# TPC Simulation

Implementation of the TPC in the ILD simulation

Uli Einhaus
ECFA Higgs Factories:
1st Topical Meeting on Simulation
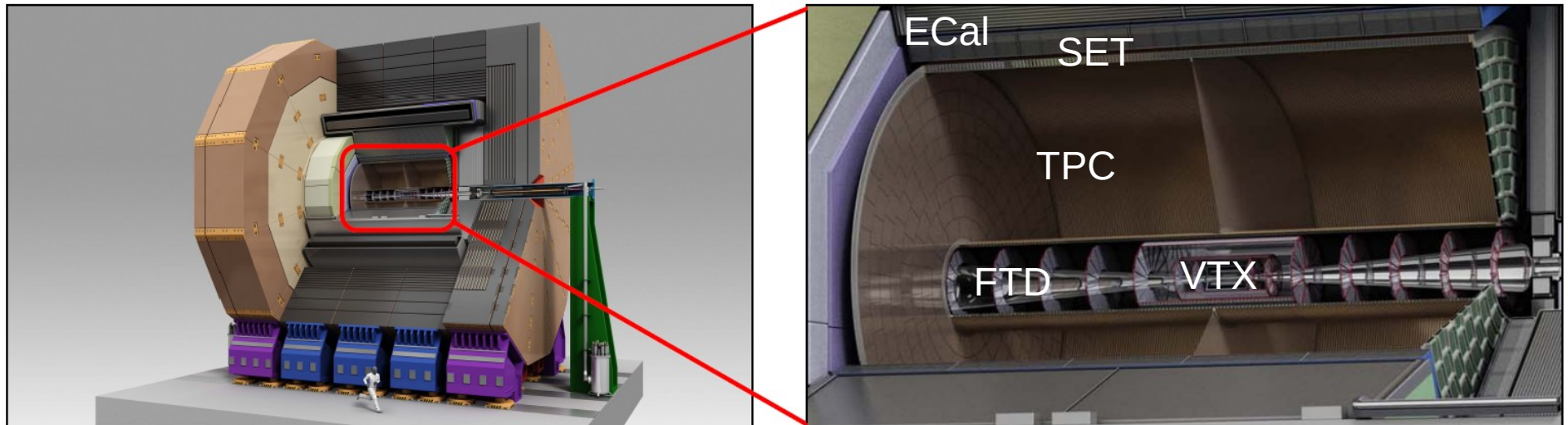01.02.2022

**HELMHOLTZ**
RESEARCH FOR GRAND CHALLENGES

ILD

DESY.

# The ILD TPC

- Main tracker of ILD, enveloped by silicon layers

$$\sigma_{1/p_T} = 2 \cdot 10^{-5} GeV^{-1} \oplus 10^{-3} \sin^{1/2}\theta/p \quad \rightarrow \quad \sigma_{r/\phi} \leq 100\,\mu m \text{ over full drift length}$$

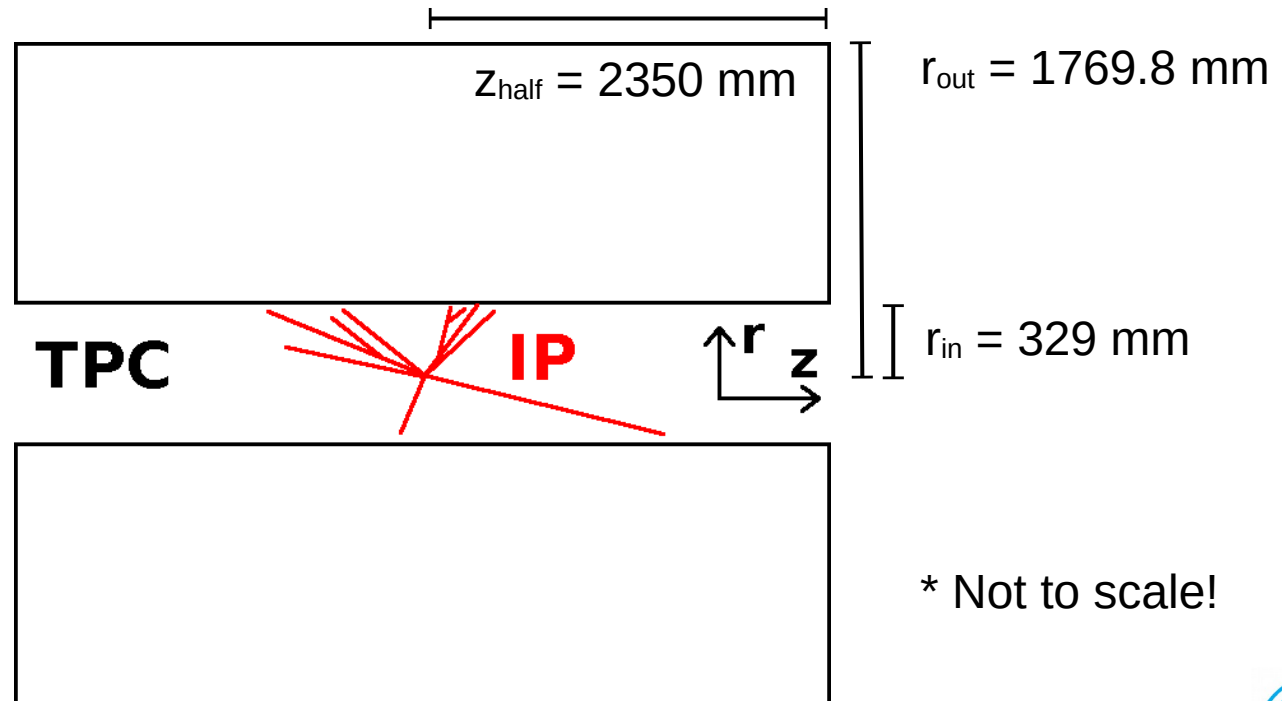Also: 5% dE/dx resolution

# ILD TPC in iLCSoft

- Part of iLCSoft: **https://ilcsoft.desy.de/portal**, **https://github.com/iLCSoft/**

- TPC description in DD4HEP, defined in lcgeo package

  - Structure: lcgeo/detector/tracker/TPC10_geo.cpp

  - Content: lcgeo/ILD/compact/ILD_[xyz]/    tpc10_01.xml, materials.xml, etc.

- Geant4 propagates particles through detailed layers of material of TPC, takes care of

  - Low energy scattering, e.g. ionisation

  - High energy scattering, e.g. photon conversion to electron-positron pair
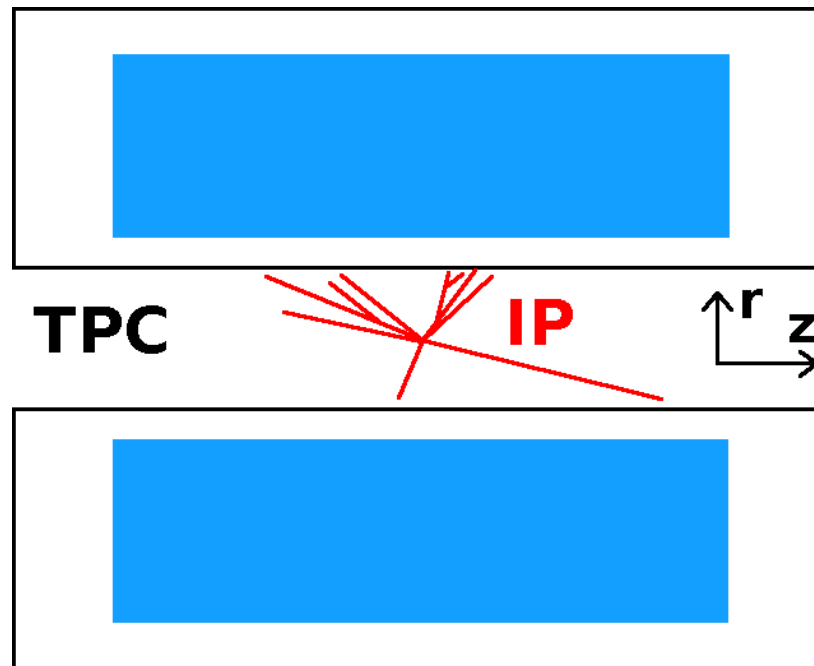
  - Decay of semi-stable particles, e.g. $K_S^0$

- TPC segmented into: sensitive gas volume, inner and outer field cage, readout, endplate and cathode, and subdivided into detailed material volumes

- Volumes are implemented as tubes with $r_{in}$, $r_{out}$, $\Delta z/2$, $\varphi_{start} = 0$, $\varphi_{end} = 2\pi$

- Geant4 calculates interaction at least at every volume transition

$z_{half}$ = 2350 mm

$r_{out}$ = 1769.8 mm

**TPC**

**IP**

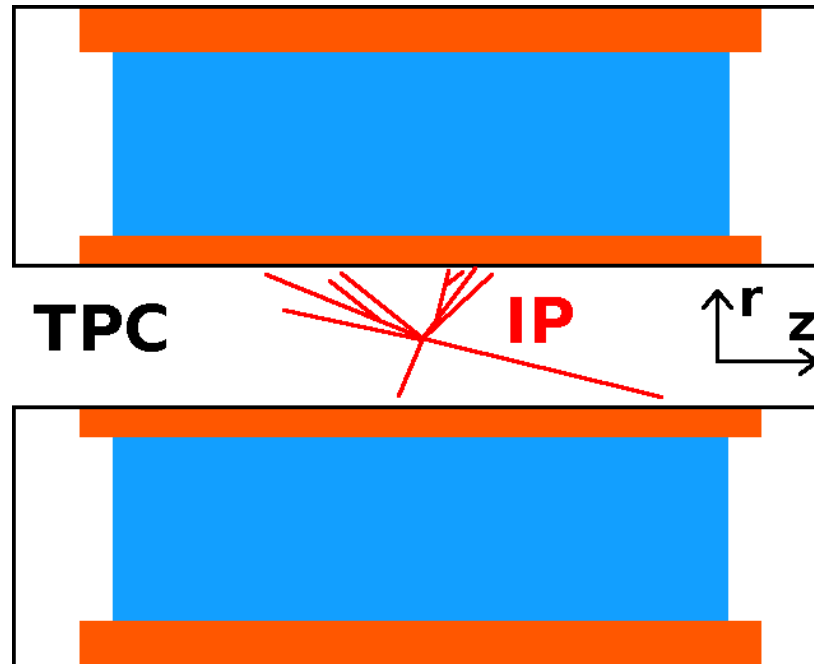$r_{in}$ = 329 mm

r z

* Not to scale!

# ILD TPC in iLCSoft

- TPC segmented into: sensitive gas volume, inner and outer field cage, readout, endplate and cathode, and subdivided into detailed material volumes

- Volumes are implemented as tubes with $r_{in}$, $r_{out}$, $\Delta z/2$, $\varphi_{start} = 0$, $\varphi_{end} = 2\pi$

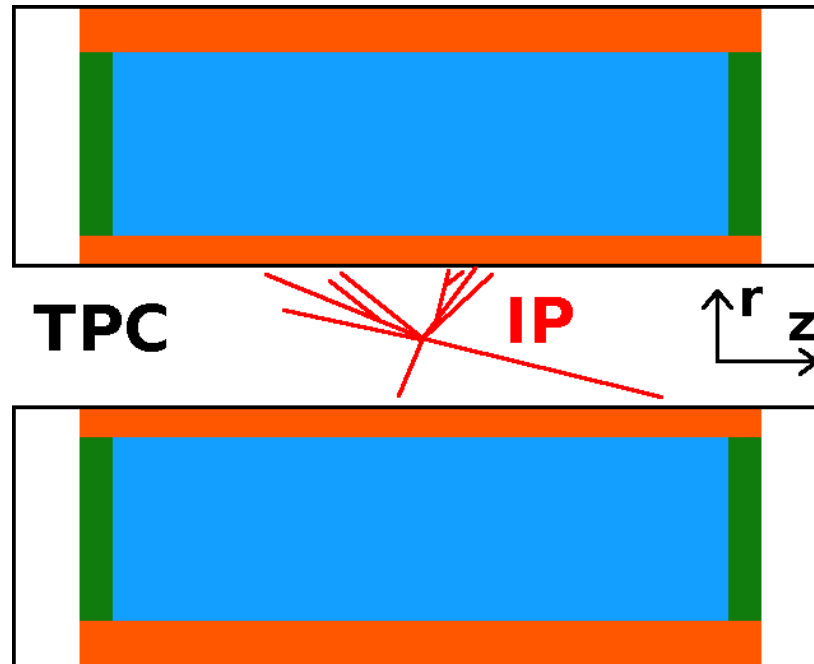- Geant4 calculates interaction at least at every volume transition

**TPC**   **IP**

$\uparrow r$  $z \rightarrow$

* Not to scale!

# ILD TPC in iLCSoft

- TPC segmented into: sensitive gas volume, inner and outer field cage, readout, endplate and cathode, and subdivided into detailed material volumes

- Volumes are implemented as tubes with $r_{in}$, $r_{out}$, $\Delta z/2$, $\varphi_{start} = 0$, $\varphi_{end} = 2\pi$

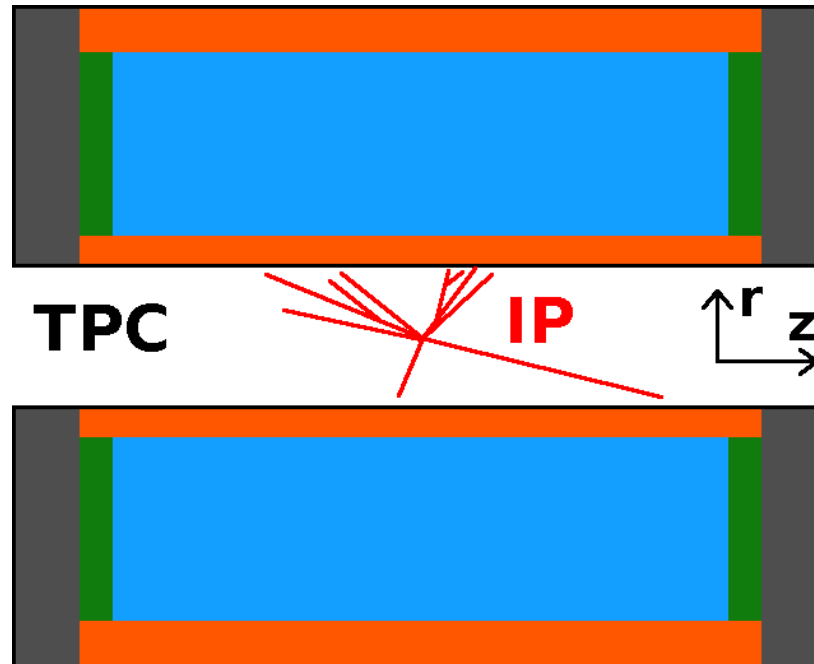- Geant4 calculates interaction at least at every volume transition

**TPC**    **IP**

$\uparrow r$  $z \rightarrow$

\* Not to scale!

# ILD TPC in iLCSoft

- TPC segmented into: sensitive gas volume, inner and outer field cage, readout, endplate and cathode, and subdivided into detailed material volumes

- Volumes are implemented as tubes with $r_{in}$, $r_{out}$, $\Delta z/2$, $\varphi_{start} = 0$, $\varphi_{end} = 2\pi$

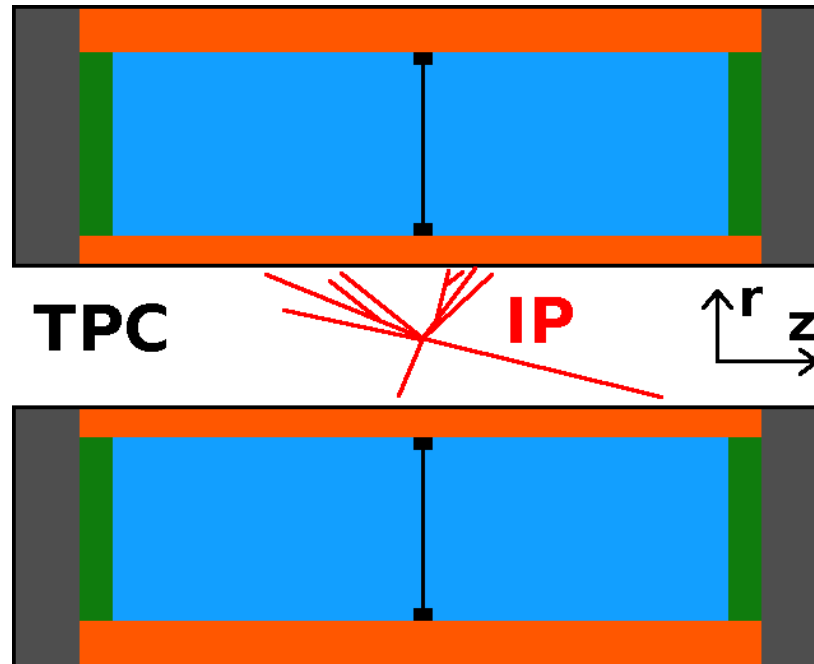- Geant4 calculates interaction at least at every volume transition

**TPC**        **IP**        $\uparrow r$  $z \rightarrow$

\* Not to scale!

# ILD TPC in iLCSoft

- TPC segmented into: sensitive gas volume, inner and outer field cage, readout, endplate and cathode, and subdivided into detailed material volumes

- Volumes are implemented as tubes with $r_{in}$, $r_{out}$, $\Delta z/2$, $\varphi_{start} = 0$, $\varphi_{end} = 2\pi$

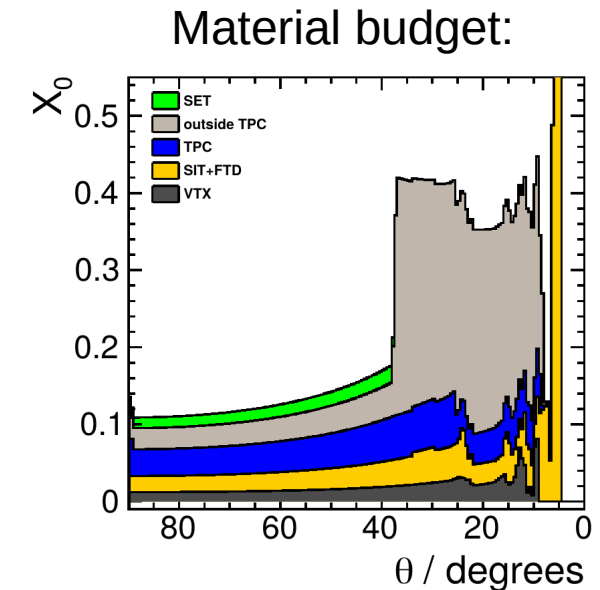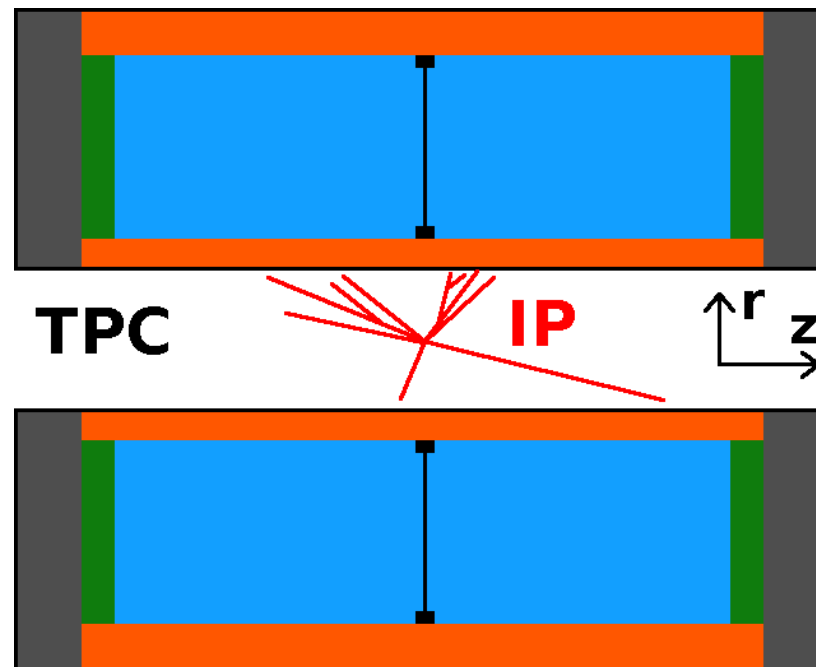- Geant4 calculates interaction at least at every volume transition



TPC    IP    r z

* Not to scale!

# ILD TPC in iLCSoft

- TPC segmented into: sensitive gas volume, inner and outer field cage, readout, endplate and **cathode**, and subdivided into detailed material volumes

- Volumes are implemented as tubes with $r_{in}$, $r_{out}$, $\Delta z/2$, $\varphi_{start} = 0$, $\varphi_{end} = 2\pi$

- Geant4 calculates interaction at least at every volume transition



* Not to scale!

# ILD TPC in iLCSoft

- TPC segmented into: sensitive gas volume, inner and outer field cage, readout, endplate and **cathode**, and subdivided into detailed material volumes

- Volumes are implemented as tubes with $r_{in}$, $r_{out}$, $\Delta z/2$, $\varphi_{start} = 0$, $\varphi_{end} = 2\pi$

- Geant4 calculates interaction at least at every volume transition



Material budget:

**SET**
**outside TPC**
**TPC**
**SIT+FTD**
**VTX**

$X_0$

$\theta$ / degrees

**https://arxiv.org/abs/2003.01116**

DESY.

# TPC segments

- Inner and outer field cage wall, extend over full z-range, except for endplate

  - Segmented in r, homogeneous is z

  - Honeycomb composite structure, insulator and field strips/high voltage

  - dr_InnerWall="25*mm"
    ```
    <row dr="0.07*mm" material="G4_Cu"  />
    <row dr="0.05*mm" material="G4_KAPTON"  />
    <row dr="0.3*mm" material="g10"  />
    <row dr="24.22*mm" material="G4_AIR"  />
    <row dr="0.3*mm" material="g10"  />
    <row dr="0.05*mm" material="G4_KAPTON"  />
    <row dr="0.01*mm" material="G4_Al"  />
    ```
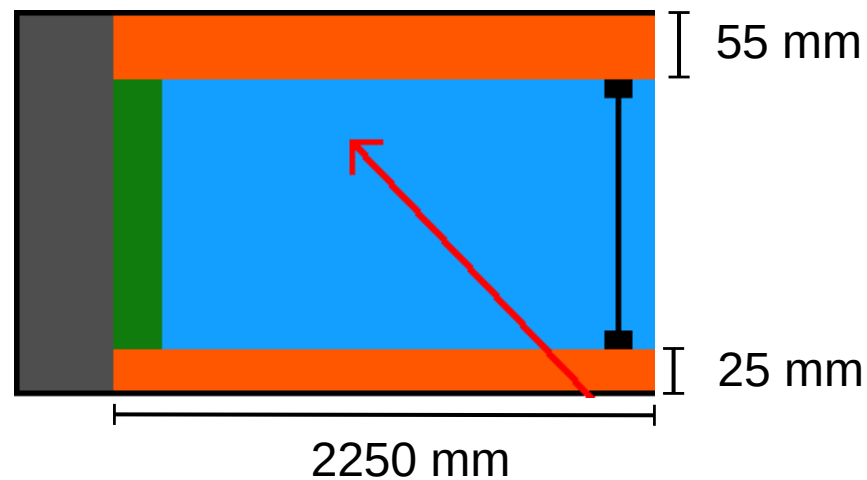
  - dr_OuterWall="55*mm"
    ```
    <row dr="0.03*mm" material="G4_Al"  />
    <row dr="0.15*mm" material="G4_KAPTON"  />
    <row dr="0.9*mm" material="g10"  />
    <row dr="52.66*mm" material="G4_AIR"  />
    <row dr="0.9*mm" material="g10"  />
    <row dr="0.15*mm" material="G4_KAPTON"  />
    <row dr="0.21*mm" material="G4_Cu"  />
    ```
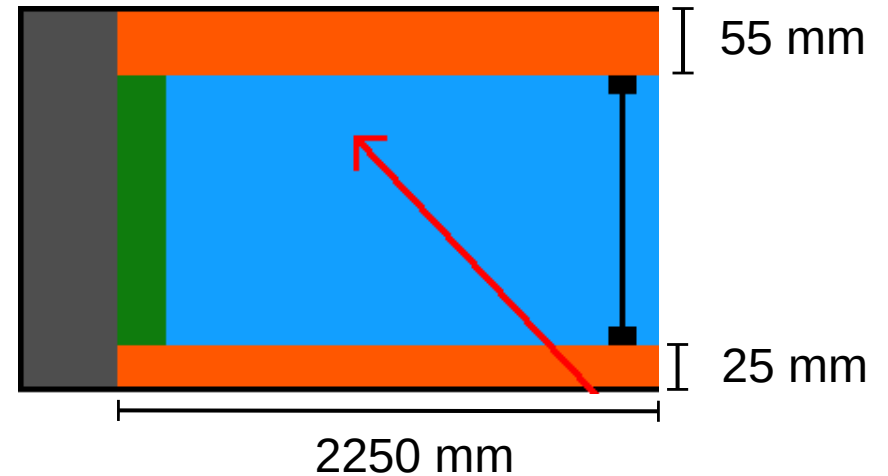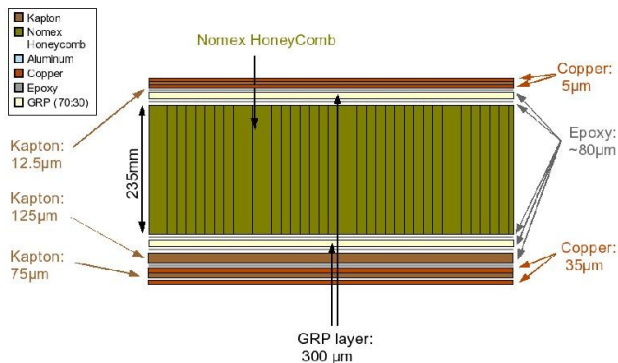


55 mm

25 mm
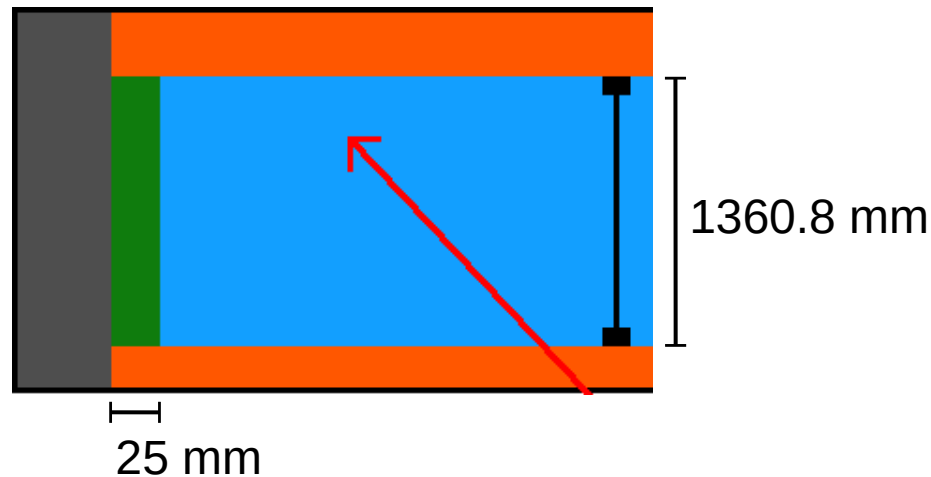
2250 mm

DESY.

# TPC segments

- Inner and outer field cage wall, extend over full z-range, except for endplate

  – Segmented in r, homogeneous is z

  – Honeycomb composite structure, insulator and field strips/high voltage





55 mm

25 mm

2250 mm

# TPC segments

- Readout

  - Inside field cage, between sensitive volume and endplate

  - Segmented in z, homogeneous is r

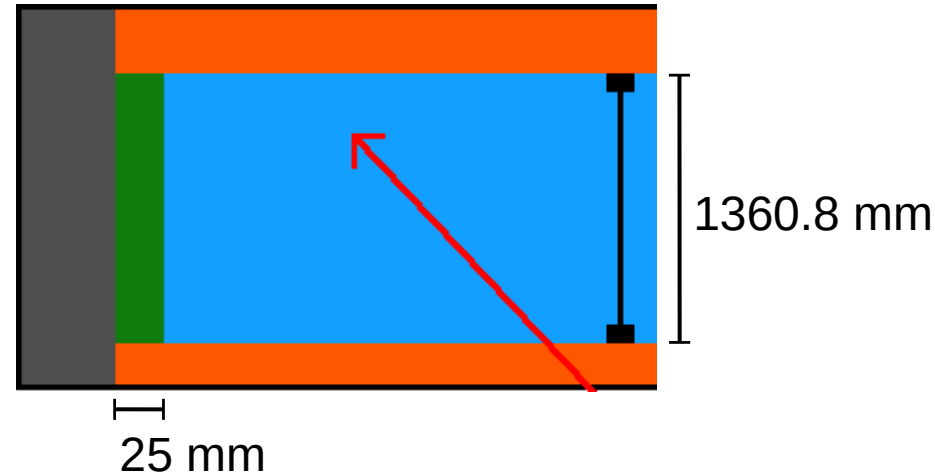  - Material represents triple GEM stack + PCB, readout ASICs, mechanics and cooling

  -
    ```xml
    <row dz="0.003*mm" material="G4_Cu" comment="gating"  />
    <row dz="0.03*mm" material="G4_KAPTON" comment="gating"  />
    <row dz="0.003*mm" material="G4_Cu" comment="gating"  />
    <row dz="4.447*mm" material="TDR_gas" comment="gating"  />
    <row dz="0.003*mm" material="G4_Cu" comment="mpgd"  />
    <row dz="0.03*mm" material="G4_KAPTON" comment="mpgd"  />
    <row dz="0.003*mm" material="G4_Cu" comment="mpgd"  />
    <row dz="4.447*mm" material="TDR_gas" comment="mpgd"  />
    <row dz="0.003*mm" material="G4_Cu" comment="mpgd"  />
    <row dz="0.03*mm" material="G4_KAPTON" comment="mpgd"  />
    <row dz="0.003*mm" material="G4_Cu" comment="mpgd"  />
    <row dz="4.447*mm" material="TDR_gas" comment="mpgd"  />
    <row dz="0.05*mm" material="G4_Cu" comment="pads"  />
    <row dz="2*mm" material="g10" comment="structural"  />
    <row dz="0.5*mm" material="G4_Si" comment="electronics"  />
    <row dz="2*mm" material="epoxy" comment="structural"  />
    <row dz="1*mm" material="G4_KAPTON" comment="structural"  />
    <row dz="2*mm" material="G4_Al" comment="Cooling"  />
    <row dz="1*mm" material="G4_KAPTON" comment="structural"  />
    <row dz="3*mm" material="CarbonFiber" comment="structural"  />
    ```
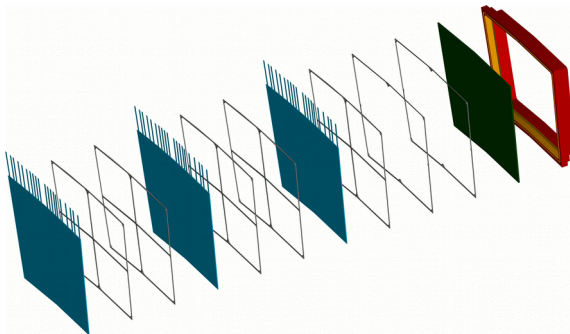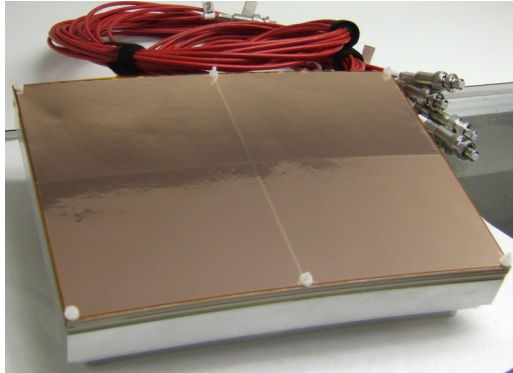


1360.8 mm

25 mm

# TPC segments

- **Readout**

    - Inside field cage, between sensitive volume and endplate

    - Segmented in z, homogeneous is r

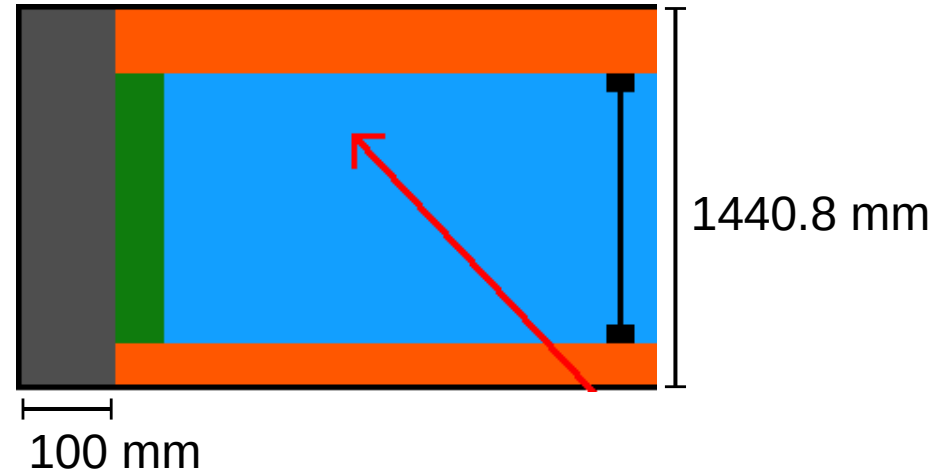    - Material represents triple GEM stack + PCB, readout ASICs, mechanics and cooling

https://arxiv.org/abs/1604.00935



1360.8 mm

25 mm

- **Endplate**

    – Aluminium space frame outside of TPC gas volume ($\rightarrow$ air) for mechanical stability, cables and services

    – Implemented as one tube (per side) with a homogeneous material

    – `<MEE unit="eV" value="97.0754229107761"/>`
    `<D unit="g/cm3" value="0.5827515446"/>`
    `<fraction n="0.00953598760814401" ref="C"/>`
    `<fraction n="0.558898138898139" ref="N"/>`
    `<fraction n="0.226789772550668" ref="O"/>`
    `<fraction n="0.0094919894919894949" ref="Ar"/>`
    `<fraction n="0.14" ref="Al"/>`
    `<fraction n="0.0096" ref="Cl"/>`
    `<fraction n="0.0433592706" ref="Si"/>`
    `<fraction n="0.00232484085105981" ref="H"/>`



1440.8 mm

100 mm

# TPC segments

- Endplate

  – Aluminium space frame outside of TPC gas volume (→ air) for mechanical stability, cables and services

  – Implemented as one tube (per side) with a homogeneous material
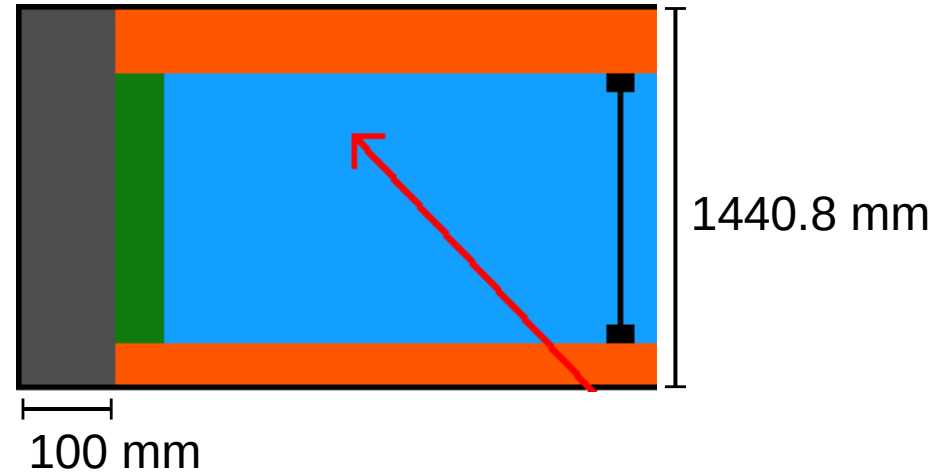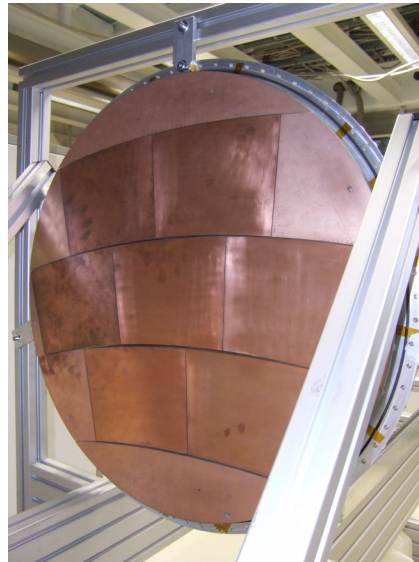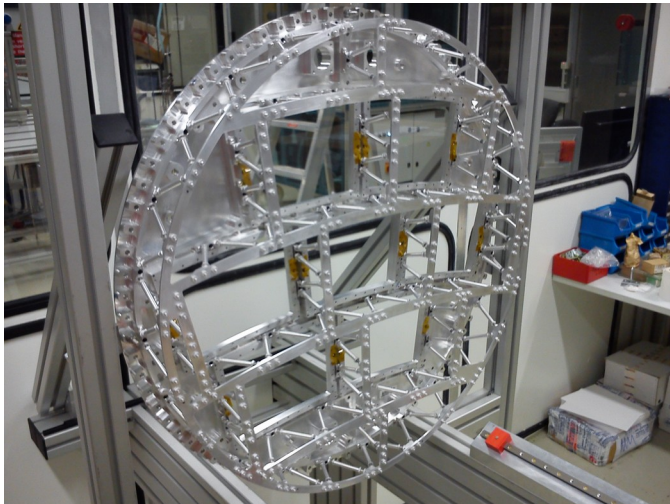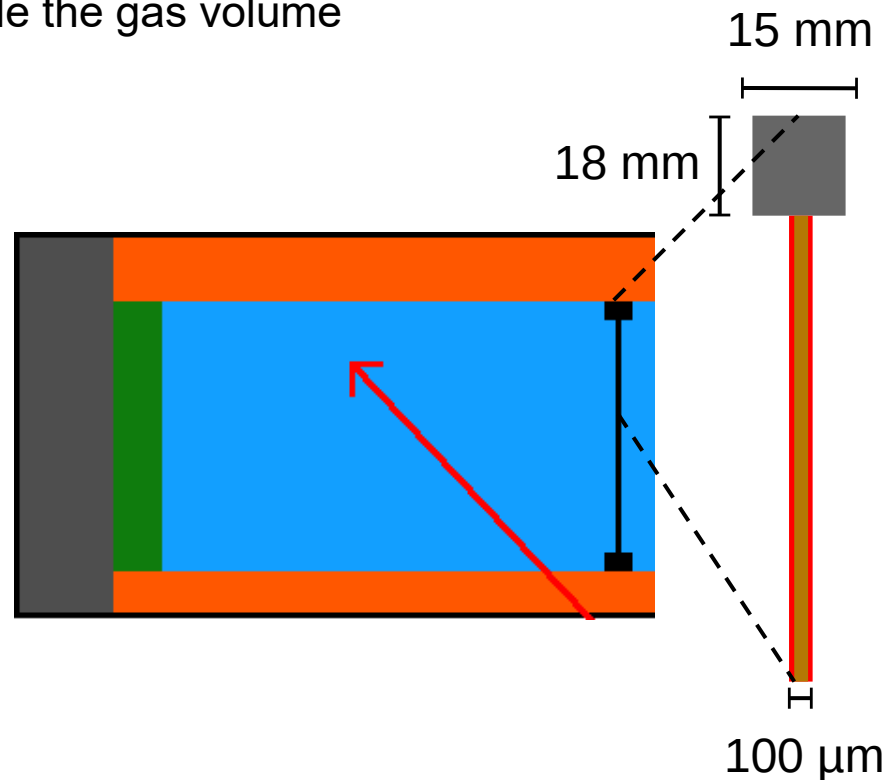
# TPC segments

- Cathode, at z = 0, subdivides TPC into two drift volumes

    - Two grips at the inner and outer field cage, inside the gas volume
      → reduction of sensitive volume by 2 x 18 mm

    - dr_Cathode_Grip="18*mm"
      dz_Cathode_Grip="15*mm"
      material_Cathode_Grip="SiC_foam"

    - Cathode insulator and conductor are mirrored
      at z = 0, total thickness of 100 µm

    - dz_Cathode_Insulator="0.046*mm"
      material_Cathode_Insulator="G4_KAPTON"
      dz_Cathode_Conductor="0.004*mm"
      material_Cathode_Conductor="G4_Cu"



15 mm

18 mm

100 µm
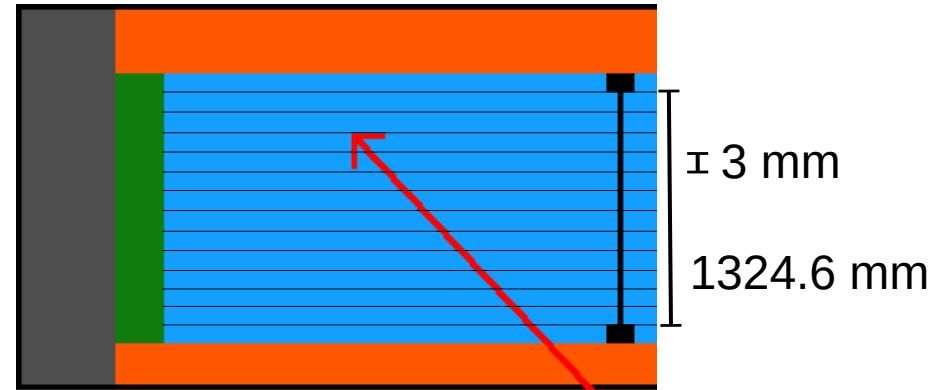
# TPC segments

- Sensitive volume → ionisation is used for digitisation and reconstruction!

    – TDR gas
    ```
    <material name="TDR_gas" state="gas">
    <MEE unit="eV" value="177.374841770826"/>
    <D unit="g/cm3" value="0.001731"/>
    <fraction n="0.95667" ref="Ar"/>
    <fraction n="0.00519198196" ref="H"/>
    <fraction n="0.02165502376" ref="C"/>
    <fraction n="0.01648299428" ref="O"/>
    ```
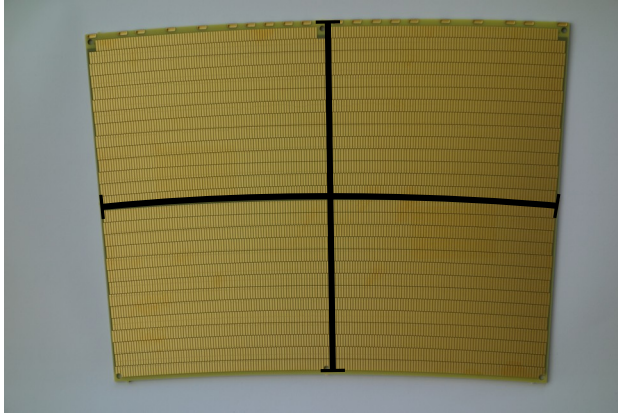
    – Readout granularity in r: 6 mm pad height,
    220 rows inside sensitive volume

    – Provide 2 tubes per row and add ionisation
    of both into one SimTrackerHit per row with
    precise center position

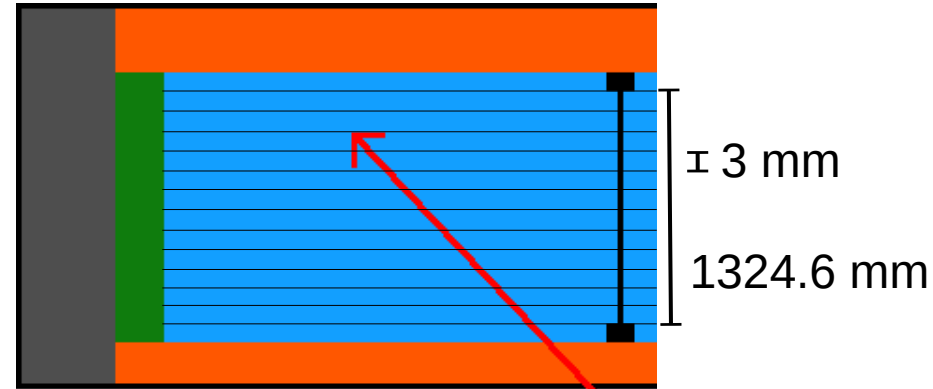    – (2 x ) 440 tubes with Δr = 3mm, Δz = 2225 mm



3 mm

1324.6 mm

# TPC segments

- Sensitive volume → ionisation is used for digitisation and reconstruction!



Pad plane of one
readout module:
~ 17 x 22 cm²



- Readout granularity in r: 6 mm pad height,
  220 rows inside sensitive volume

- Provide 2 tubes per row and add ionisation
  of both into one SimTrackerHit per row with
  precise center position

- (2 x ) 440 tubes with $\Delta r$ = 3mm, $\Delta z$ = 2225 mm

3 mm

1324.6 mm

# TPC segments

- Sensitive volume → ionisation is used for digitisation and reconstruction!

  - One row:

    **track**

    **pads**
    **h = 6 mm**

    **ionisation**
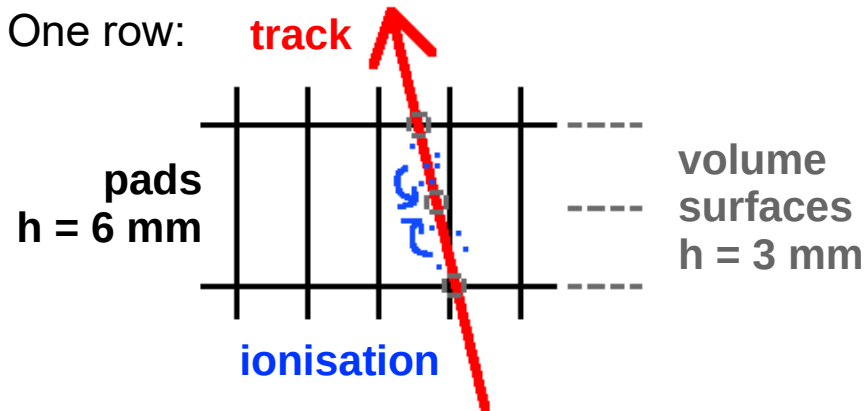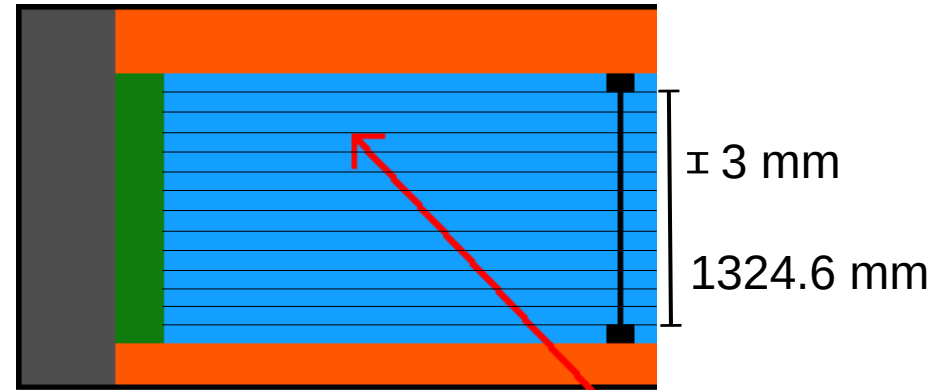
    **volume surfaces h = 3 mm**

  - Readout granularity in r: 6 mm pad height, 220 rows inside sensitive volume

  - Provide 2 tubes per row and add ionisation of both into one SimTrackerHit per row with precise center position

  - (2 x ) 440 tubes with Δr = 3mm, Δz = 2225 mm

3 mm

1324.6 mm

DESY.

# TPC Digitisation

- Geant4 → SimTrackerHits → TrackerDigi → TrackerHits → TrackerReco → Tracks

- TPC Digitisation takes Sim input and transforms it into an equivalent of what an actual detector would see, taking into account various resolutions

- Hits which are closer than the double-hit resolution $\Delta_{r/\Phi}$ = 2 mm or $\Delta_z$ = 5 mm are merged

- Hit positions are smeared in r/φ and z according to the diffusion which depends on the hit z position, i.e. the drift distance, and the track direction in Φ and θ

$$\sigma^2_{r/\phi} = \left( 50^2 + 900^2 \sin^2 \phi + \left( \frac{25^2}{22} \cdot \left( \frac{4\,T}{B} \right)^2 \sin \theta \right) \frac{z}{cm} \right) \mu\,m^2 \qquad \sigma^2_z = \left( 400^2 + 80^2 \cdot \frac{z}{cm} \right) \mu\,m^2$$

- Resolutions and diffusion constants are vetted by test beam measurements by the LCTPC collaboration

# TPC dE/dx

- The specific energy loss dE/dx, which is used for PID, is reconstructed directly from the energy deposited by Geant4 via truncated mean of reco hits, but is corrected on track level to represent the resolution measured in LCTPC test beams (~ 4.5%)

- In 2020, a new Geant version (v.10.04) included physics-list updates with better treatment of atomic sub-shell energies, bringing the resulting hit energy distribution closer to the one measured in test beam and reducing the impact of post-hoc adjustment
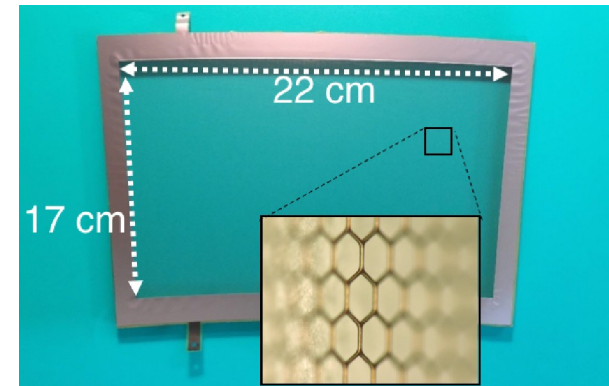
# MarlinTPC
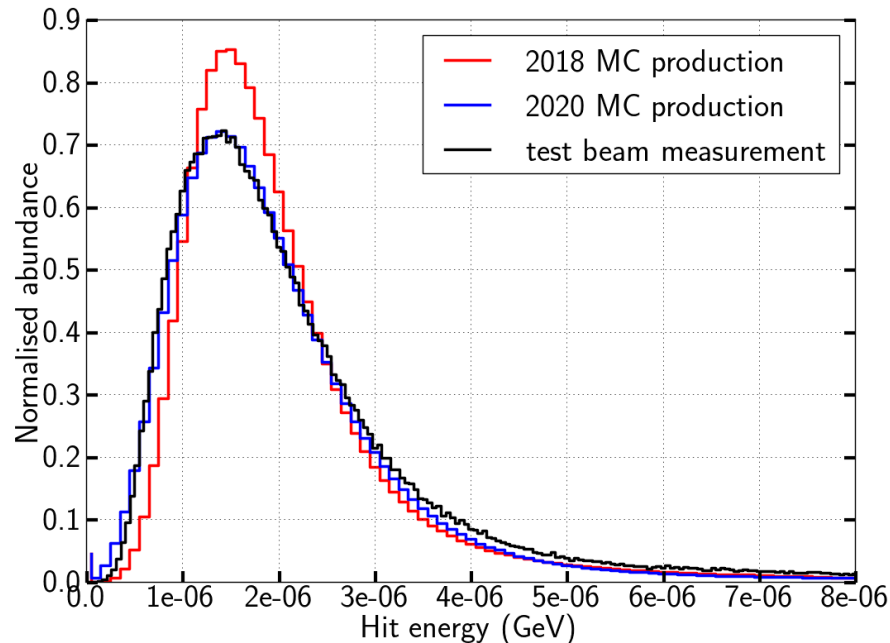
- For detailed studies of the TPC: **https://znwiki3.ifh.de/MarlinTPC/**

- Simulation of individual electrons from the ionisation, via individual drift, amplification, charge distribution on the anode pad plane and digitisation

- Allows to study impact of altering TPC parameters, like gas or readout granularity, or the impact of field distortions

# Field Distortions

- Field distortions in the TPC deflect the drift and can worsen the resolution

- Effects from static distortions can be reduced by alignment
  In test beam data shown to reduce residuals to the μm level
  Ongoing work in LCTPC to reduce level of static field distortions

- Variable distortions from ion backflow can be mitigated via a gating GEM

  – → only possible with bunch trains at linear collider

  – gating GEM transparency > 80%, via test beam

  – ion backflow < $10^{-4}$ during gating, via simulation



https://arxiv.org/abs/1801.04499

# Conclusion

- The ILD TPC is simulated to a high degree of detail

- Geant4 ionisation is convoluted with test-beam gauged resolutions

- A more detailed simulation based on single electrons is available with MarlinTPC, but is significantly more CPU-costly

- Materials are included with segmentations at the µm level in track direction, homogeneous in the transverse direction, avoiding complex structures like individual field strips or the space-frame endplate – a more detailed description would be possible but again more computing intense

- Field distortions are not included (yet), but mitigation techniques are available


→ ILD TPC: Detailed, Fast & Verified!