Development of a straw-tube chamber prototype for the inner detector of a future e^+e^- collider experiment

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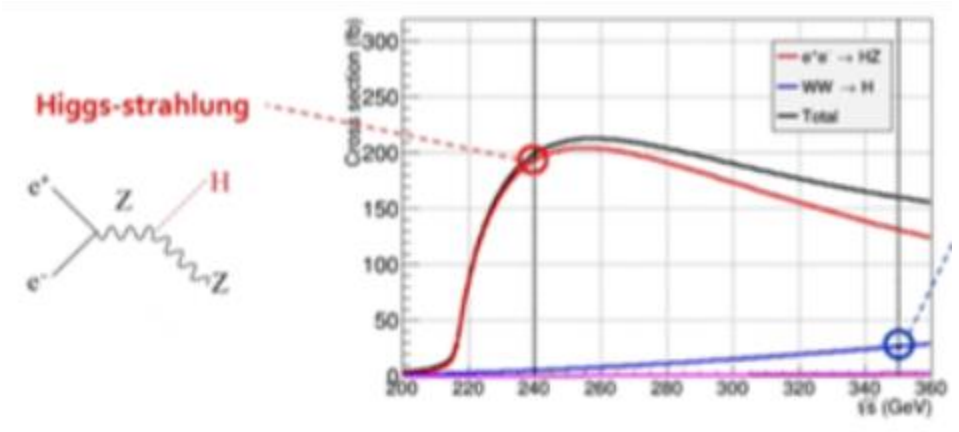
DPG Frühjahrstagung – Göttingen (04.04.2025)

Future Circular e^+e^- Collider - FCCee

- Planned after HL-LHC with a circumference of 91,2 km



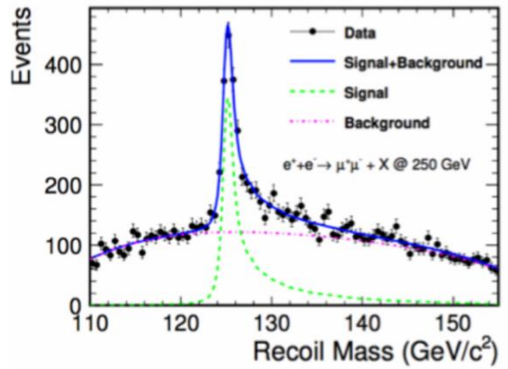
Higgs Factory:

- $\sqrt{s}$ = 240 GeV
- Higgs radiation drives requirements for the inner detector
- Precision measurement of the total width of Higgs

  ✓ Know initial state with good accuracy and final state consists of two bodies

  - Measure momentum of Z → Calculate recoil mass of H → total width of H

  → model independent measurement (no decay products of H)



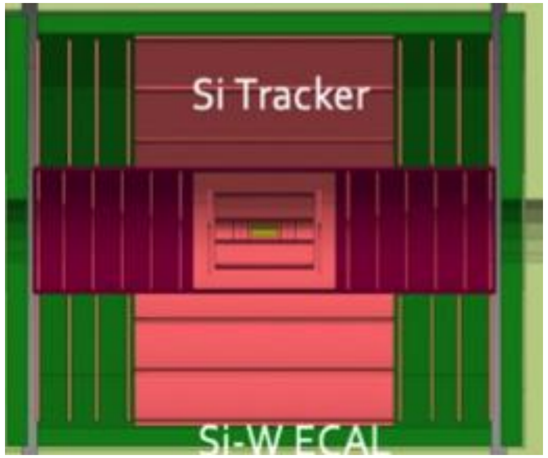
- Beam energy known down to 0.1% → want to achieve same resolution for Z

measurement → $\frac{\sigma(p_T)}{p_T} \sim$ 0.1% for p_T = 50 GeV

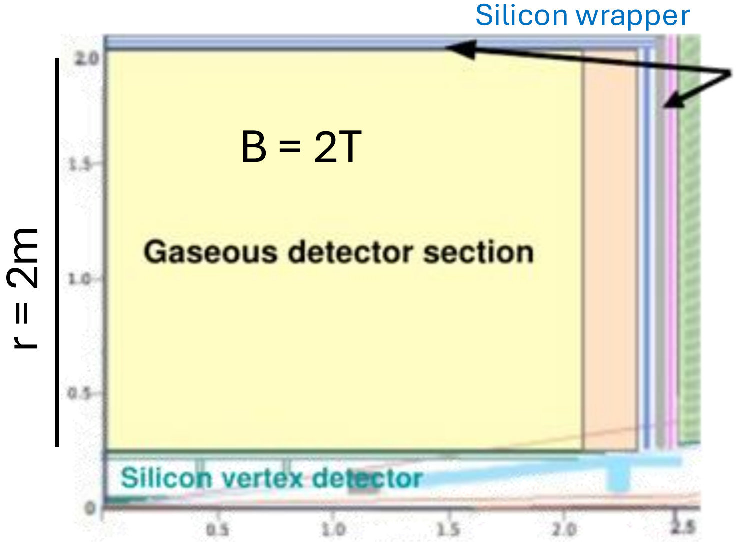
https://indico.cern.ch/event/1408681/contributions/6107963/attachments/2946580/5178215/MPP_straw_dev.pdf

Setup & requirements for the inner detector

All silicon detector



https://agenda.linearcollider.org/event/10211/contributions/53543/attachments/39282/61939/FCC-ee-Detectors-20240115.pdf



Silicon + gaseous detector

https://indico.cern.ch/event/1408681/contributions/6107963/attachments/2946580/5178215/MPP_straw_dev.pdf

Contributions to momentum resolution:

position resolution

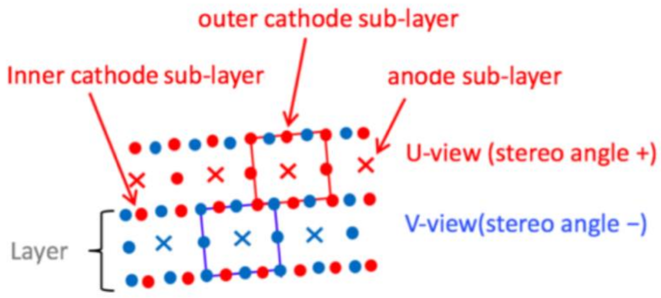
multiple scattering (MS)

	Advantages	Disadvantages
Silicon detectors	Excellent position resolution (5 μm)	Material budget → MS
Gaseous detectors	Low material budget Particle identification (often w. He)	Position resolution limited (100 μm)

Inner detector – gaseous volume

Drift chamber:

- Gaseous volume equipped with $\sim$ 350.000 wires



Straw tubes

- Drift tube with wall thickness of $\sim \mu m$

Advantages of a Straw Tube Chamber

✓ Each tube is an individual detector unit
  - A single broken wire affects only the corresponding tube, but not whole tracker

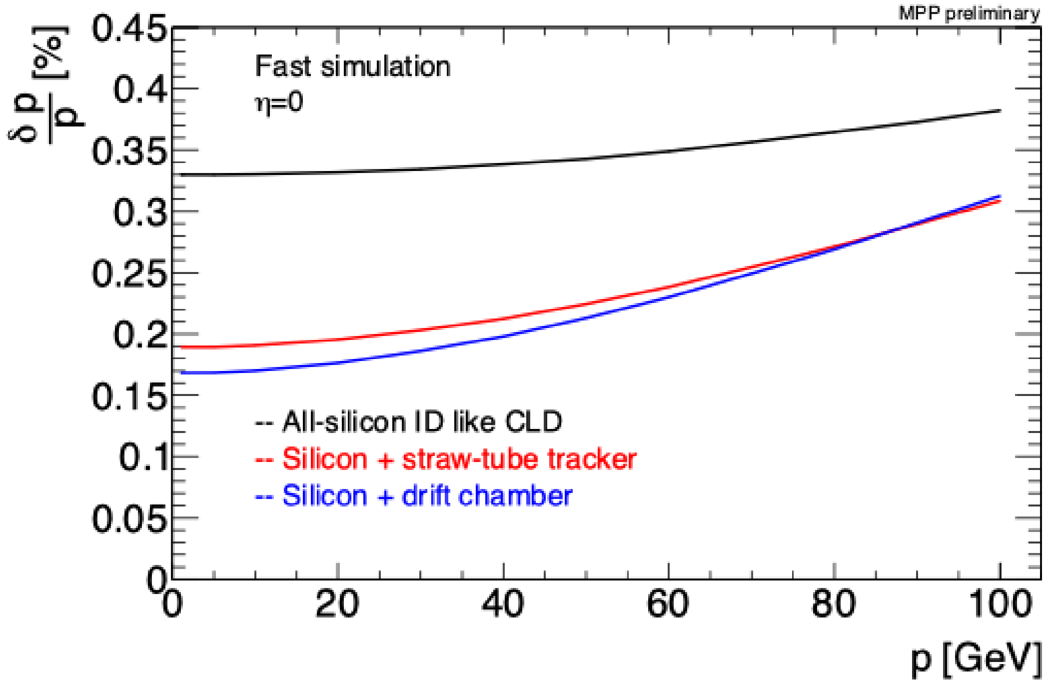
✓ Possibility to use different gases in different tubes

Comparison of the momentum resolution

Gaseous detector	Drift chamber	Straw tube
Material budget	$2.6 \cdot 10^{-5} X_0$	$9 \cdot 10^{-5} X_0$

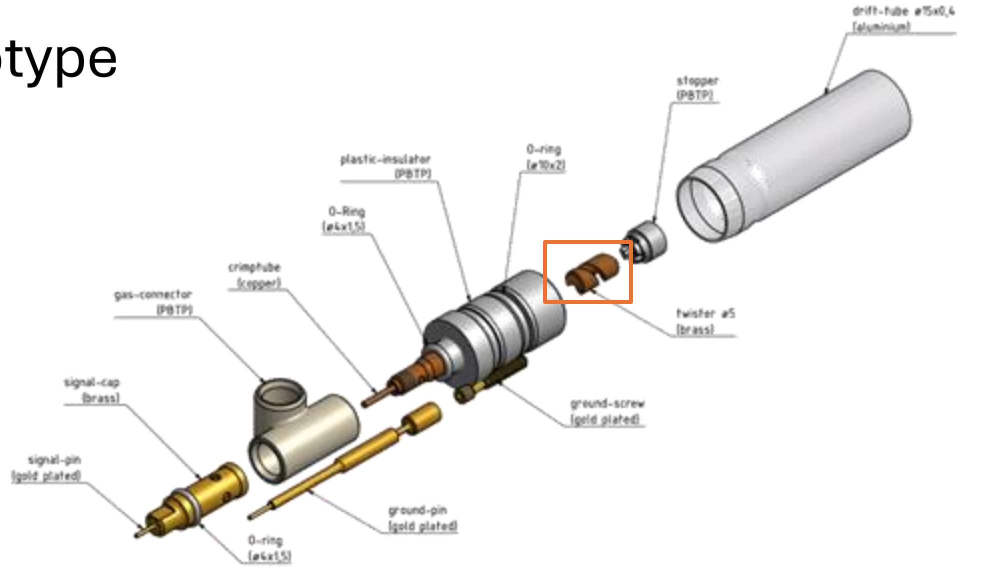
- The radiation length per layer is comparable for both gaseous options

- All silicon detector: hard to achieve a resolution $< 0.3\%$
- Momentum resolution of both gaseous options comparable



Small muon drift tubes (sMDT)

- Based on sMDTs, we are developing a straw tube prototype
- MPP developed sMDTs for the ATLAS Muon Upgrade

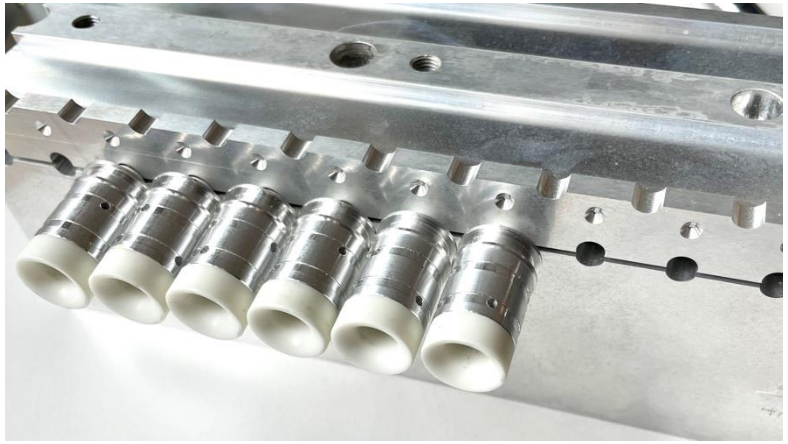


https://wwwatlas.mpp.mpg.de/ftp/outgoing/sMDT/BIS/MuonPhase2IDR/sMDT/sMDTIDR/sMDT_0.pdf

sMDT parameters

Wall thickness:	0.4 mm
Tube radius:	7.1 mm
Wire radius:	50 μm
Spatial resolution:	$\sim$ 100 μm
Operating gas:	Ar/CO2 (93/7)
Operating voltage:	2730 V
Operating pressure:	3 bar

Mechanical precision of whole chamber 10 μm



Straw Tube prototype

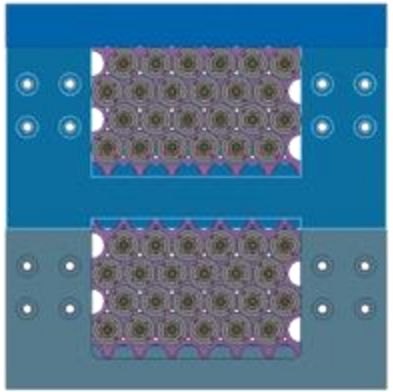
Straw parameters

Walls made of thin mylar double coated with Al

Thickness:	$\sim \mu m$
Tube radius:	7.1 mm
Wire radius:	50 μm
Operating gas:	He/iC4H10 (90/10)
Operating voltage:	1624 V
Operating pressure:	1050 mbar

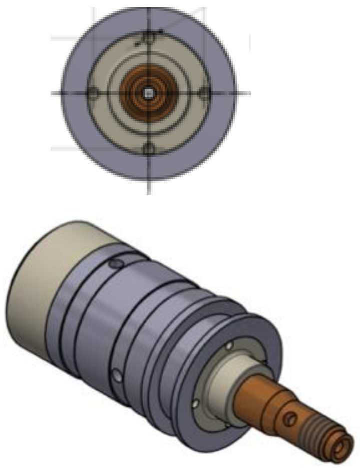
- Producing 48 Straw Tubes of 1.45m length (+ 7 spares) → 2 layers with 6 x 4 Straws

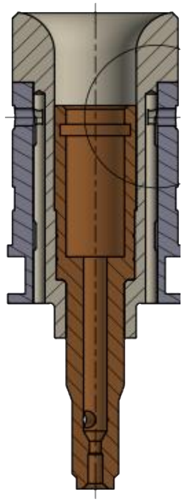
- Need of a support structure bc. of flexible tube wall



Straw Tube prototype - endplug

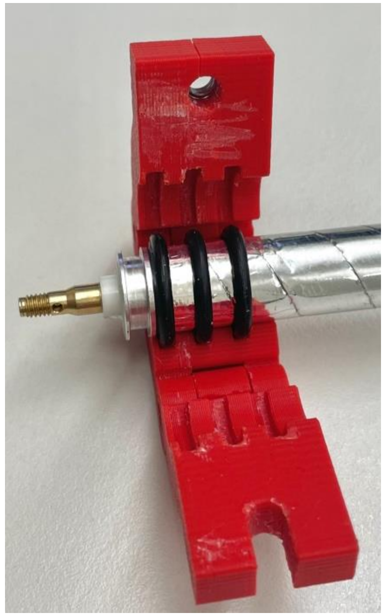
- Reuse electronics and gas supply system from ATLAS sMDTs
- The endplugs needed to be adapted for the purpose of gluing instead of crimping
- Goal: gas tightness and electric contact





- Glueing channel beneath the surface of the endplug
- Inner ring: mechanically good glue
- Outer ring: electrically conducting glue

Glueing clamp



- O – rings surrounding the glueing channels
- Three-part clamp to prevent creases in the straw wall

Straw Tube production - tests

Tests conducted	Results
Gas leakage test <u>Operating conditions</u> Ar/CO2 (93/7) at a pressure of p = 1100 mbar	No leaks detected by sniffing Argon
Resistivity Measurement with digital voltmeter to check if the electrical glueing was successful	✓
Dark current <u>Operating conditions</u> Ar/CO2 (93/7) at a pressure of p = 1100 mbar	Goal: current below 2 nA Result: tested up to 2.73 kV which corresponds to a gas gain of 380.000.000 → within the limit

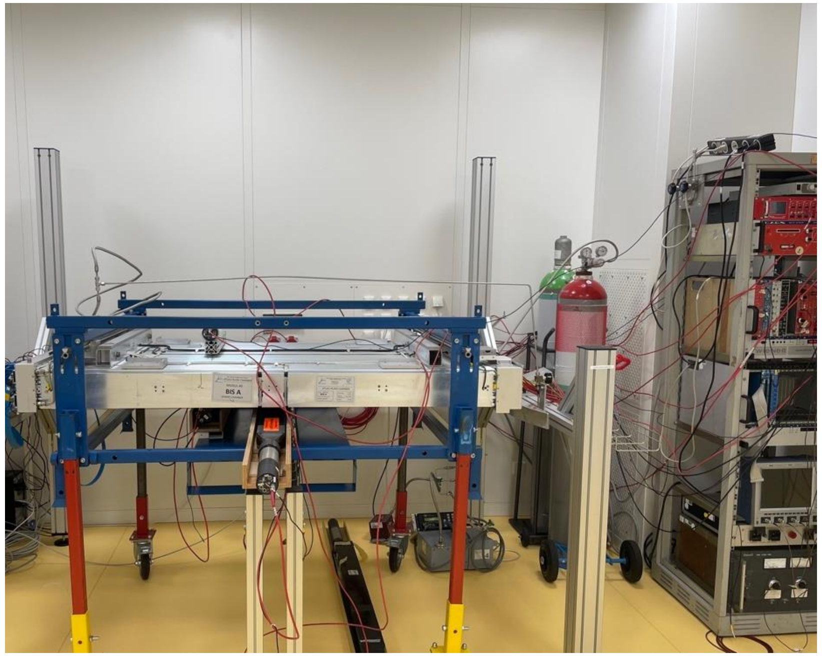
Helium-isobutane studies

As already anticipated, we want to use Helium to fill the Straw tubes

- First experimental cosmic ray tests can already be conducted without the straw tube chamber by using a sMDT chamber of ATLAS (2 multilayer with 58x4)
- Conduct simulations with Garfield ++
  - interpreting experimental measurements and for electronic development

Importance:

- Gain experience with the gas mixture He/iC4H10 (90/10)
- Tune the simulation program Garfield ++ due to weaknesses:
  - Simulate ionization process (number of primary electrons)
  - Predict the transport of electrons in Helium gas
  - ➢ hard to have a reliable prediction of the gas gain



Helium-isobutane studies – Diethorn formula

- From experimental data analysis we receive an efficiency vs voltage curve
- Since the gas gain prediction of Garfield++ is limited, we set the gain as input parameter
  - ➢ receive an efficiency vs (gas) gain curve

- For comparison and tuning we need to convert gain into voltage which is possible via the

Diethorn formula:

$$G = \left[\frac{E(r_{min})}{E_{min}(\varrho_0)\varrho_{gas}}\right]^{\frac{r_{min}\,E(r_{min})\ln(2)}{\Delta V}}$$

$E(r_{min})$ Electric field at wire

ϱ_{gas} pressure of used gas

Diethorn parameter	He/iC4H10 (90/10)
$E_{min}(\varrho_0)$	$32.4 \pm 2.98 \frac{V}{cm\ Torr}$
ΔV	$26.01 \pm 0.53\,V$

https://doi.org/10.1016/S0168-9002(96)00581-5

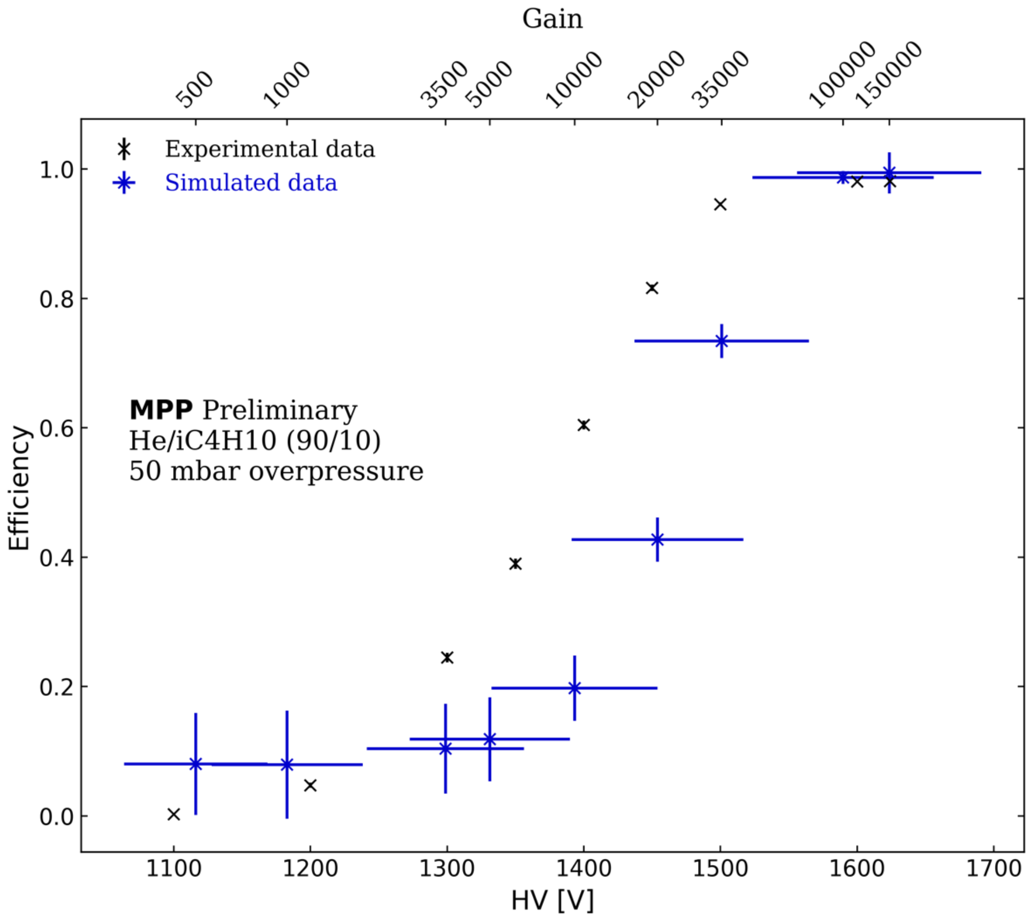
Helium-isobutane studies – efficiency curve

Experimental efficiency curve (x):

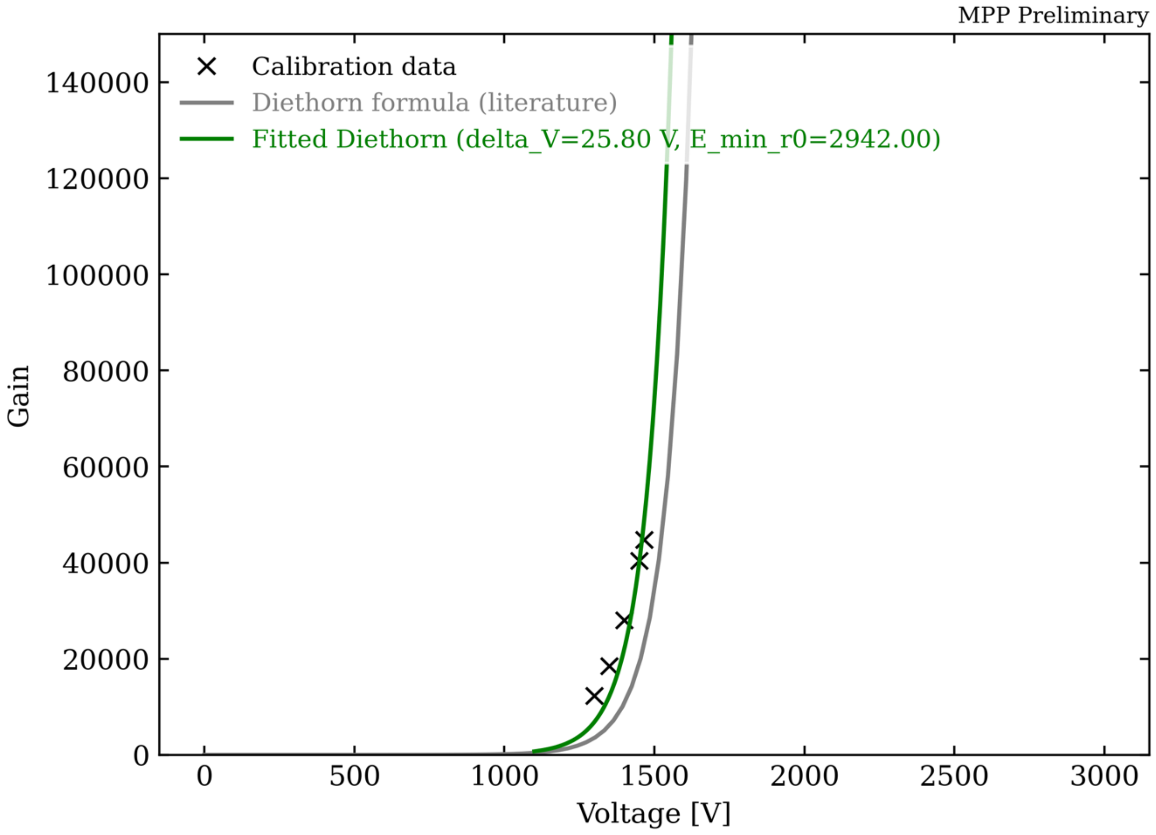
- Set one multilayer to the operating voltage of 1624V
- Vary the voltage of the other multilayer
- Trigger on cosmic rays
- Require at least 4 hits in multilayer at operating voltage

Observation:

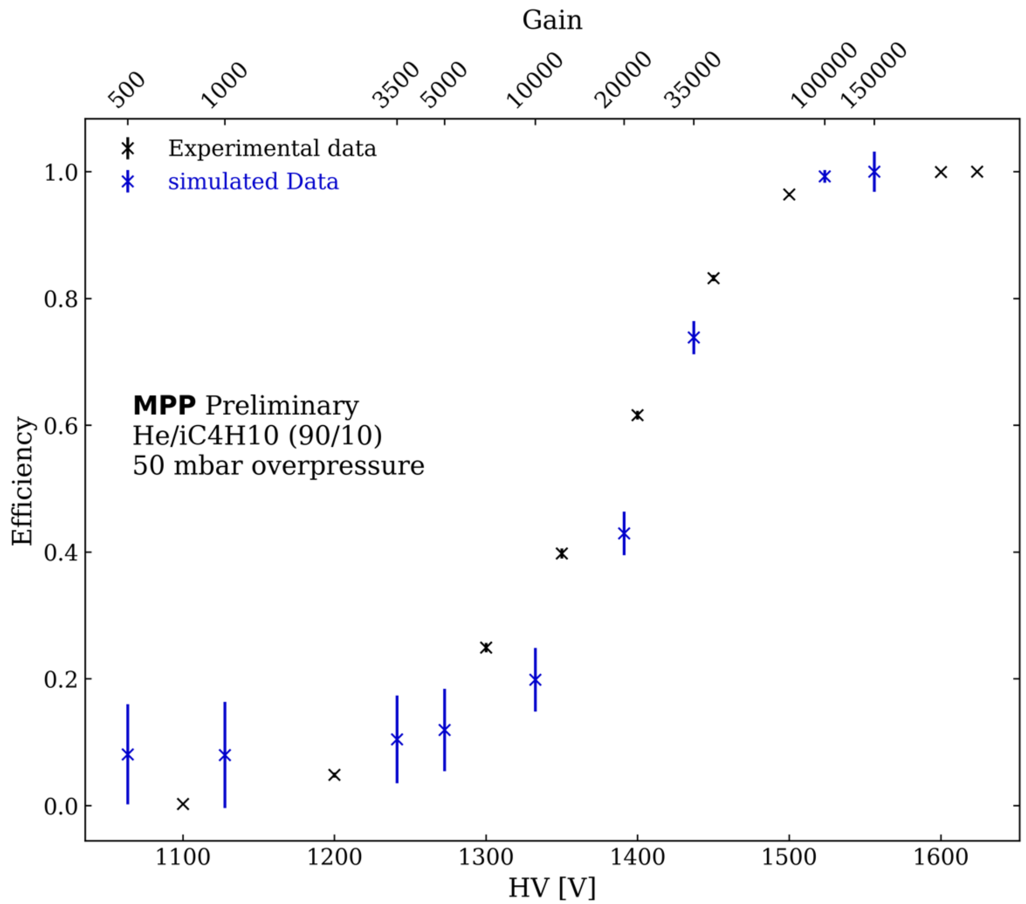
- Within the uncertainties of the simulation data the agreement is acceptable
- It would be better to tune the conversion for good matching of experiment and simulation



Helium-isobutane studies – efficiency curve



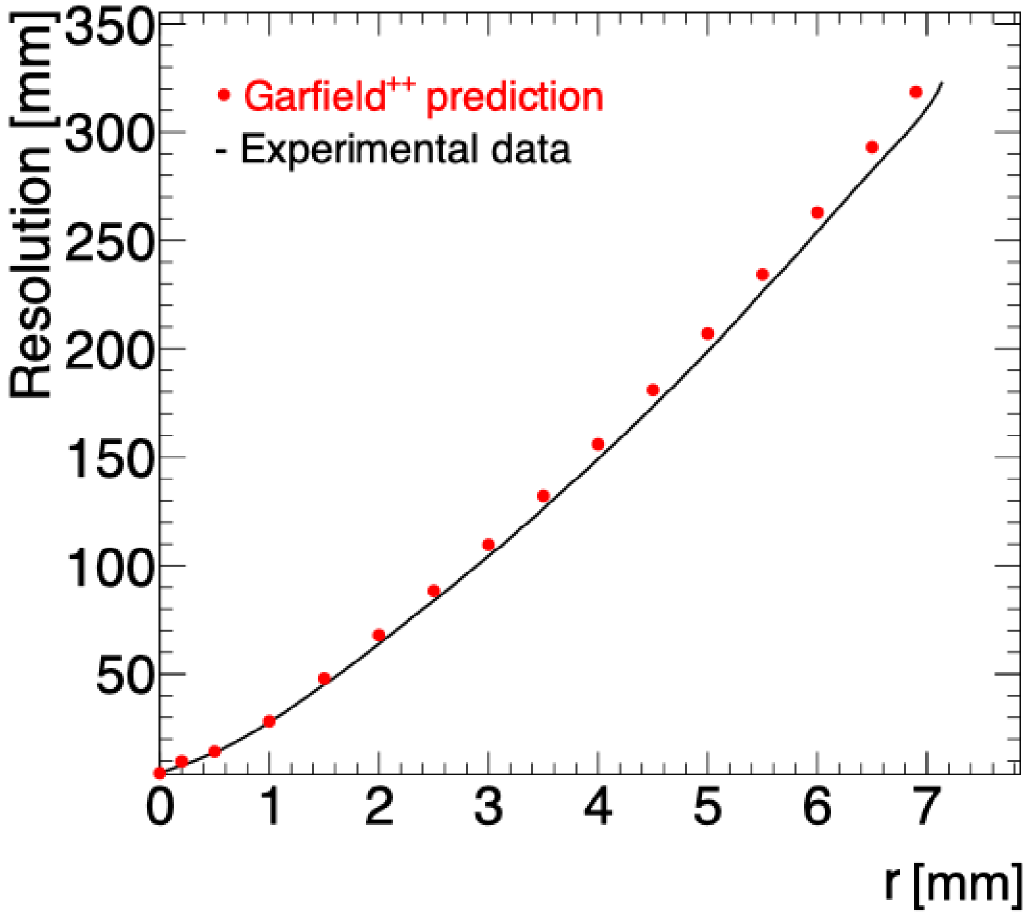
→



Fit of the Diethorn formula within the uncertainties of the parameters fits the data well and provides a suiting conversion of Gain to Voltage for our experimental purposes

Helium-isobutane studies – rt relation

- rt relation of experimental (black) and simulation (red) data (same dataset of comic rays as before)
- Overall good agreement:
  - Maximum drift time of ~ 300 ns in both data sets
  - Drift velocity in experiment is slightly higher than predicted by the simulation

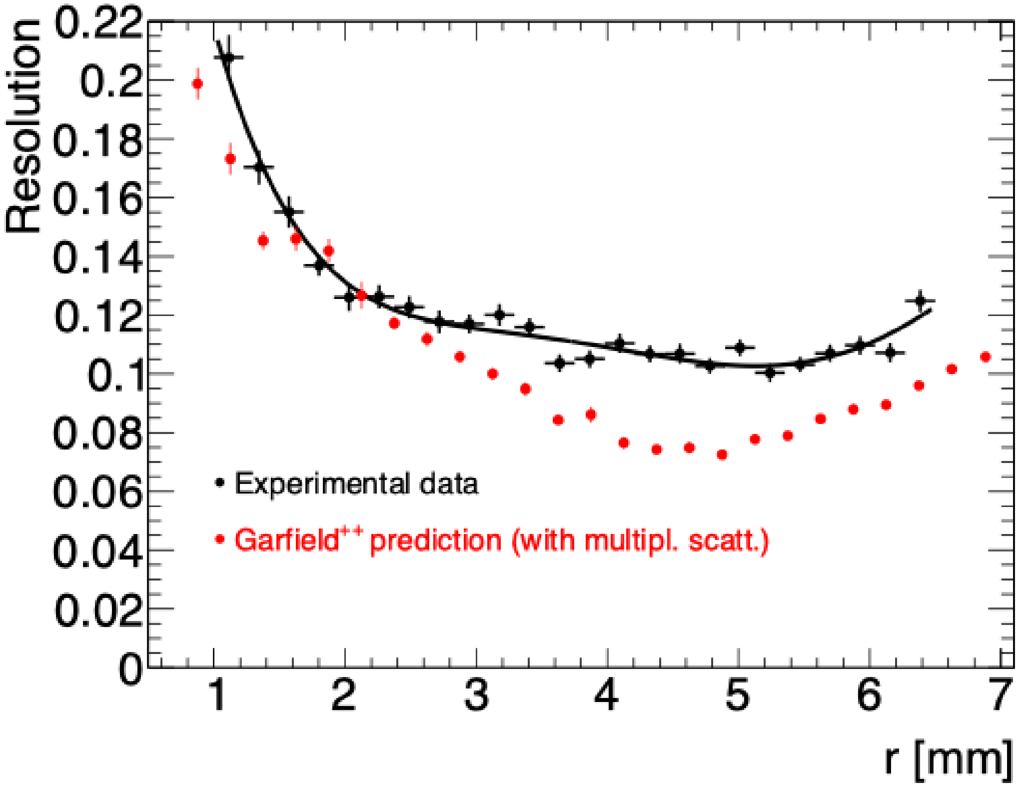


Helium-isobutane studies - resolution

- Spatial resolution of simulation better than in the experiment

- Difference in resolution results from:
  - The difference in drift velocity impacts the resolution which explains the difference partly
  - Study multiple scattering correction
    - Here it was taken from GEANT4
    - Long experimental run with lead absorber

Cosmic rays
He/iC4H10 (90/10)
50 mbar overpressure



Summary

Motivation of inner detector concept for FCCee:

- precision measurements of the Higgs boson → need of an excellent momentum resolution
- combine silicon and gaseous detectors
- advantageous to provide particle identification capabilities

Straw tubes as possible implementation

- Compatible with drift chamber
- Provides advantages such as being an independent detector unit

Producing a Straw tube chamber prototype at MPP

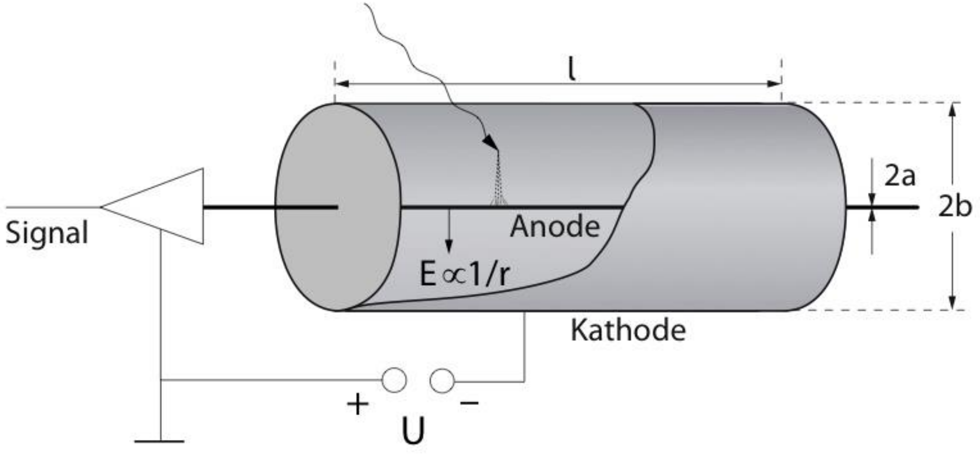
- Characterize complete prototype using the test beam in July at CERN

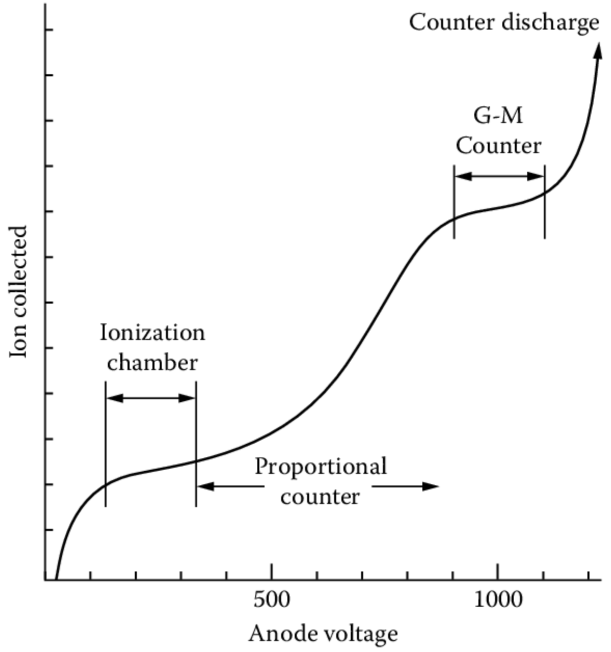
Tune Garfield++ → get reliable simulation predictions for our purposes

Backup

Gaseous Drift tube

- Detector Volume filled with gas (noble + quencher)
- Particle ionizes gas
- Apply voltage
    - Depending on the strength, the chamber is operated in different modes e.g.:
        - Ionization chamber
        - Proportional counter





- https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.researchgate.net%2Ffigure%2FGas-filled-detector-response-curve-as-a-function-of-the-applied-voltage_fig2

Momentum resolution

- The momentum resolution is composed of two components
  1. Position resolution

$$\frac{\sigma_p}{p} = \frac{2p}{Bq}\,\frac{1}{L^2}\,\sqrt{\frac{5}{N}}\,\sigma$$

  2. Multiple scattering contribution

$$\frac{\sigma_p}{p} = \frac{13.6\ \mathrm{MeV}}{qcBL}\,\sqrt{\frac{N\,d}{X_0}}$$

Nomenclature

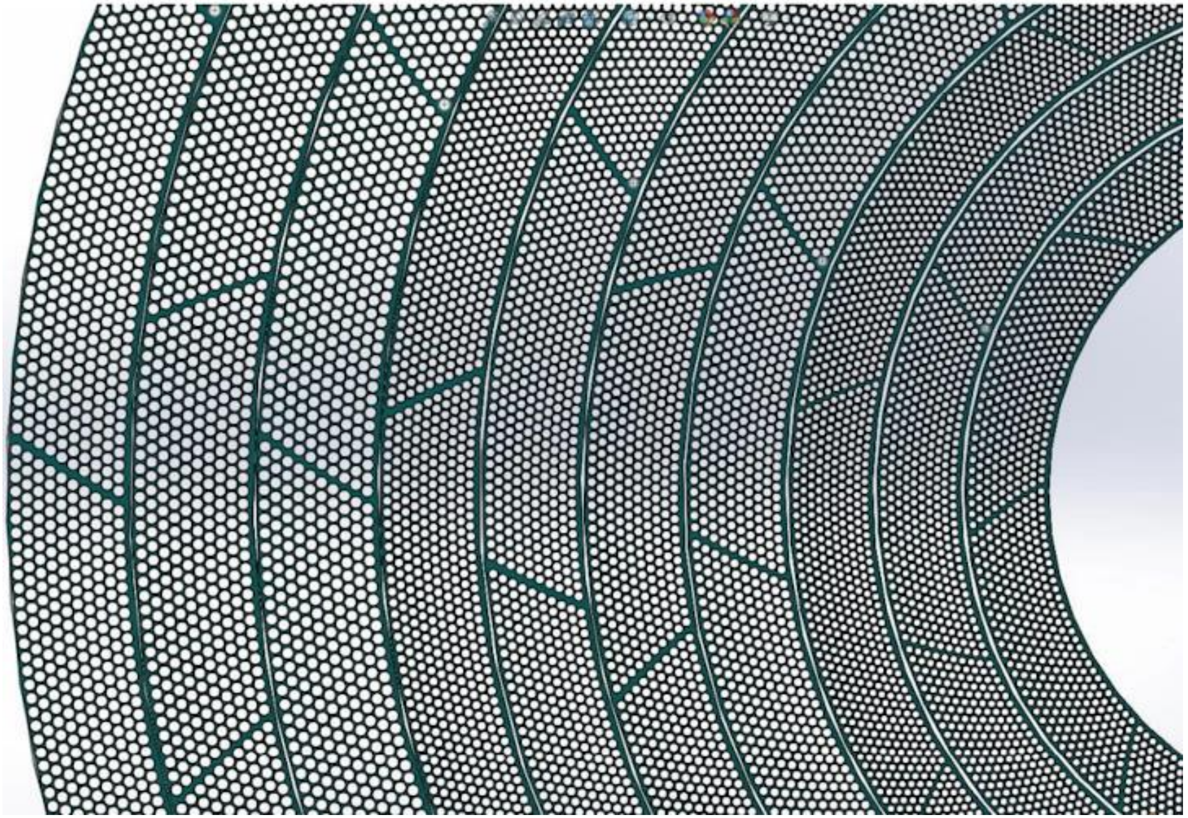
p	particle momentum
q	charge of particle
B	magnetic field
L	length of the particle trajectory
N	number of measurement layers
σ	average spatial resolution
$\frac{N\,d}{X_0}$	amount of detector material

Resolution contributions (CLD, IDEA, Allegro)

Concept	Material	Position resolution	Multiple scattering resolution	Momentum resolution
CLD	7.5 %	0.06 %	0.31%	0.32 %
IDEA	4 %	0.13 %	0.23 %	0.26 %
Straws	4.5 %	0.13 %	0.24 %	0.27 %

Simulation of the inner detector

- Preliminary study of a straw tracker for gaseous volume
- 100 straw layers with increasing tube diameters from 10 mm to 15 mm with increasing distance from the beamline



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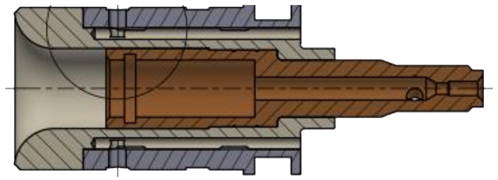
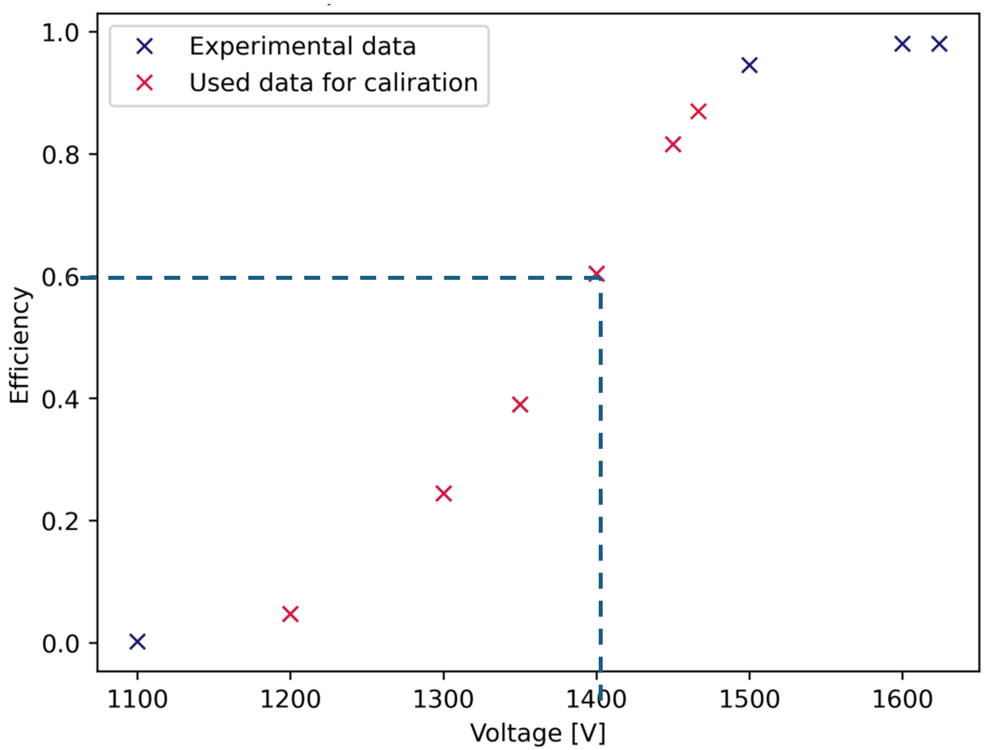
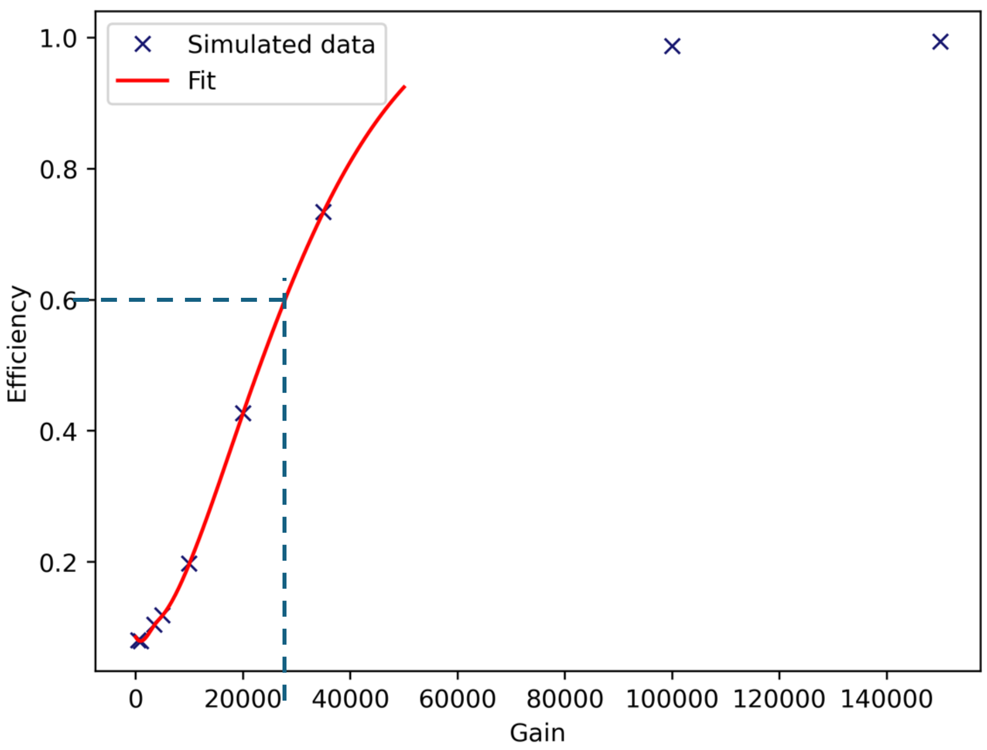
Gas leakage test Operating conditions Ar/CO2 (93/7) at a pressure of p = 1100 mbar	No leaks detected by sniffing Argon
Resistivity Measurement with digital voltmeter to check if the electrical glueing was successful	✓
Endplug leakage Operating conditions Air at Atmospheric pressure 	Goal: current below 100 pA Result: tested until 2.8 kV → within the limit
Dark current Operating conditions Ar/CO2 (93/7) at a pressure of p = 1100 mbar	Goal: current below 2 nA Result: tested up to 2.73 kV which corresponds to a gas gain of 380.000.000 → within the limit

Calibration of diethorn formula



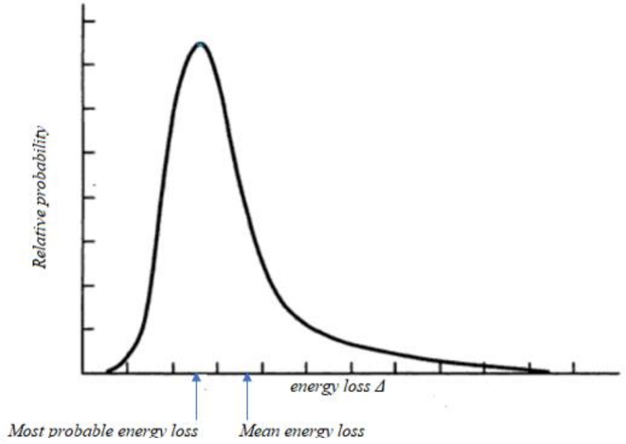


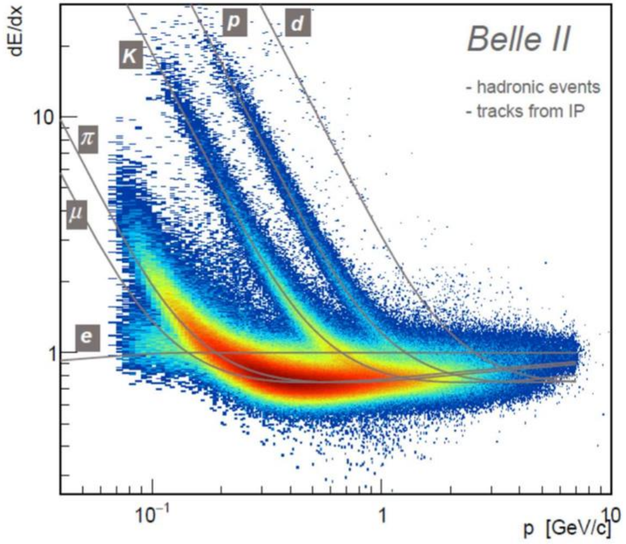
For example:

- Write out voltage at a specific efficiency (exp data)
- Check what the gain value of this efficiency corresponds to in the simulation

dE/dx measurement

- Beside a good momentum measurement, one wants to perform particle identification
- Standard procedure via calculating energy loss vs momentum
- Problem: energy loss follows a landau distribution
  - Caused by delta electrons (highly energetic, rare)
  - Impression of increased energy loss
  - Misinterpretation for particle identification





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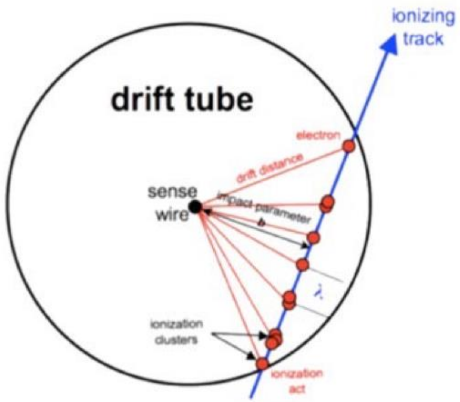
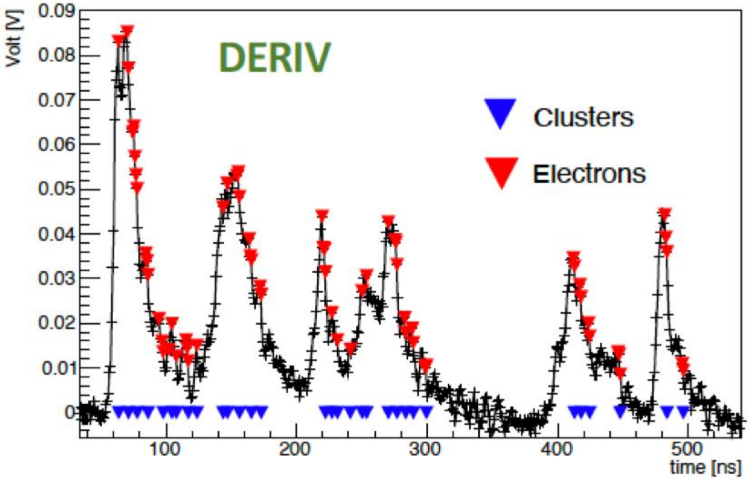
dN/dx measurement

- Counting ionizations (= peak) along the track
- Delta electrons minor influence → Poisson distribution
- Particle separation capabilities enhanced by a factor of 2

- BUT: the standard gas mixture Ar/CO2 won‘t work
- Ionization energy Argon: 15,8 eV
- USE: He/iC4H10
- Ionization energy Helium: 24,6 eV
- Less ionization clusters
- More separation in time





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