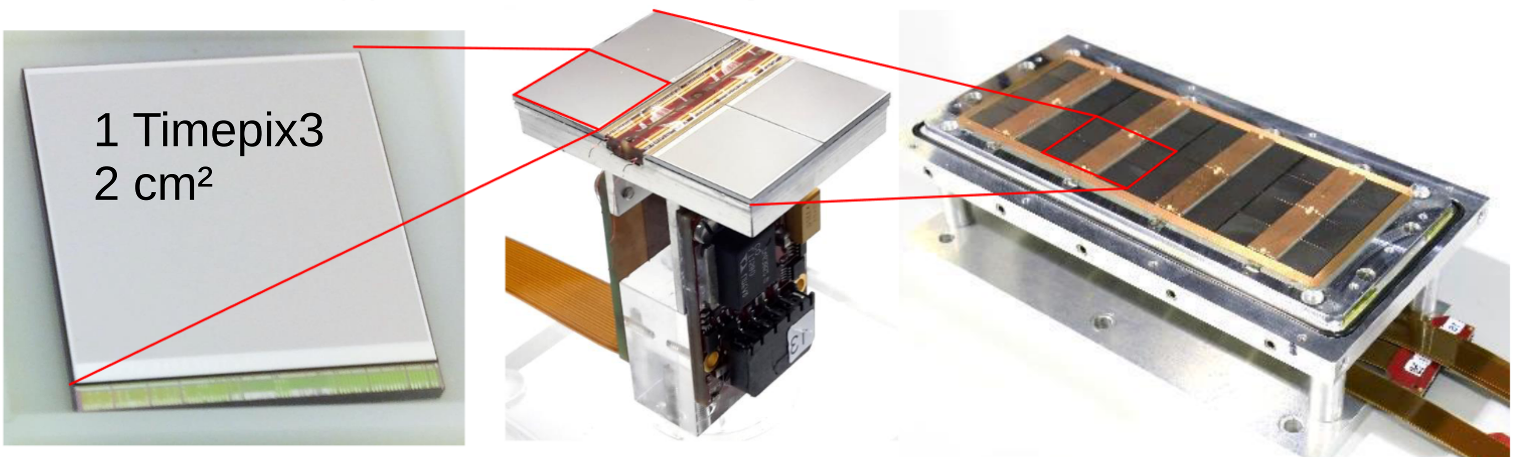
TPC Readout Technologies

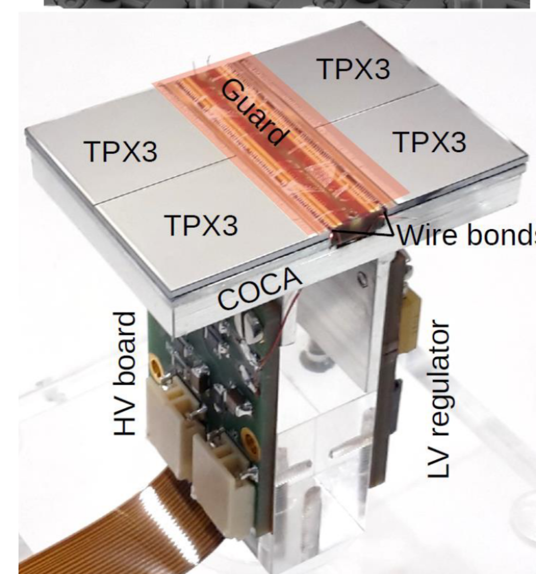
- Pixelised readout with Micromegas grown and etched on top of Timepix 3 ASIC: GridPix, by Nikhef & Uni Bonn
- Matching pitch of 55 µm of pixels and mesh, 65 k channels over 2 cm^2
- Detects individual electrons

C. Ligtenberg: GridPix for future experiments
https://indico.cern.ch/event/889369/contributions/4011330/



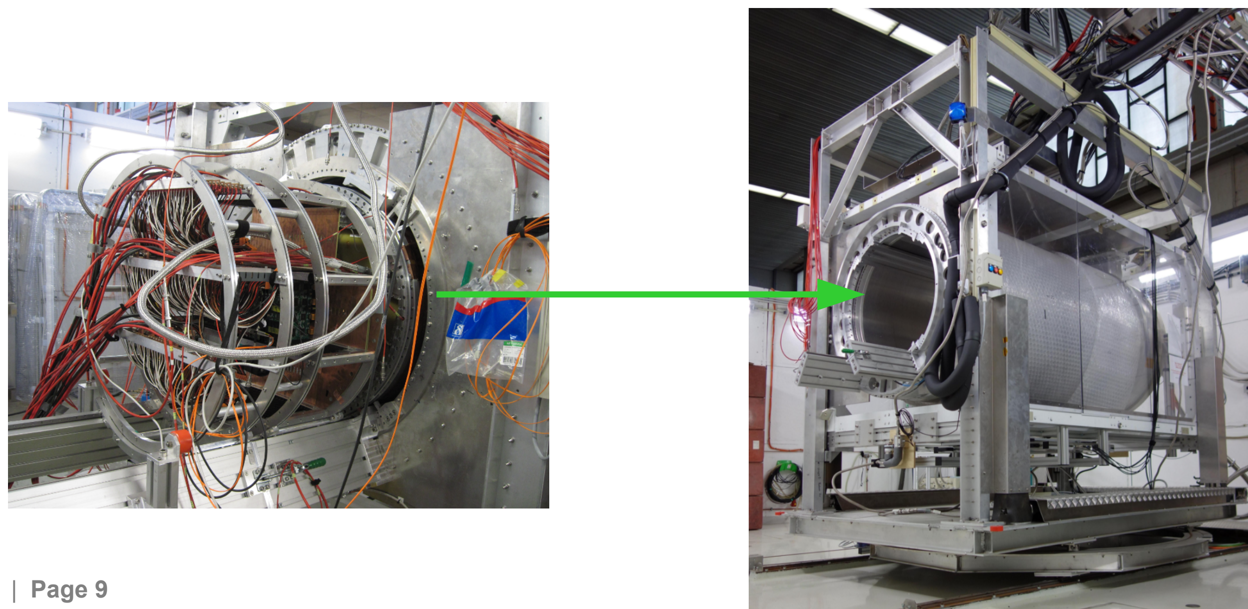






Test Beam Results

- dE/dx resolution extrapolated to ILD
- Pad-based systems, beam test @DESY II test beam facility:
  - 4.7 % (GEMs) **https://arxiv.org/abs/2006.08562, paper in preparation**
  - 4.6 % (GEMs) **https://arxiv.org/abs/1801.04499**
  - 5.0 % (Micromegas) **https://agenda.linearcollider.org/event/7826/contributions/41602/**



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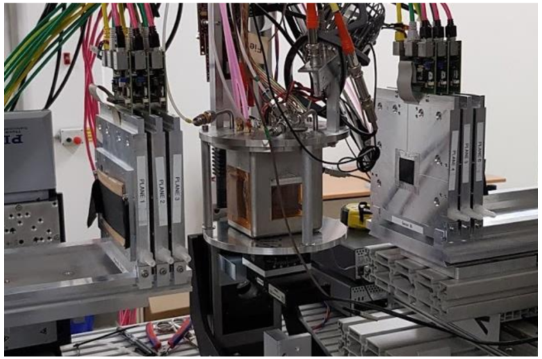


- Transformed to dE/dx resolution extrapolated to ILD
- GridPix, beam test at ELSA test beam @Uni Bonn
- 3.5 % by method 1: electron counting per 20-pixel intervals, 90 % truncated sum
- 3.4 % by method 2: cluster counting, by applying a weight w_i to every recorded electron, depending on the distance d_i to its sucessor; w_i extracted from simulation

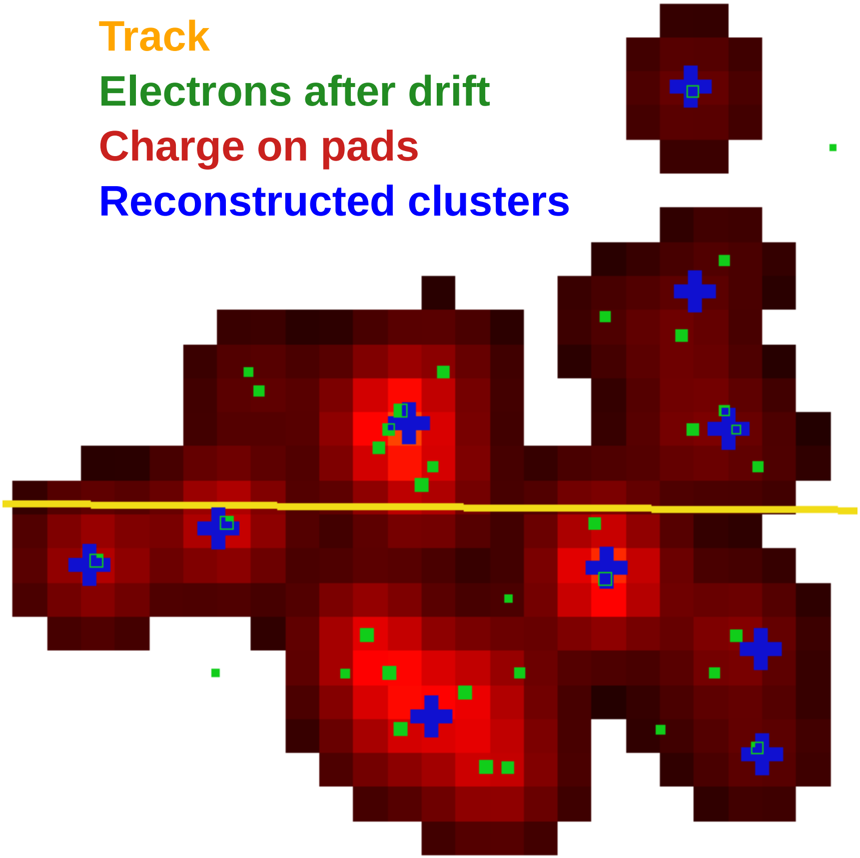
$$\mu' = \frac{1}{N_{\text{hits}}} \sum_{i=0}^{N_{\text{hits}}} w(d_i) d_i,$$

- 3.26 % combined
- https://arxiv.org/abs/1902.01987 (numbers revised since publication of proceedings)

- New test beam with full module done in 2021 - waiting for analysis!

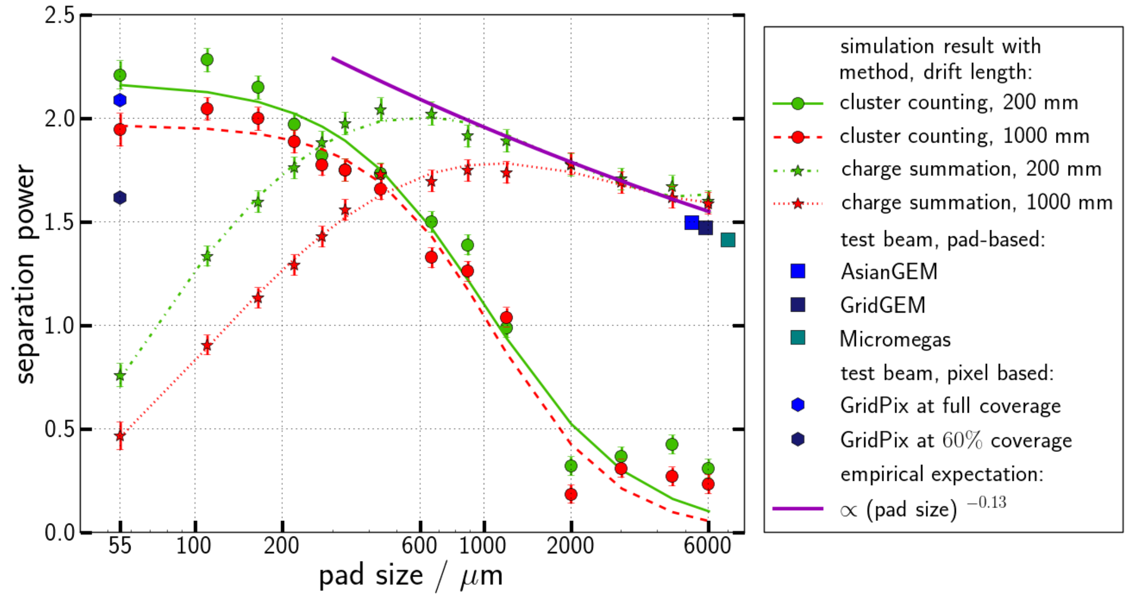
Simulation Studies of Intermediate Granularity

- Used MarlinTPC package of iLCSoft to simulate detailed ionisation, GEM amplification and varying square pad sizes
- Reconstructed clusters using Source Extractor software package **doi:10.1051 / aas:1996164**
- Source Extractor looks for faint sources in 2D-sky maps; convolves with Mexican Hat, splits along minima/maxima and fits source profile
- Compare pions and kaons with constant track length of 300 mm
- Optimised amplification voltage (gain) for each pad size



Simulation Studies of Intermediate Granularity

- Higher granularity helps for charge summation down to 0.5-1 mm, consistent with empirical expectation, gain ~ 15 %
- Cluster counting takes over below 200 µm, gain another 15 %
- Simulation connects pad- and pixel-based test beam results, but GEM simulation loses applicability below 100 µm
- Anode coverage fraction is important parameter



[https://arxiv.org/abs/2205.12160]

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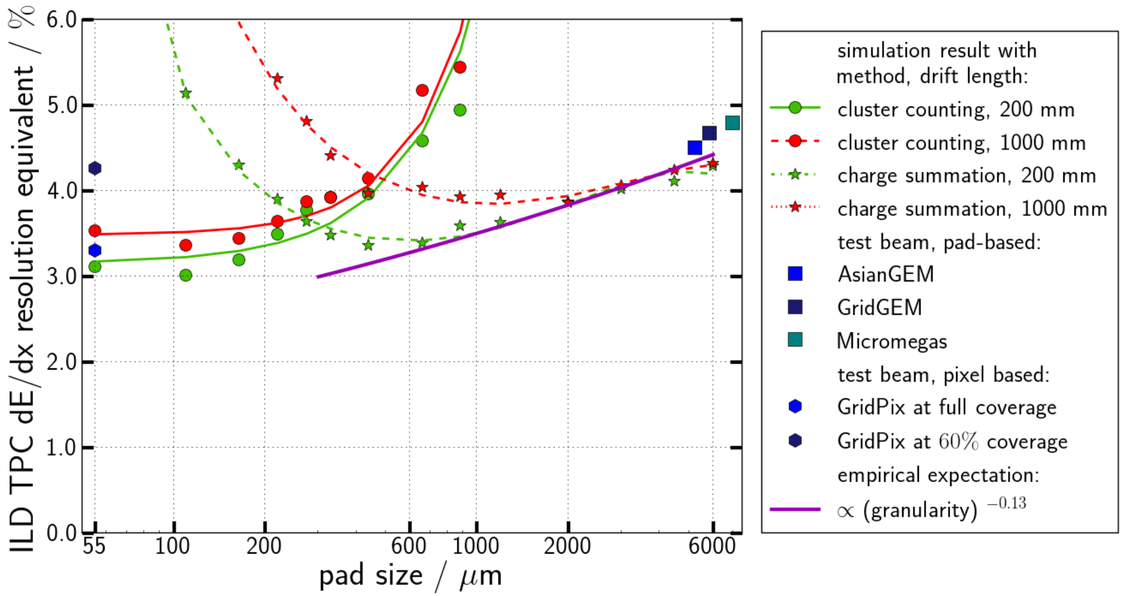
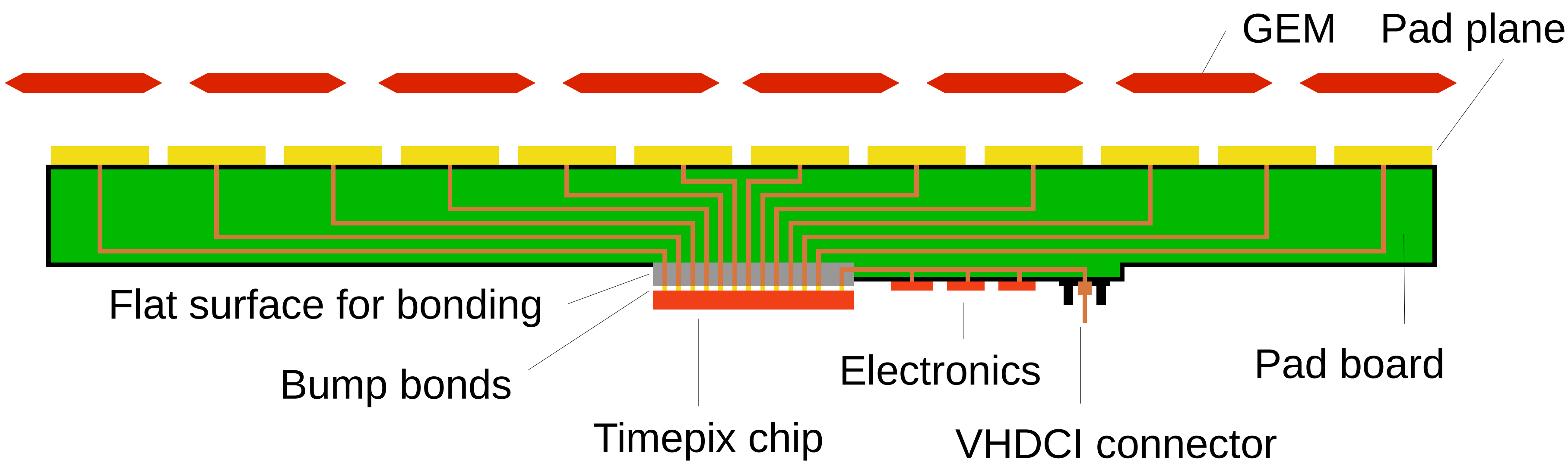


[https://arxiv.org/abs/2205.12160]

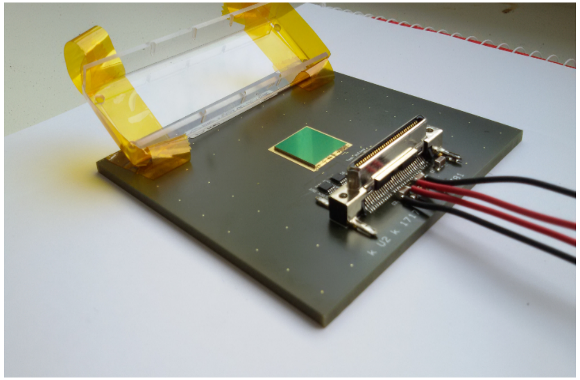
Ropperi – Readout Of a Pad Plane with ElectRonics designed for pIxels

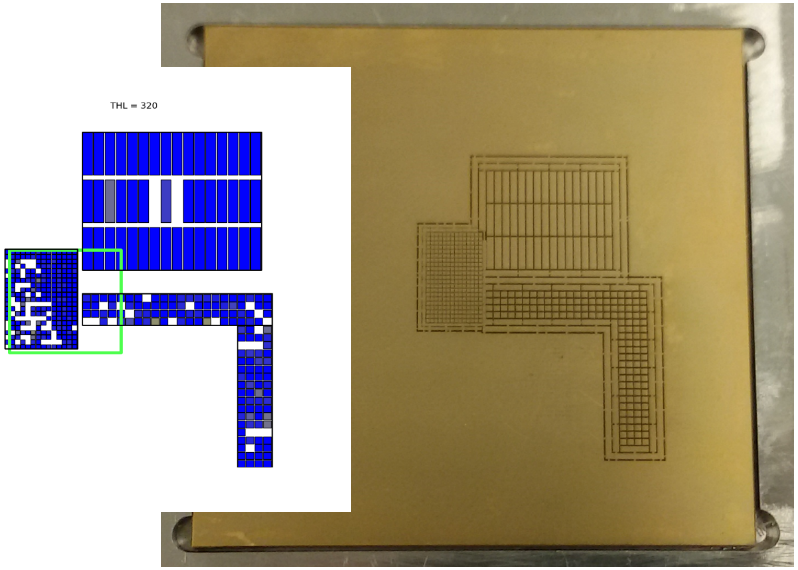
- Novel approach to enable intermediate-size pads
- Use pad plane on PCB, connect pixel chip directly on bottom side
- Pad size limited by feature size of PCB material to 700 µm
- Timepix ASIC, 55 µm pixel pitch

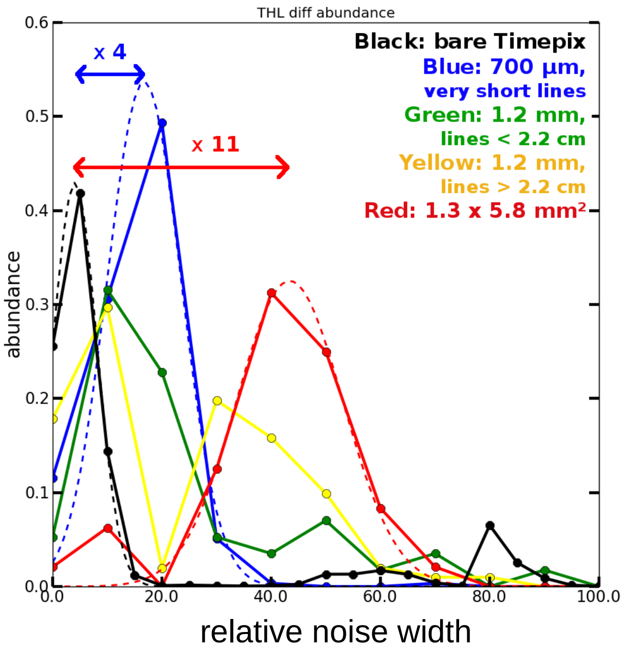


Ropperi

- Challenge: bonding → successful gold-stud bonding @KIT, but lack of long-term thermo-mechanical stability
- Challenge: capacitative noise → threshold scan revealed that noise is up to ~ factor 10 increased, signal from GEM amplification is large enough for S/N > 10 and to reconstruct clusters in simulation

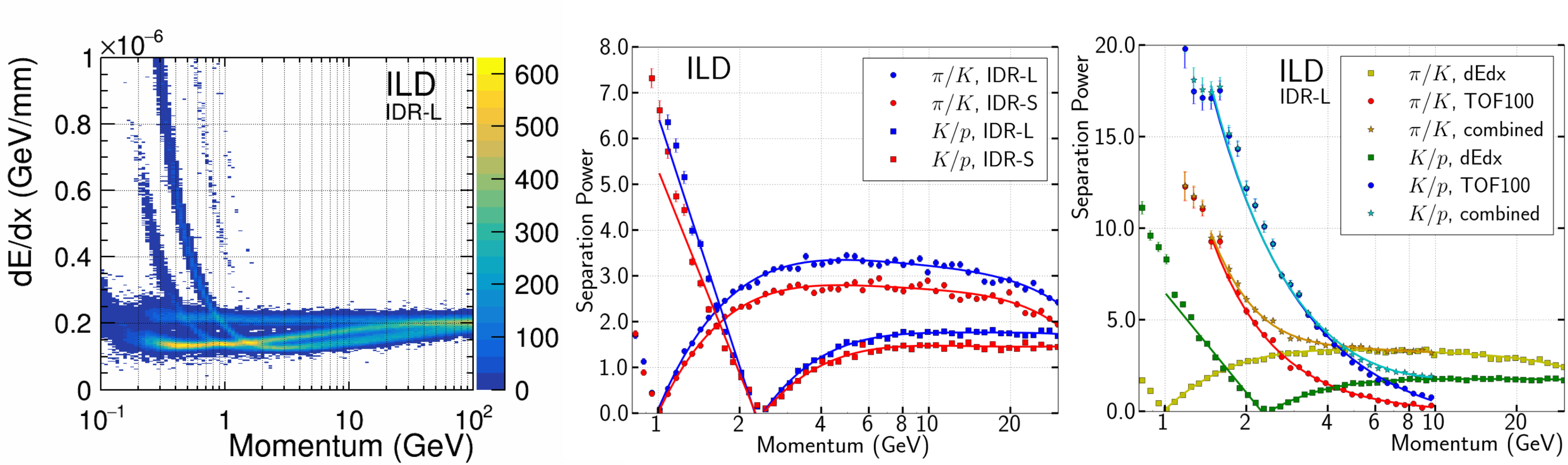






Application to ILD

- In recent MC productions for ILD physics analysis dE/dx was added on TPC hit level, reconstructed to track dE/dx (70% truncated mean), which is used for subsequent particle identification



The ILD Concept Group: Interim Design Report
https://arxiv.org/abs/2003.01116

- Recent move from ILD to study applicability at circular colldier (FCC, CEPC)
  → TPC crucial question, ionisation is an issue
- See: **https://agenda.linearcollider.org/event/9725/**

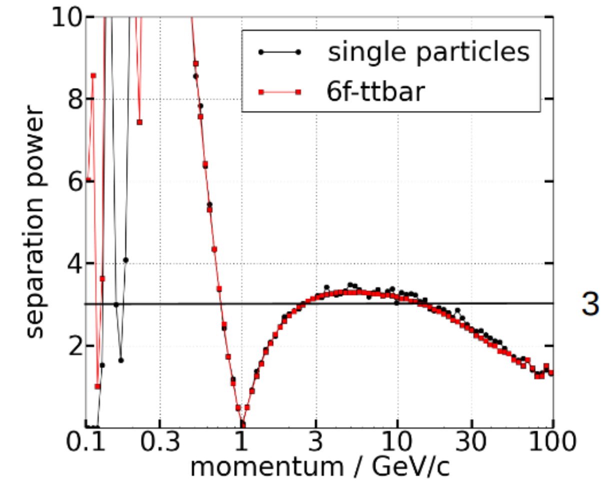
Peter Kluit:

Conclusions: Pixel TPC at the FCC-ee CEPC

Running FCC-ee or CEPC at the Z pole with a L of 200 10^{34} cm^{-2} s^{-1}:

- YES: a pixel TPC can reconstruct the Z events in one readout cycle
- YES: the current readout of the Timepix3 chip can deal with the rate
- The current power consumption is 1W/cm^2. So good cooling is important but in my opinion no show stopper; but needs extensive R&D.
- Track distortions in the TPC drift volume are a concern:
  - It is possible to reduce the IBF for a pixel TPC by making a device with a double grid
  - One can limit the track distortions to stay within maximally 800 μm
  - This needs dedicated R&D that can be performed in the new lab in Bonn
- The above listed items need detector R&D to do the best job
- The Z physics program at FCC-ee or CEPC with an ILD-like detector with a Pixel TPC (with double grid structures) sliced between two silicon trackers (SIT and SET) can be fully exploited. This statement needs more quantitative studies.
- A pixel TPC can perfectly run at WW, ZH or tt energies where track distortions are several orders of magnitude smaller

PID largely unaffected:



Examples for charged-hadron PID applications at ILD

- Z and W hadronic decay branching fractions via flavour tagging: P. Malek, UE
- Forward-backward asymmetry in $e^+e^- \rightarrow q\bar{q}$: R. Pöschl, F. Richard, S. Bilokin, A. Irles, Y. Okugawa, J. Marquez, e.a.
- $H \rightarrow s\bar{s}$ with s-tagging: M. Basso, V. Cairo
- Kaon mass with TOF: UE
- Track refit with correct particle mass: Y. Radkhorrami, B. Dudar

*** references in backup!**

Summary

- Pad-based TPC readout structures with 6 mm granularity achieve the ILD target dE/dx resolution of 5 % (or better).
- Pixelised readout with a 55 µm granularity achieves a resolution of 3.5 % with dE/dx, and of 3.3 % if combined with cluster counting.
- Simulation shows: the higher the granularity, the better the performance.
  Cluster counting kicks in at the pixel level O(200µm).
- Ongoing study if TPC is feasible at circular collider
- PID can contribute to high level reconstruction and a large number of physics analyses, and clear dependencies on the PID performance can be observed.

Thank you for your attention!

Are there questions?

Backup - References

- Hadronic Z decay: P. Malek PhD thesis https://ediss.sub.uni-hamburg.de/handle/ediss/9634
- Hadronic W decay: U. Einhaus PhD thesis (in prep.), talk https://agenda.linearcollider.org/event/8437/
- Forward-backward asymmetry in $e^+e^- \rightarrow q\bar{q}$:
  - S. Bilokin 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/
- $H \rightarrow s\bar{s}$ with s-tagging: M. Basso, V. Cairo e.a. https://arxiv.org/abs/2203.07535
- Kaon mass with TOF: U. Einhaus https://pos.sissa.it/380/115/
- Track refit with correct particle mass: Y. Radkhorrami, B. Dudar https://agenda.linearcollider.org/event/8498/