SORBONNE UNIVERSITÉ

LPNHE PARIS

Performance of the **High-Angle Time Projection Chambers** in the **Upgraded T2K Off-Axis Near Detector ND280**

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on behalf of the T2K HA-TPC WG

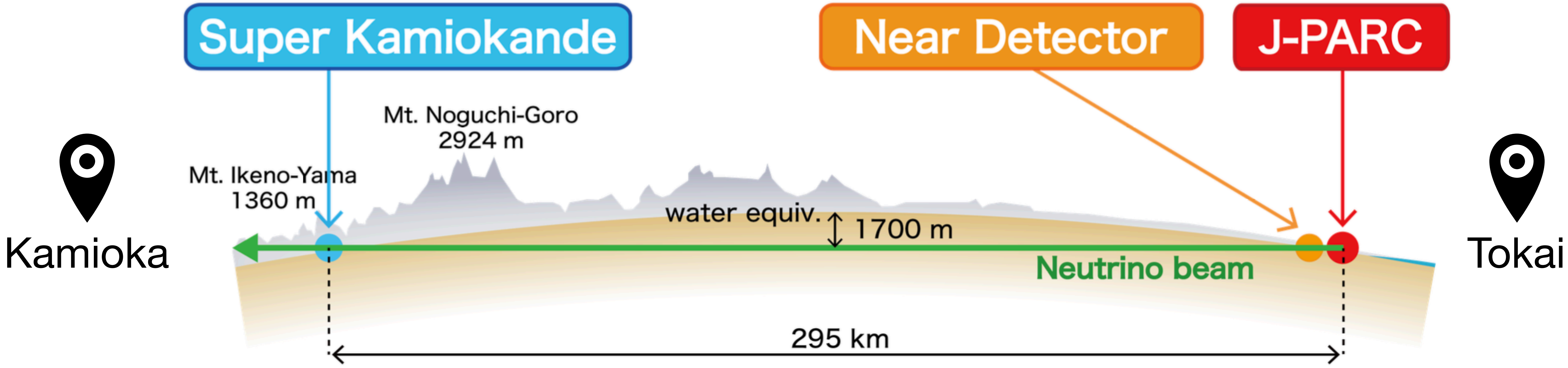
IRN Neutrino meeting 2025, Lyon

cnrs

T2K

The T2K Experiment

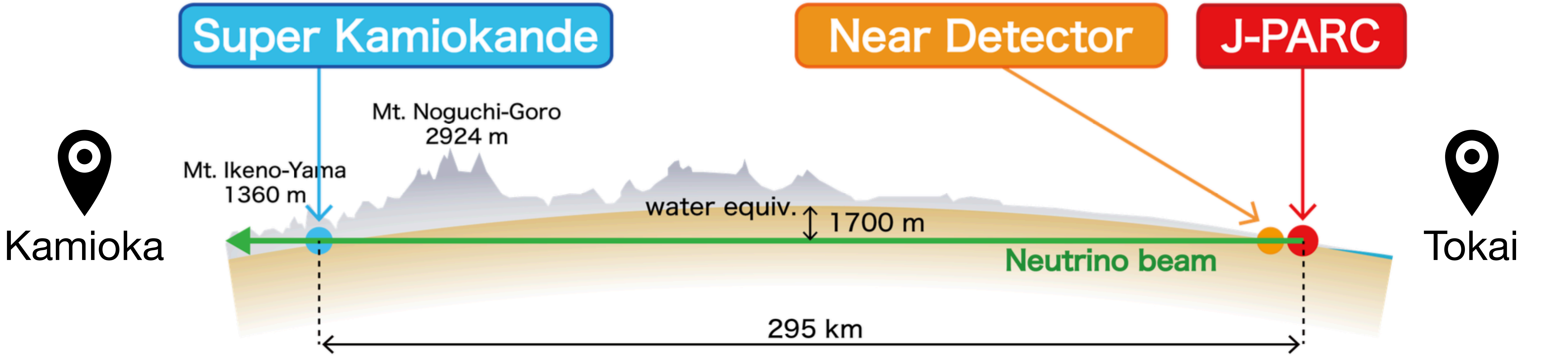
a long-baseline neutrino oscillation experiment



Tokai To Kamioka

The T2K Experiment

a long-baseline neutrino oscillation experiment

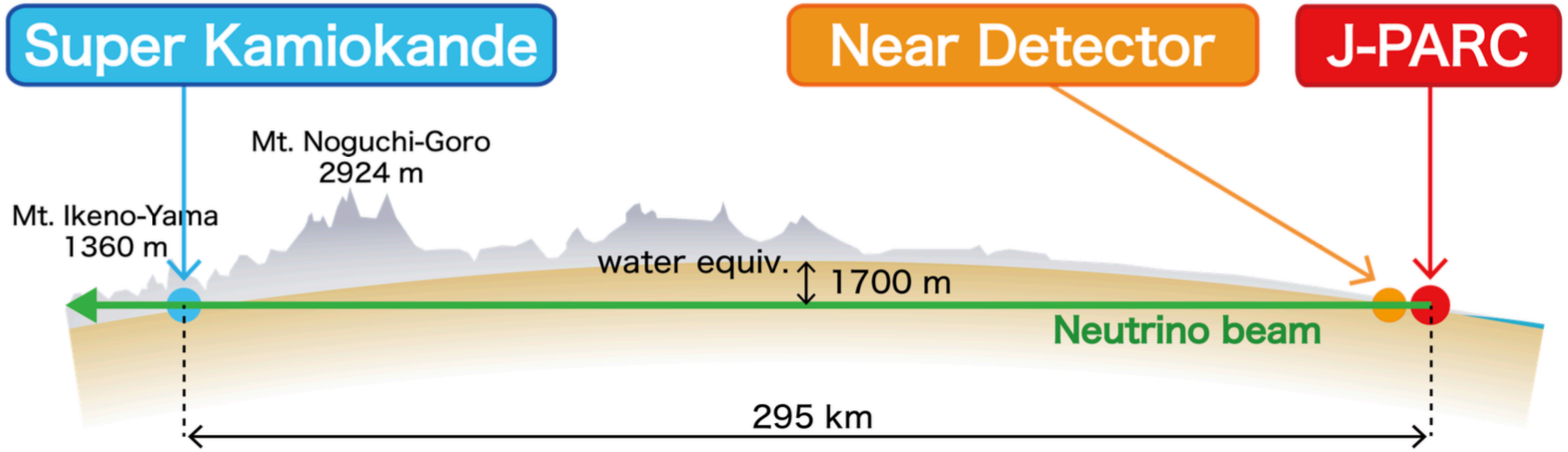


Tokai To Kamioka

The T2K Experiment

*with the help of NA61/SHINE experiment @ CERN

a long-baseline neutrino oscillation experiment

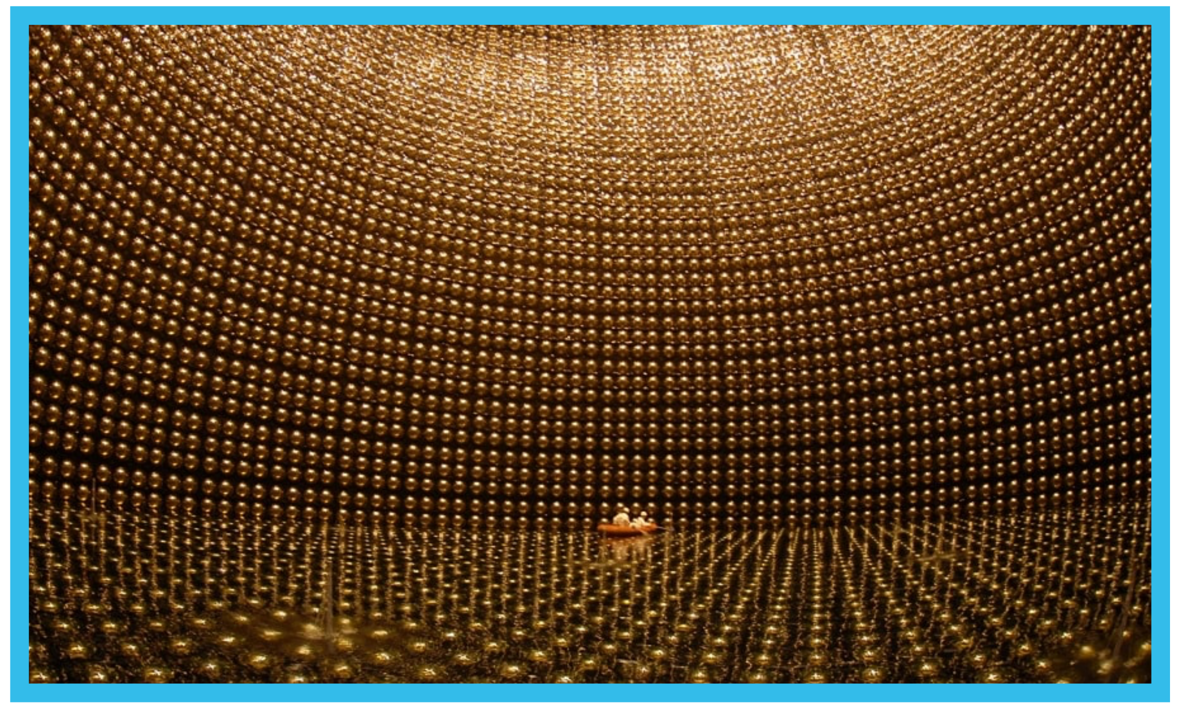


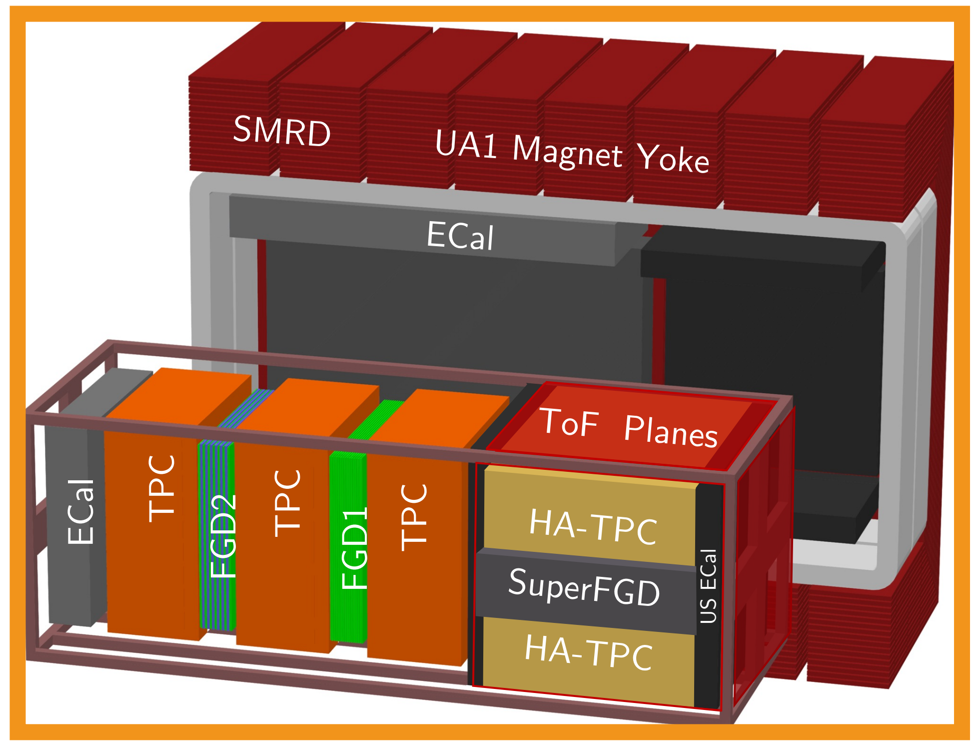
measure the ϕ_ν after the oscillation

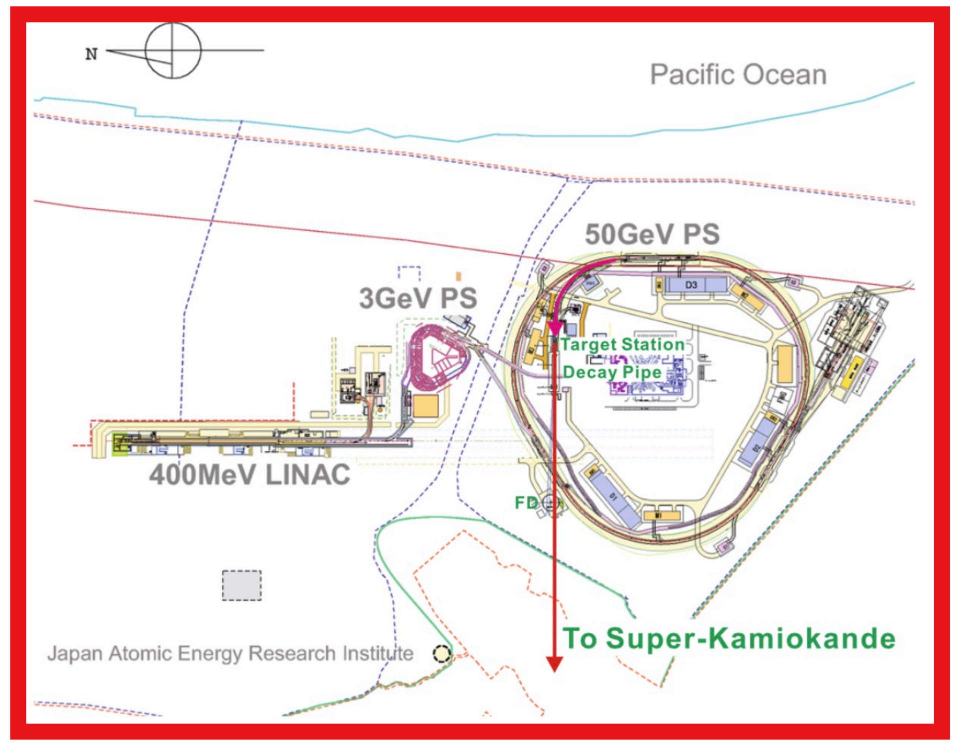
295 km

characterise the ϕ_ν before the oscillation *

ν_μ beam production

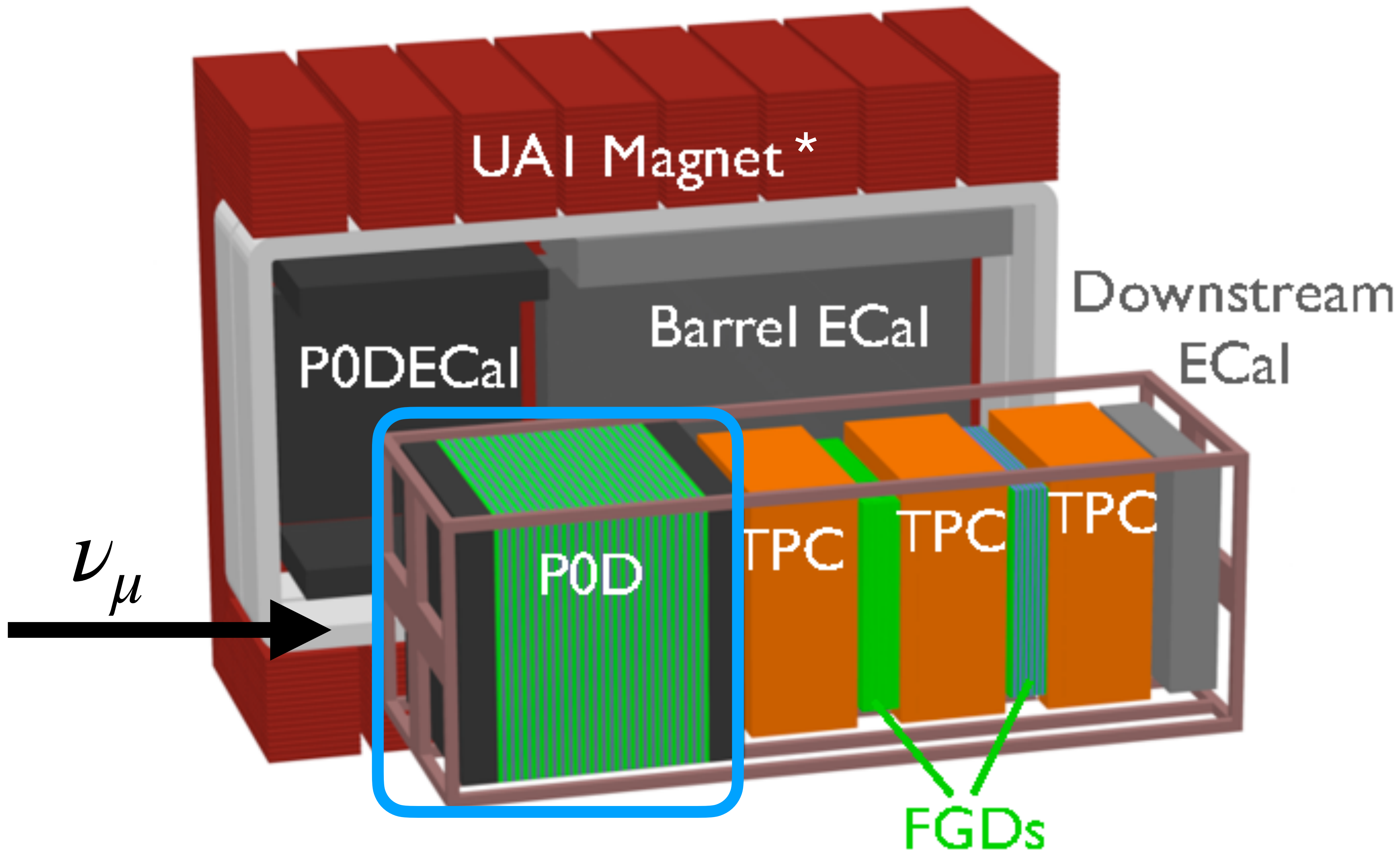




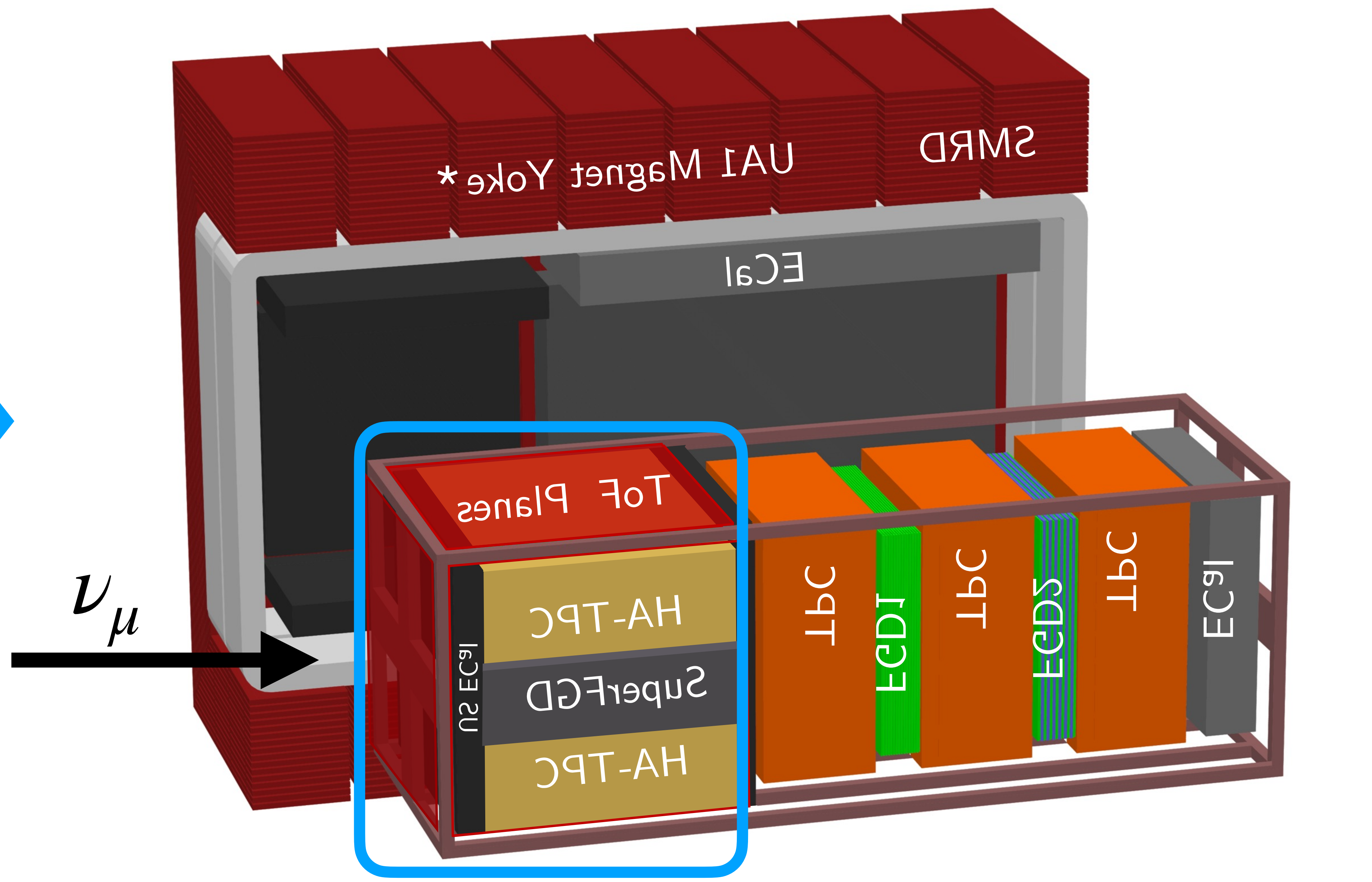


The ND280 upgrade

*UA1 magnet inherited from UA1 experiment



ND280 upgrade



- **P0D :** precisely **quantify** the π^0 **production** in neutrino interactions (main **background** to ν_e appearance)

- **P0D** did **not** play an **important role anymore** because of :
  - large θ_{13}
  - improvement in reducing $\mathrm{NC}\pi^0$ background at SK
  - precise knowledge of π^0 cross section

The ND280 upgrade

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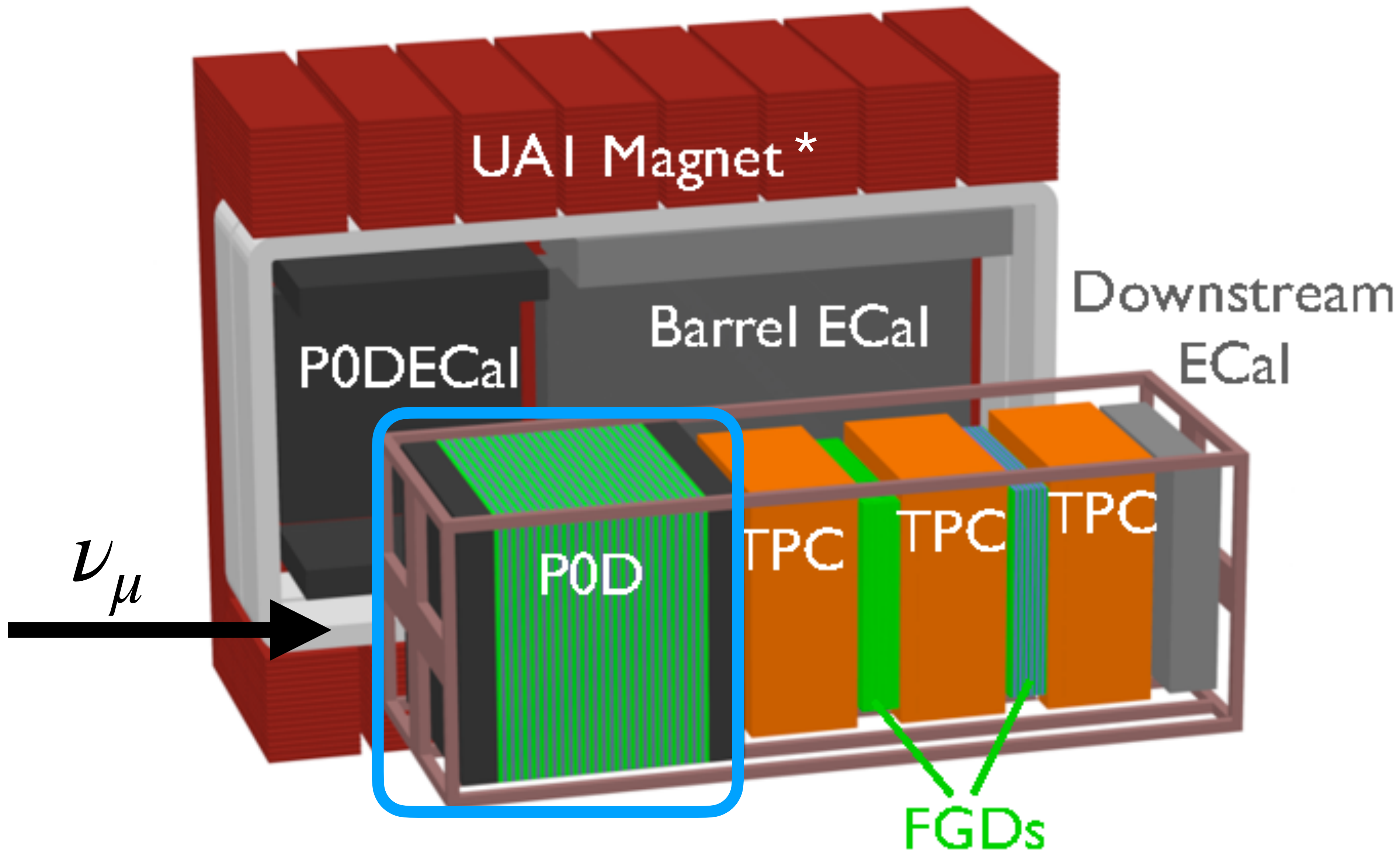

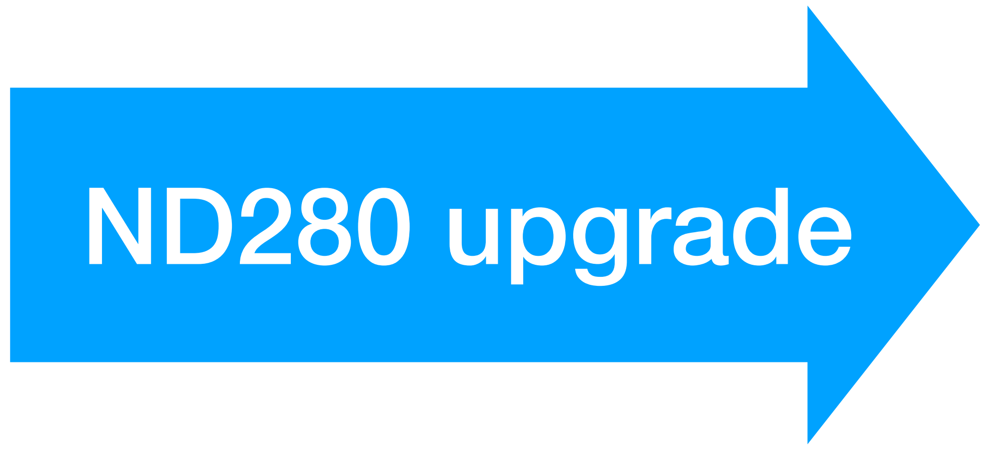

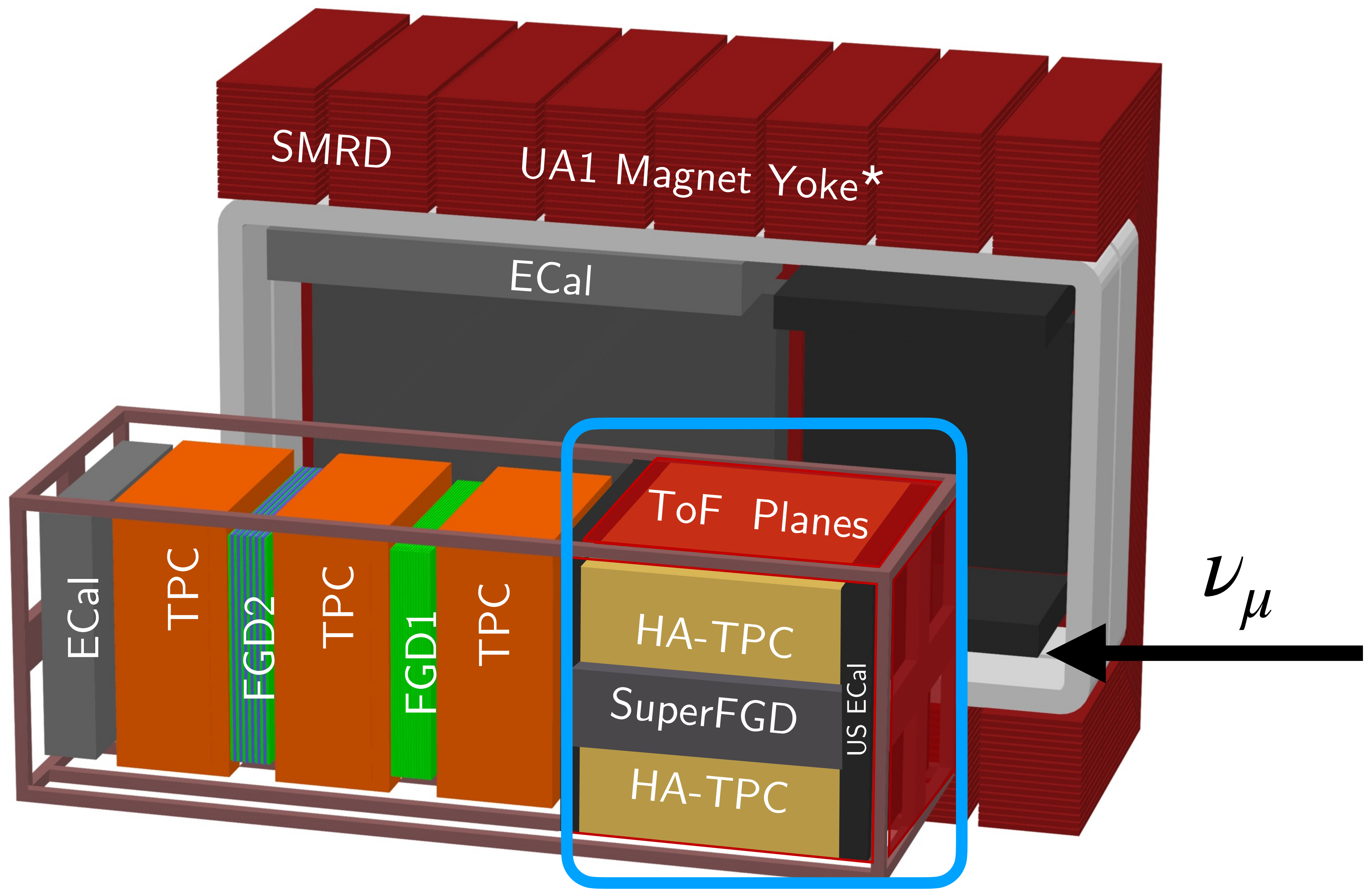

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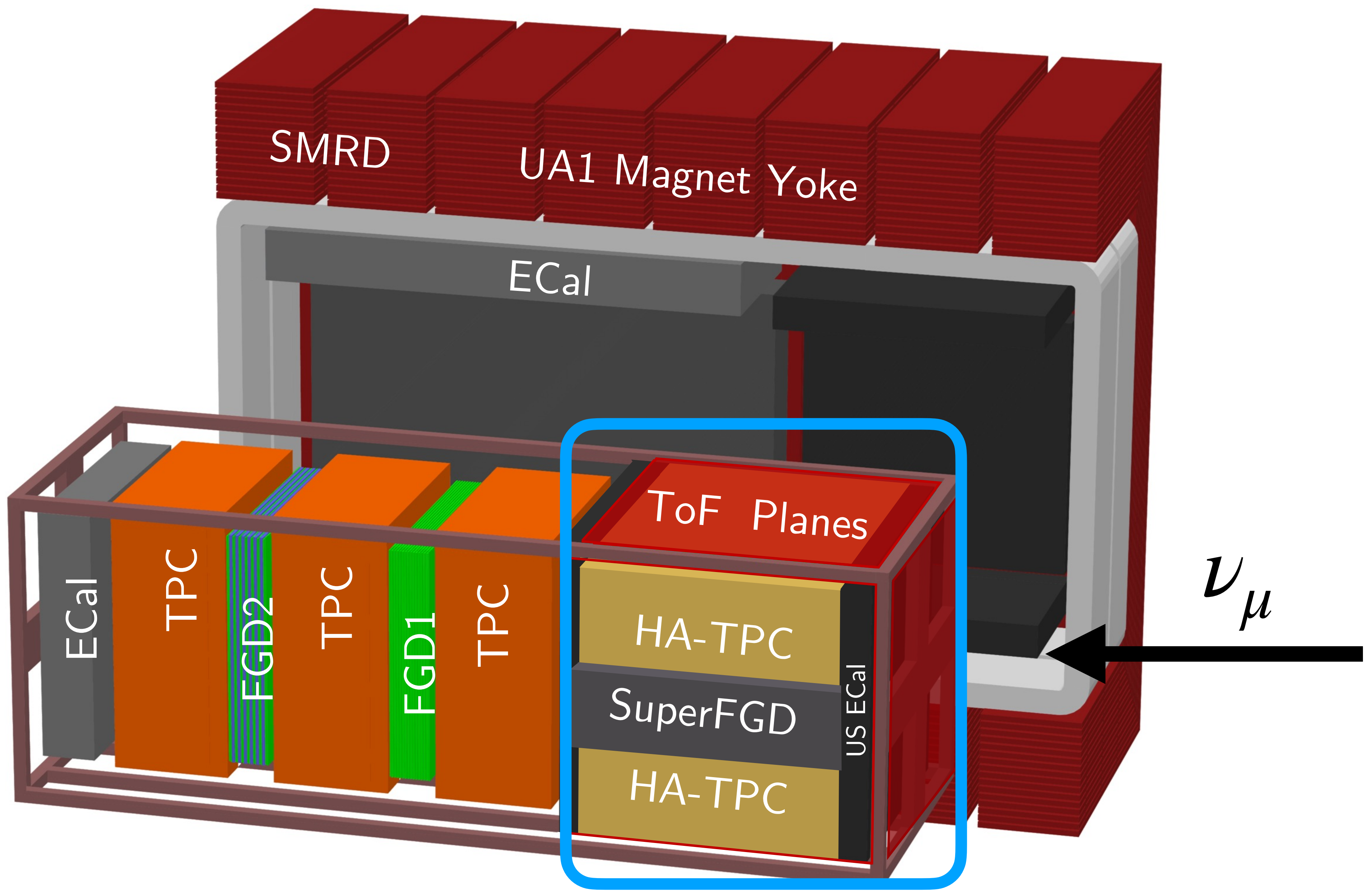
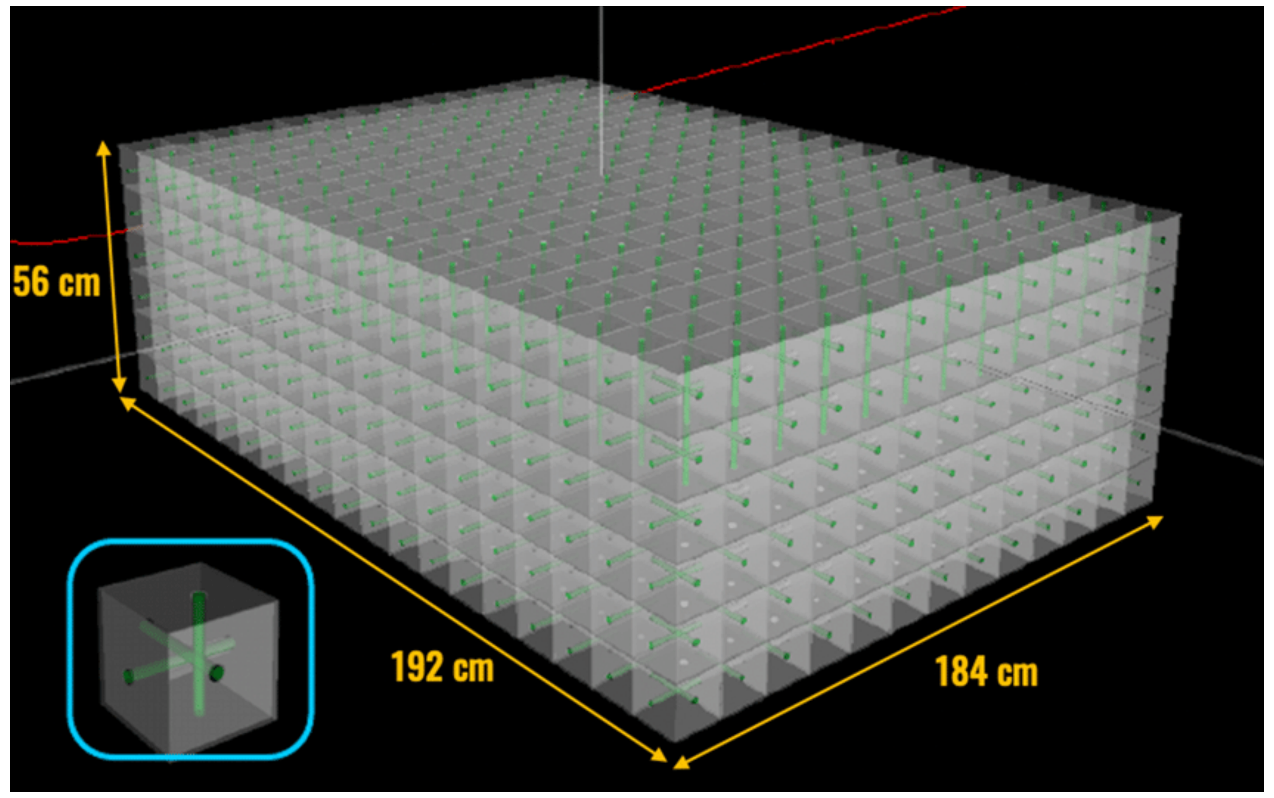
The ND280 upgrade
the motivations

- **reduce** the ~400 MeV/c **reconstruction momentum threshold** and **increase** the interaction **probability**



SuperFGD



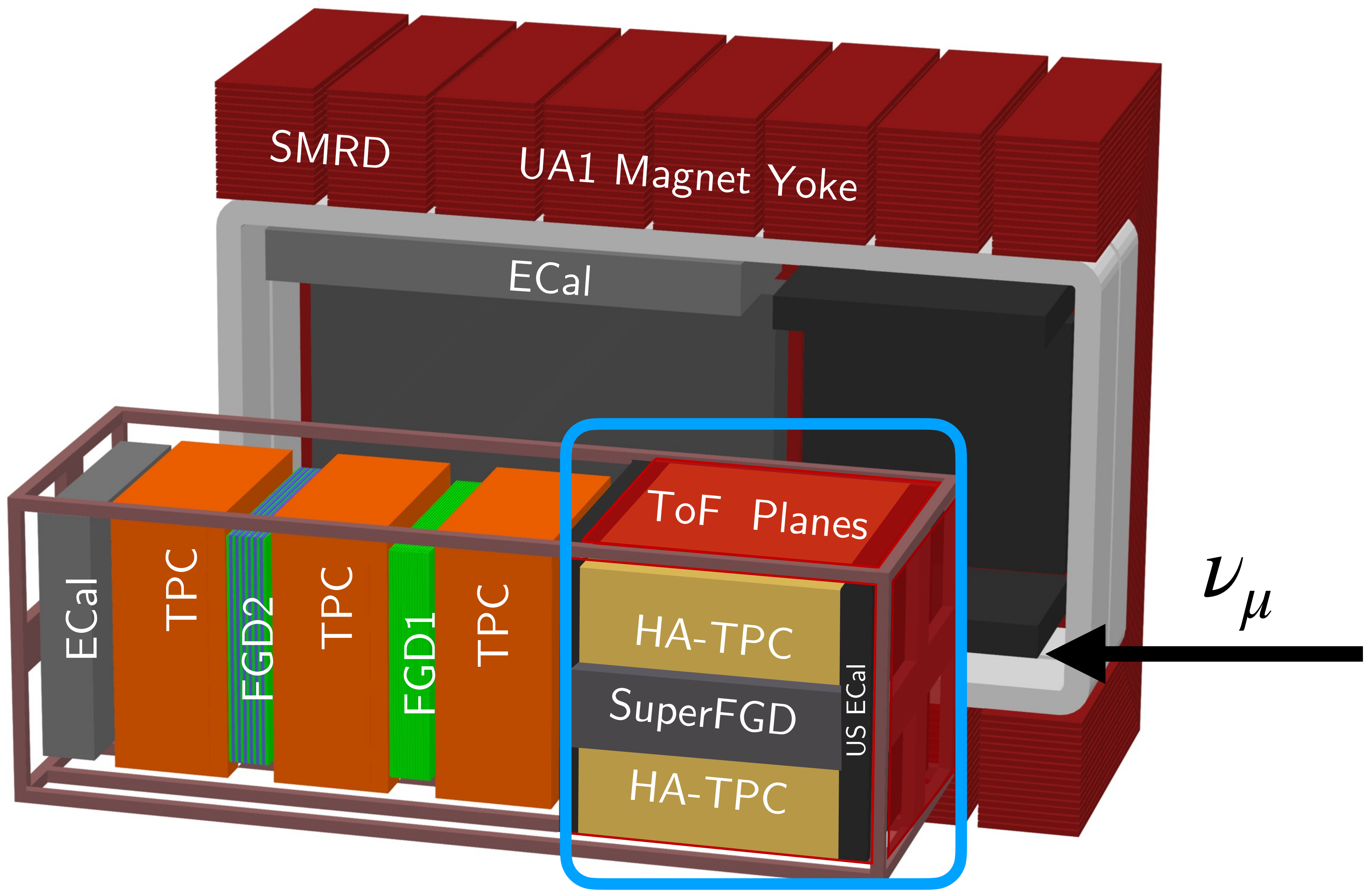
T2K's novel detector concept :

- **2 million plastic scintillating cubes** read out with WLS fibers
- sub ns time resolution per cube
- 1 cm 3D **granularity** ⇒ reconstruct **short tracks**
- 3 projections ⇒ isotropic tracking

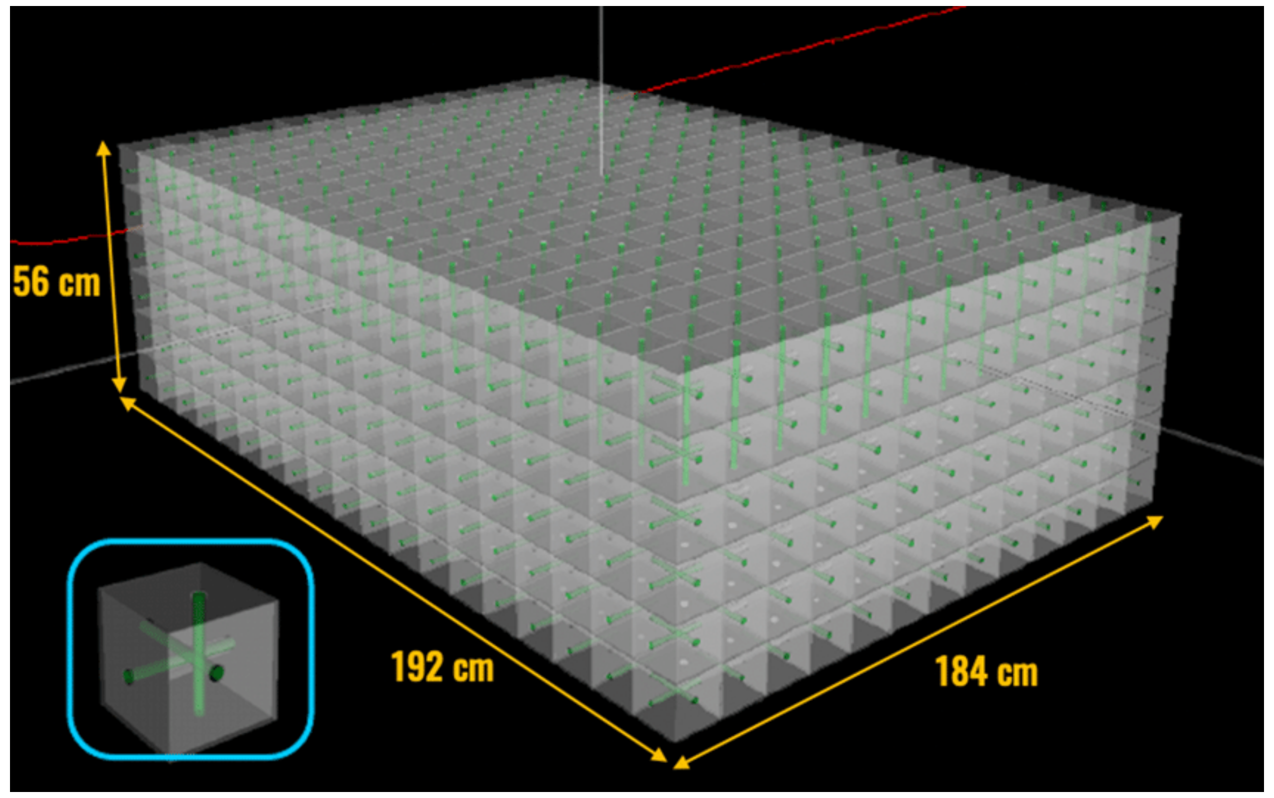
The ND280 upgrade

the motivations

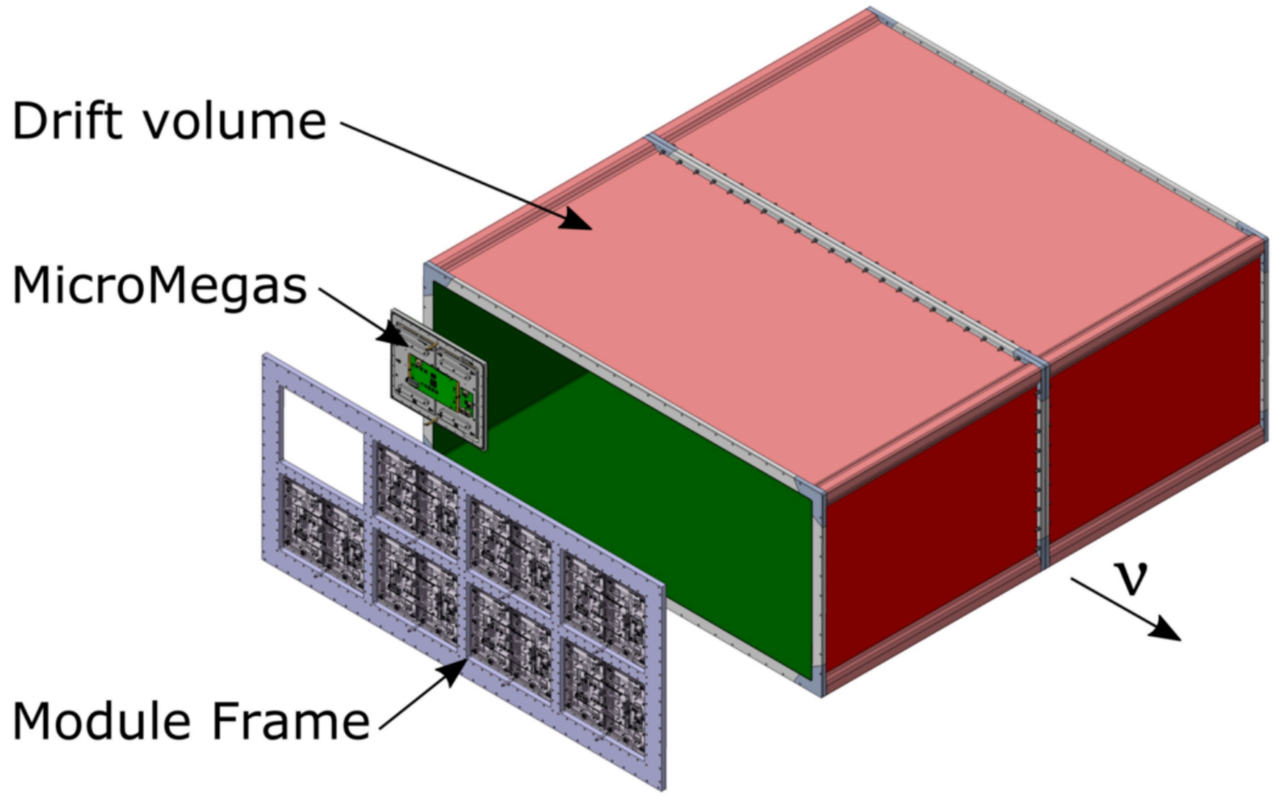
- **reduce** the ~400 MeV/c **reconstruction momentum threshold** and **increase** the interaction **probability**
- **reproduce** the 4π **angular acceptance** of the far detector



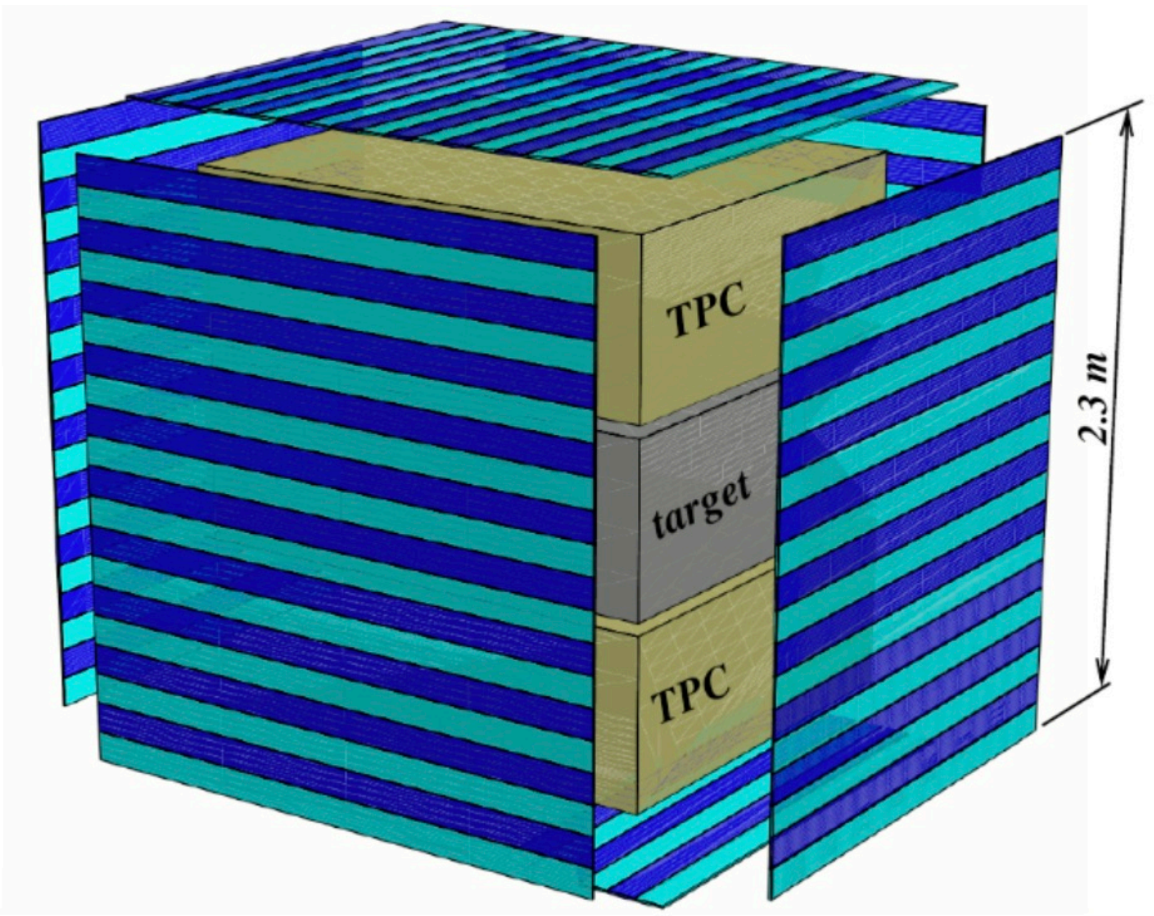
SuperFGD



2 HA-TPCs



6 TOF panles

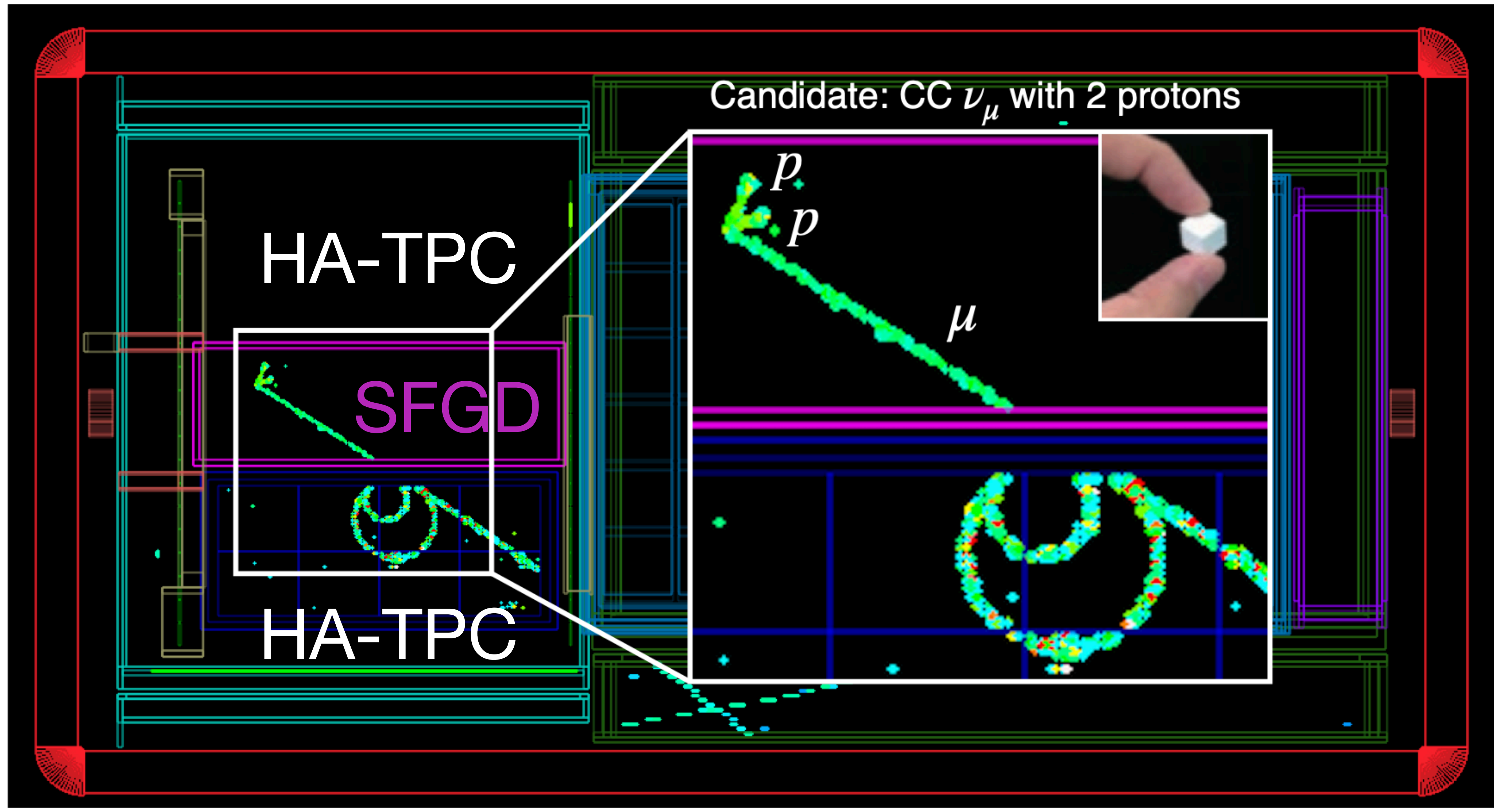


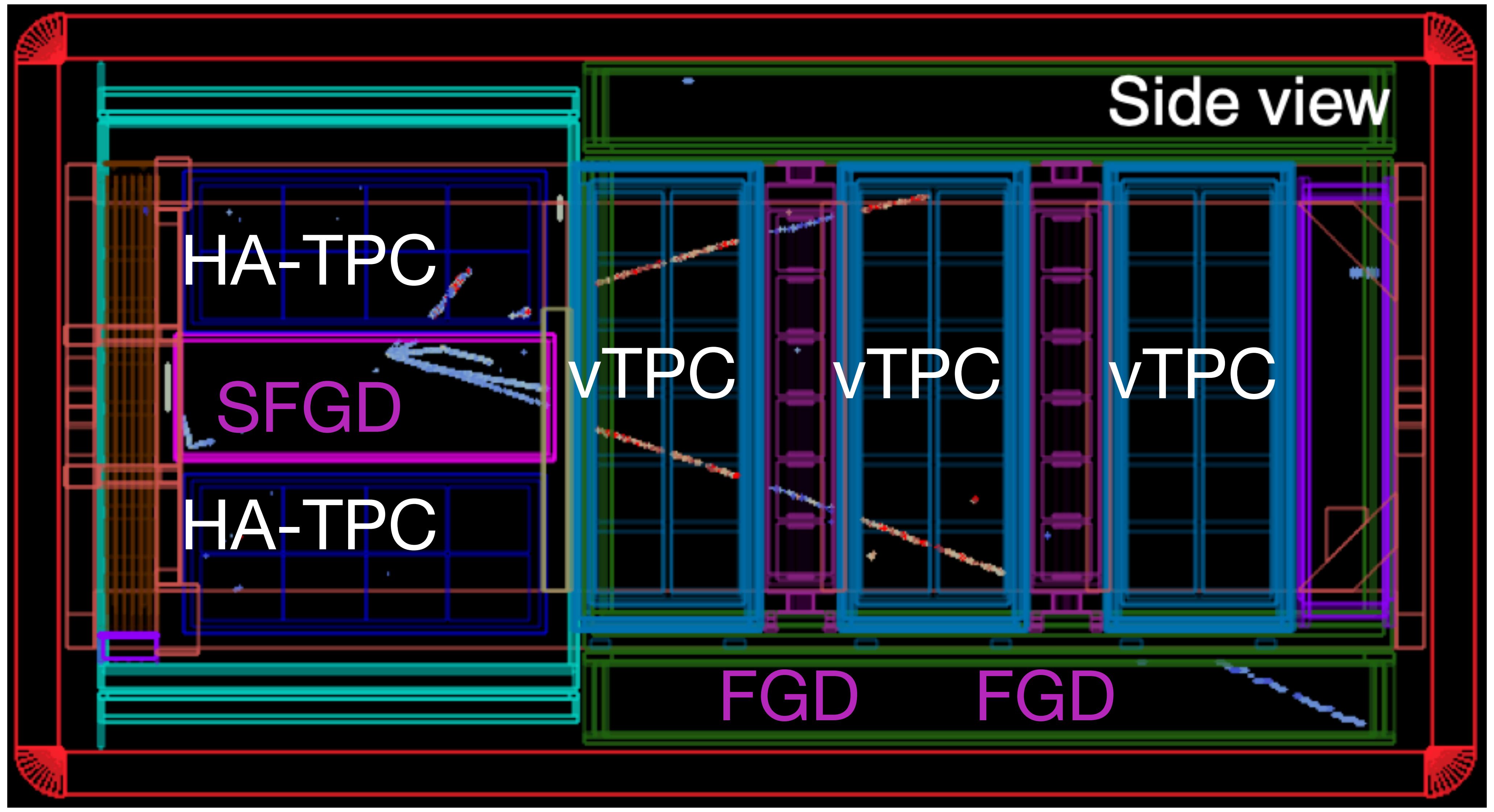
The ND280 upgrade

2 nice event displays

ND280 upgrade is **installed** and **fully operational** since **November 2024**

- ν interactions in the **new target** SFGD
- SFGD high granularity allows to see **proton** (short) **tracks**
- in $\bar{\nu}$ mode it is possible to **measure neutrons kinematics** by time of flight
- **full angle coverage** thanks to top and bottom HA-TPC
- forward going tracks are **matched** with the **downstream tracker**





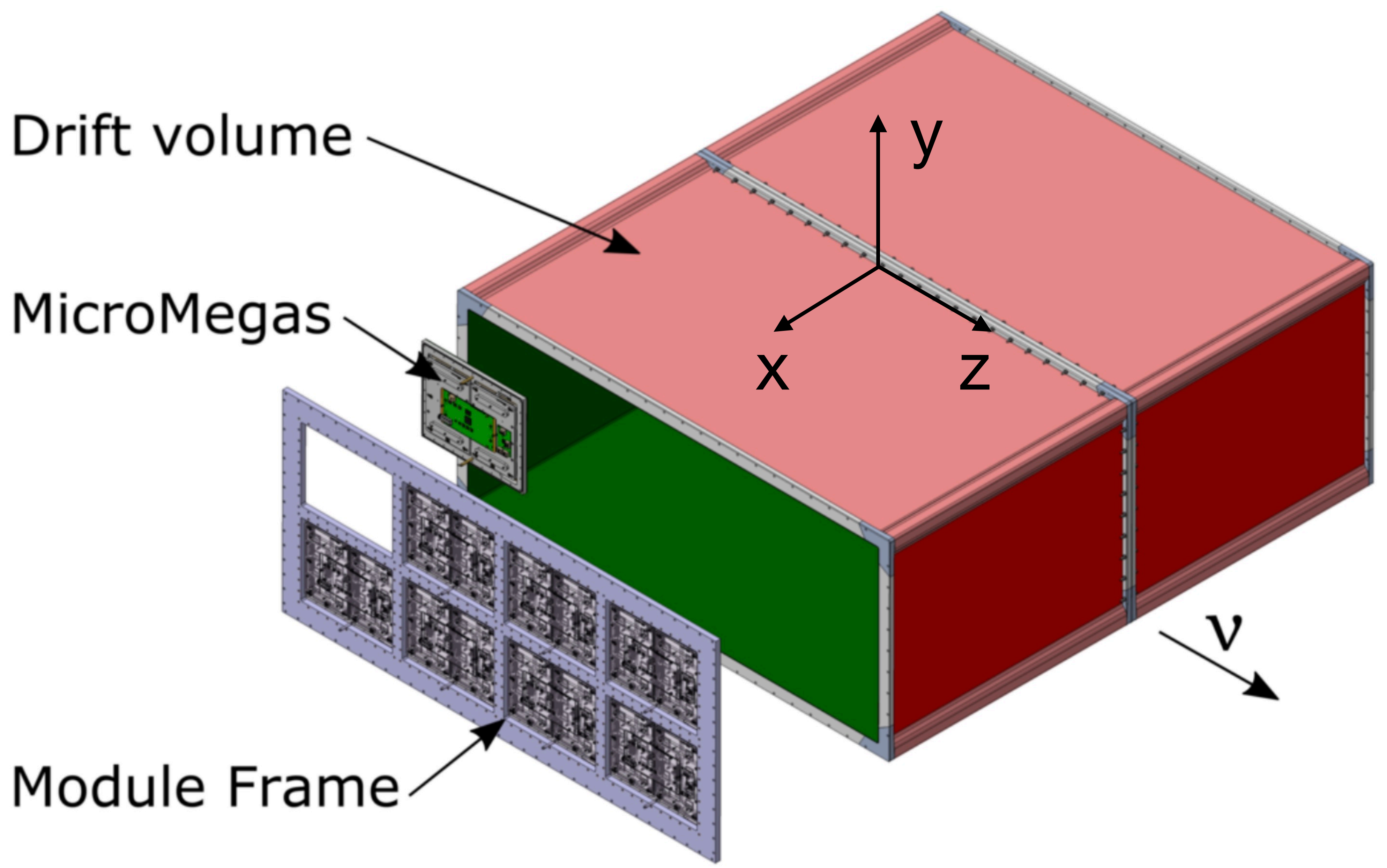
The High-Angle TPCs of upgraded near detector of T2K

Introduction

The High-Angle TPC

*EP = End Plate

*ERAM = Encapsulated Resistive Anode Micromegas



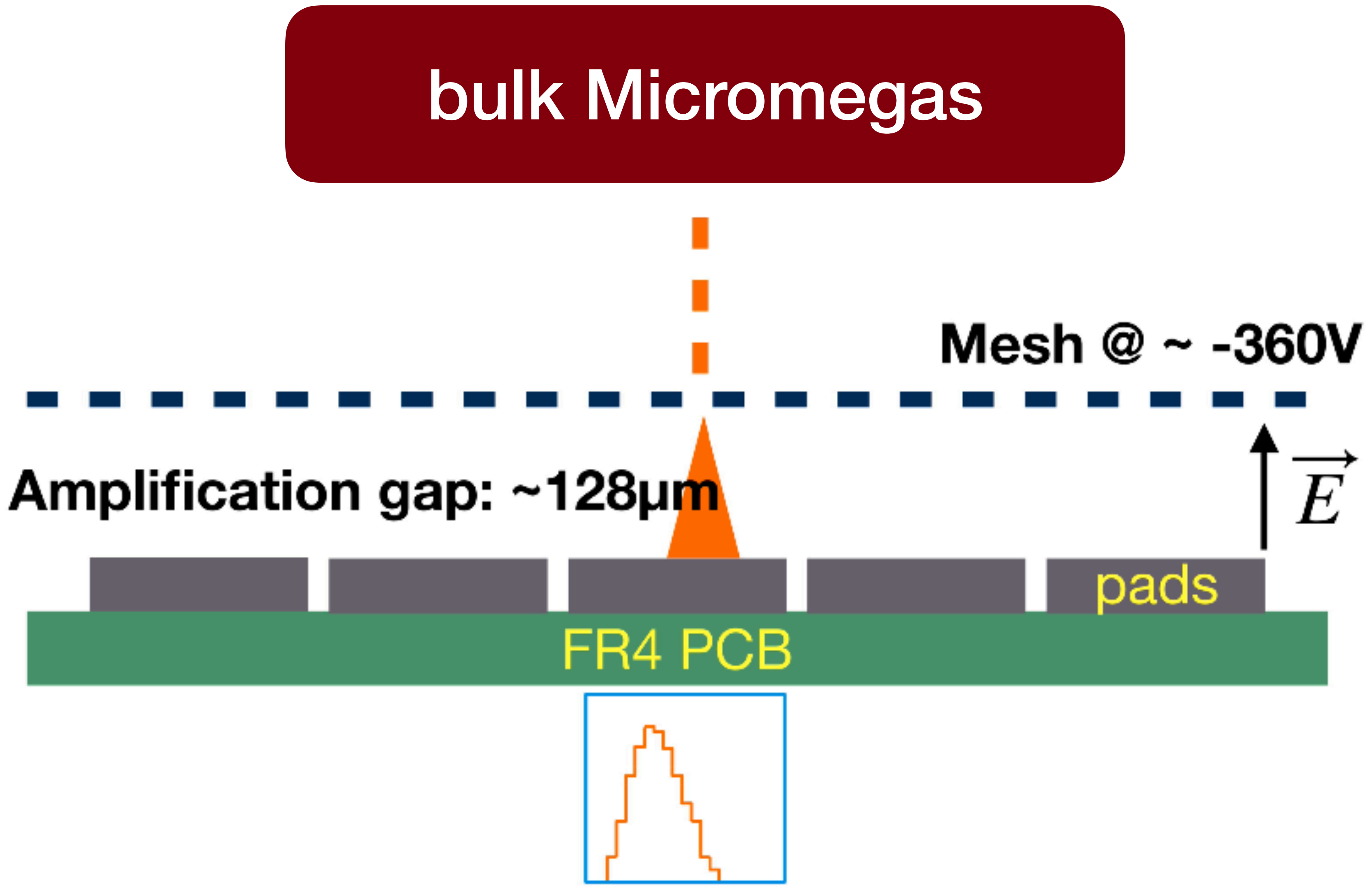
- box-like shape **gaseous detector** ($Ar:CF_4:iC_4H_{10}$ = 95:3:2)
- (uniform) $\vec{E}$ in **X-direction**, (uniform) $\vec{B}$ in **X-direction**: charged particles curve in the (Z,Y) plane
- **cathode** in the **middle**: **2 EPs*** for each HAT where the drifted electrons arrive
- **8 ERAMs* for each EP:** new read-out system, upgrade of the bulk Micromegas
- **1152 pads** for each ERAM organised in a 32 x 36 matrix

The Resistive Anode Micromegas of the HA-TPCs

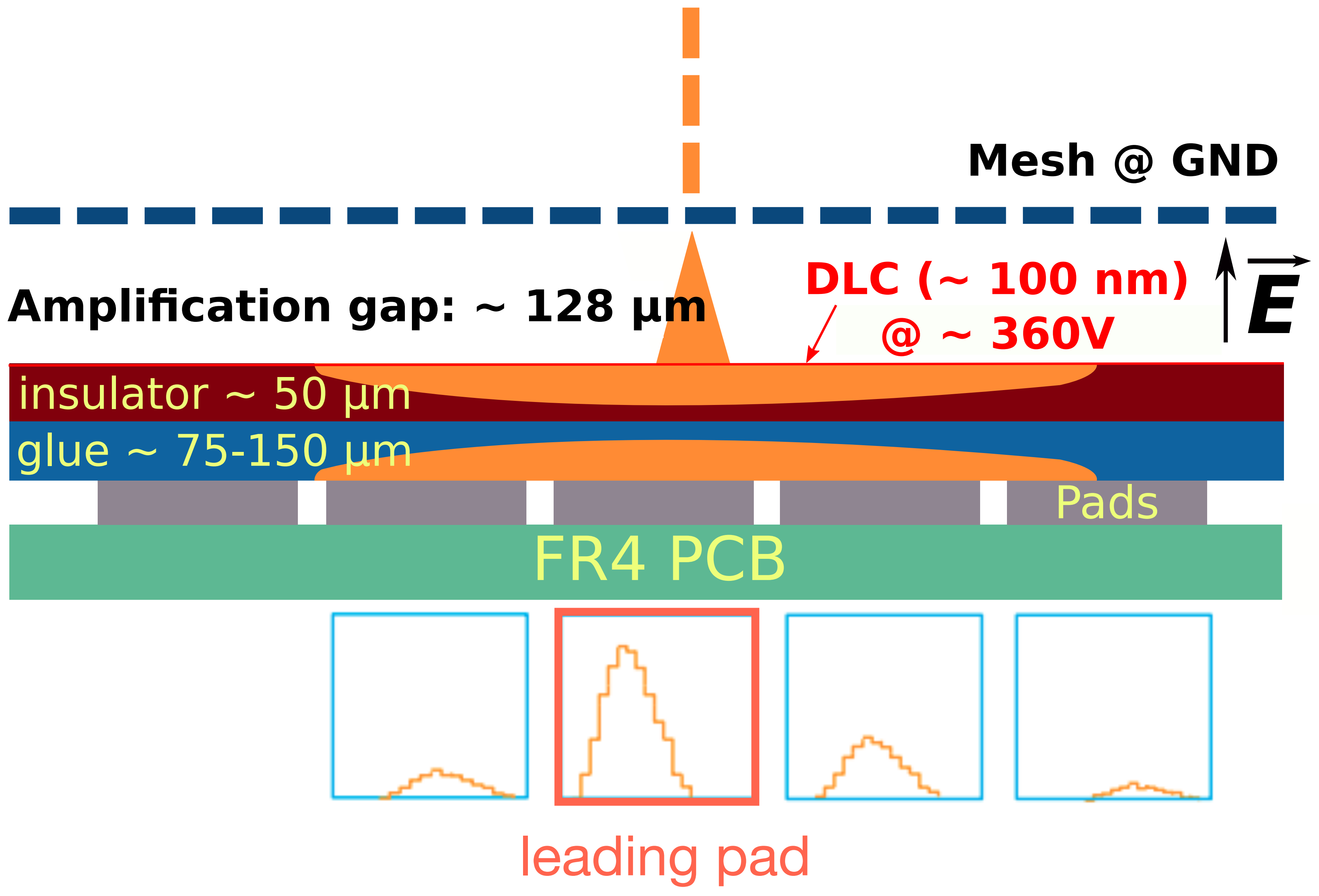
the bulk Micromegas upgrade

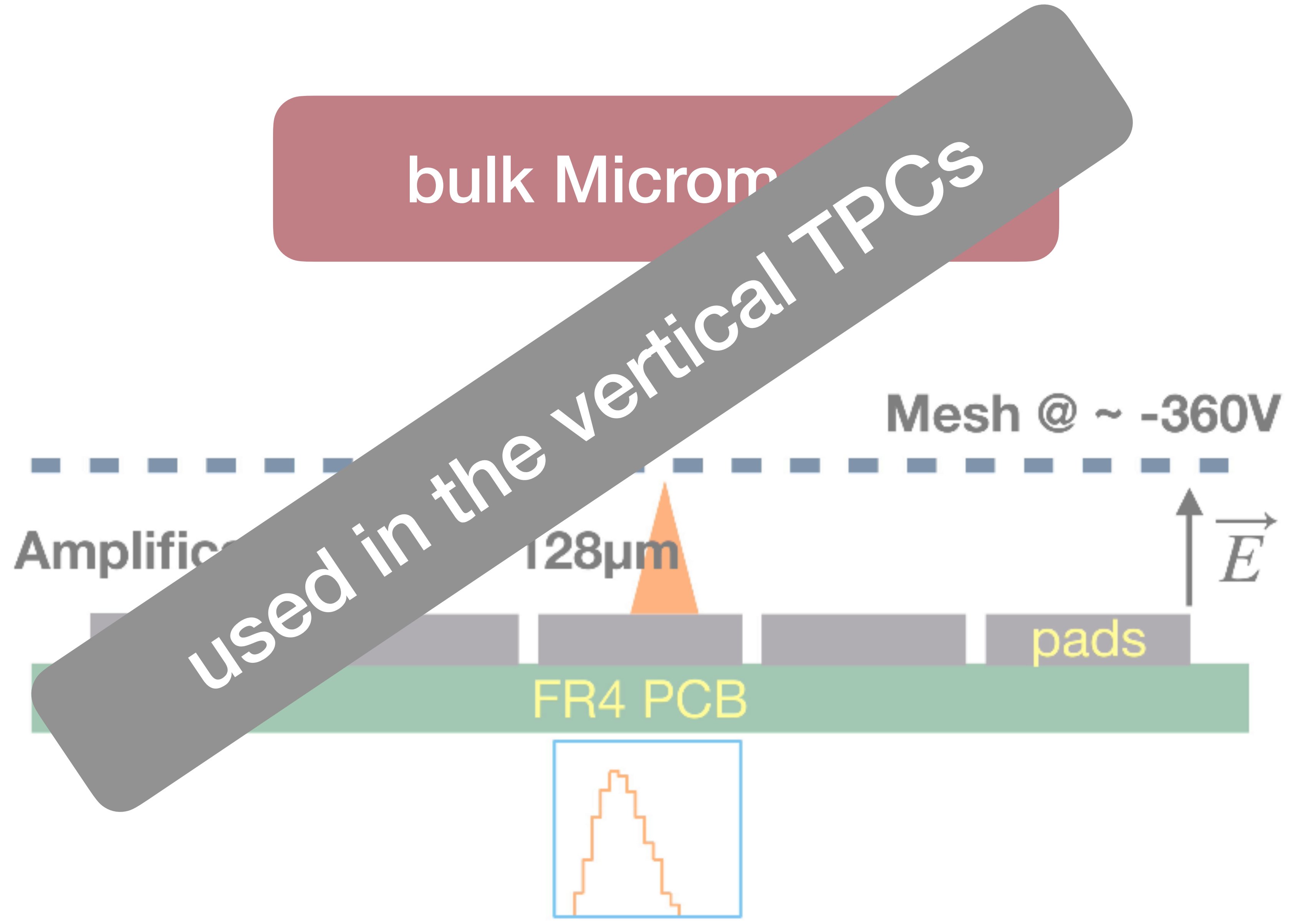
In both **bulk** and **resistive Micromegas**:

- **drifted electrons** arrive to the anode plane
- the signal goes through an **avalanche** process
- the signal arrives to the **pad** where it is read-out



The Resistive Anode Micromegas of the HA-TPCs





- **signal** on the anode plane is **spread over multiple pads**
- the combination of information form the **leading pad** and its **neighbours** allows for a **more precise reconstruction** of the **initial particle**
- **spatial resolution** is **improved** compared to bulk Micromegas

The performance of the HA-TPCs

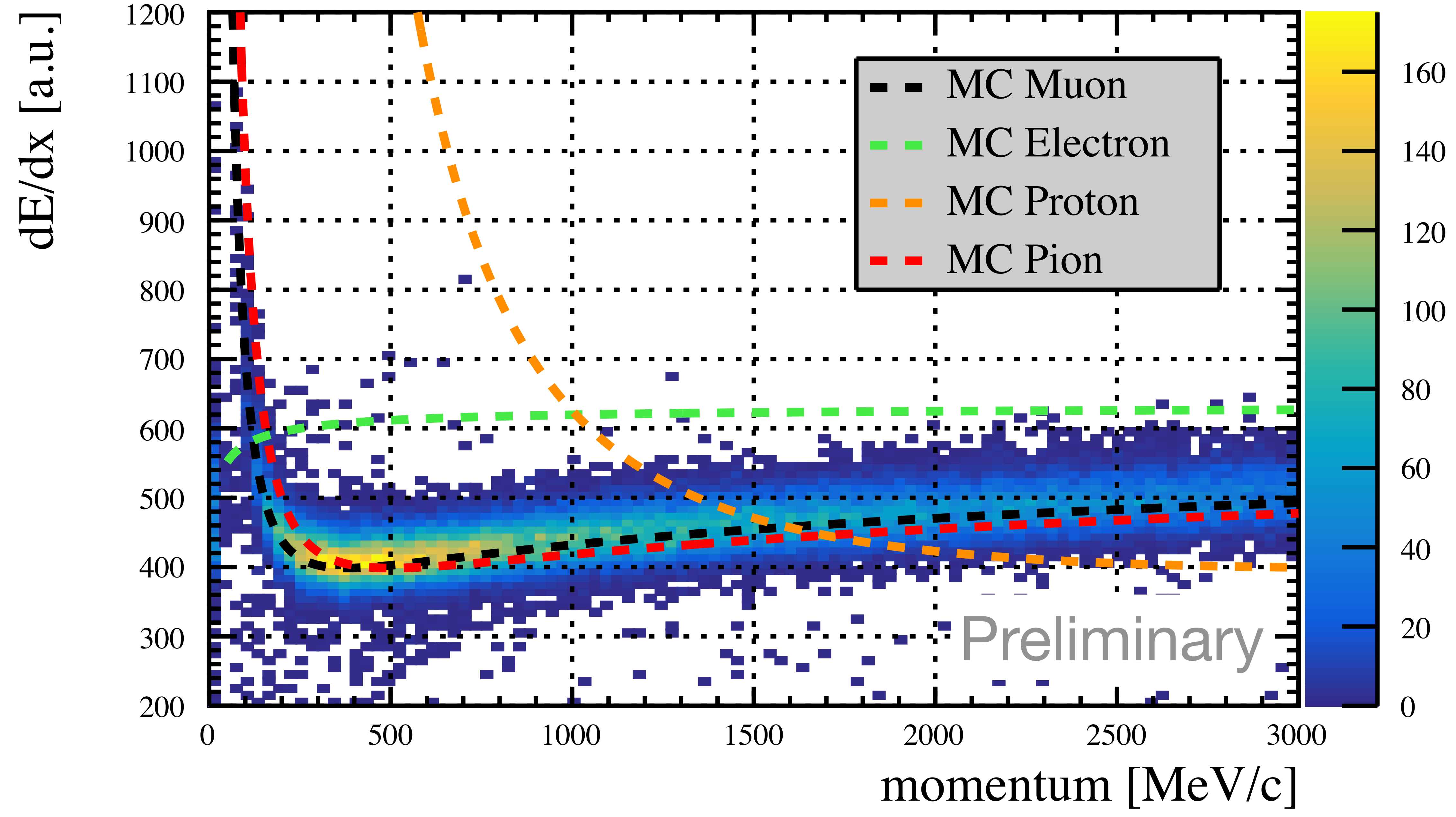
HA-TPCs perfomance

- **spatial resolution (SR)**
  - **related** to the **momentum** resolution
  - better SR ⇒ more precise momentum estimation
  - requirement: momentum resolution < 10% ⇒ SR **< 0.6 mm**
- **dE/dx resolution**
  - is used in combination to the momentum to evaluate the likelihood of the particle being an e^-, μ^- or a p
  - better dE/dx res ⇒ more **reliable PID**
  - requirement: dE/dx resolution < **10%**

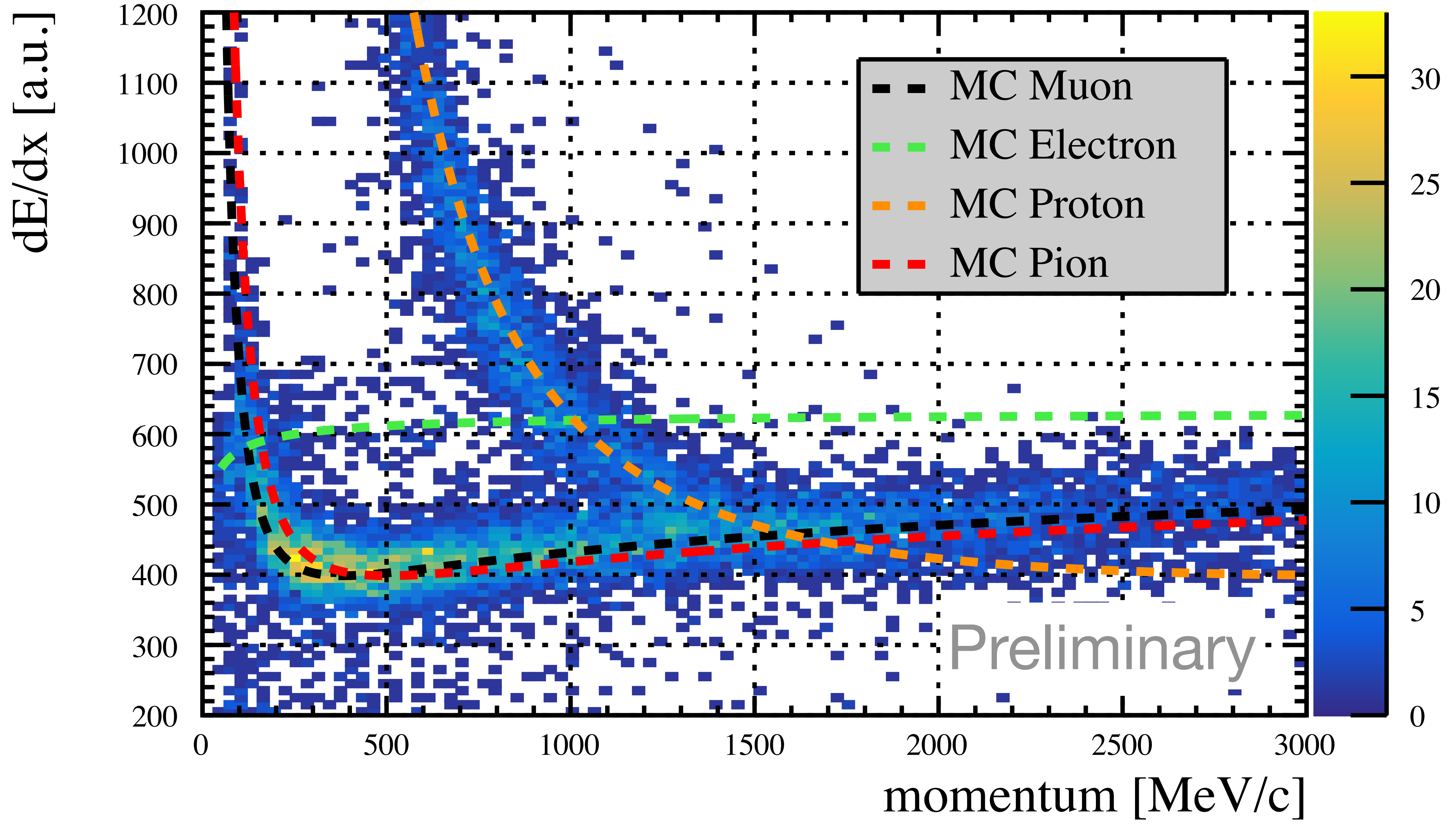
dE/dx vs momentum

beam data + MC predictions

negative tracks



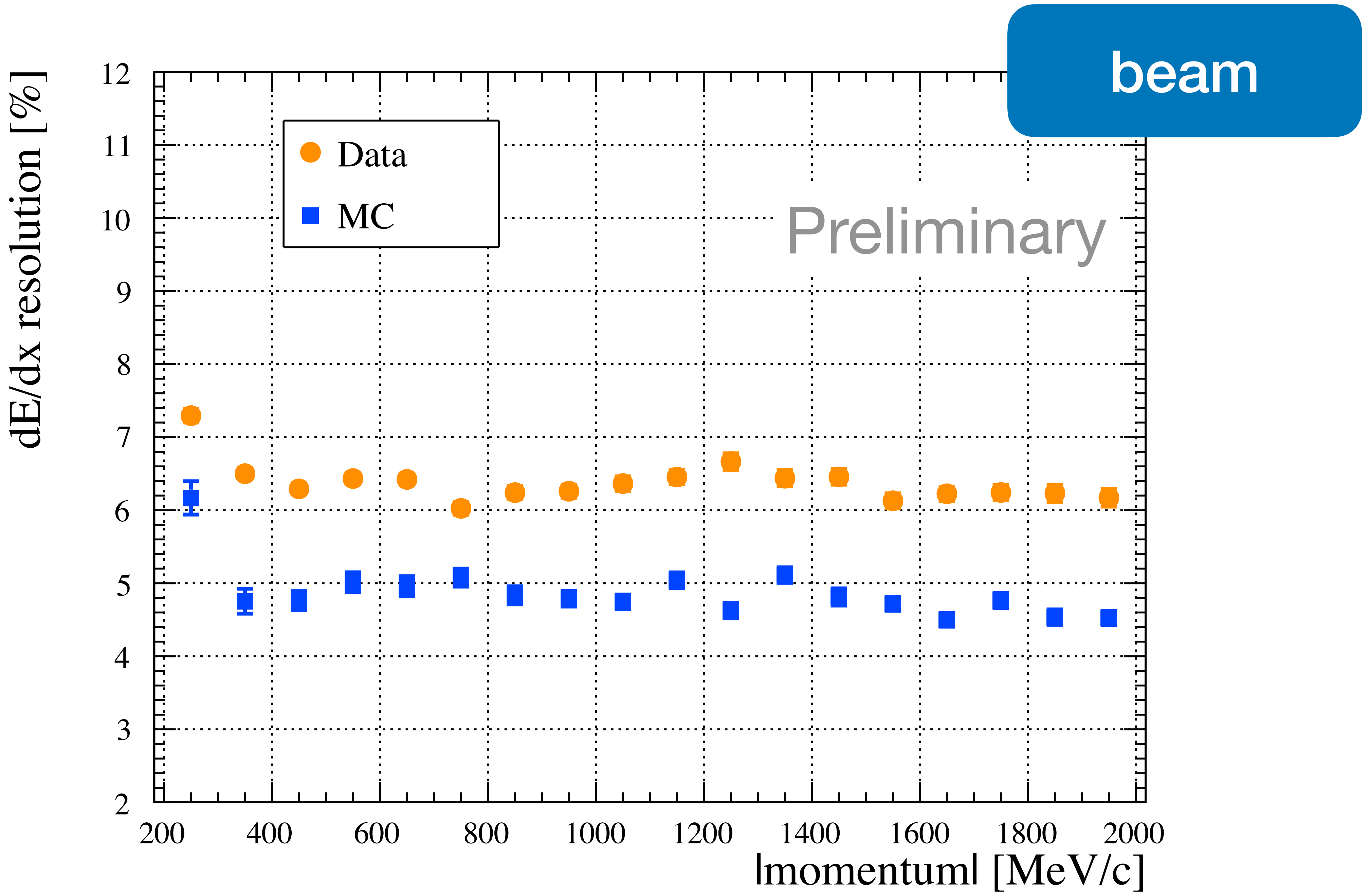
positive tracks

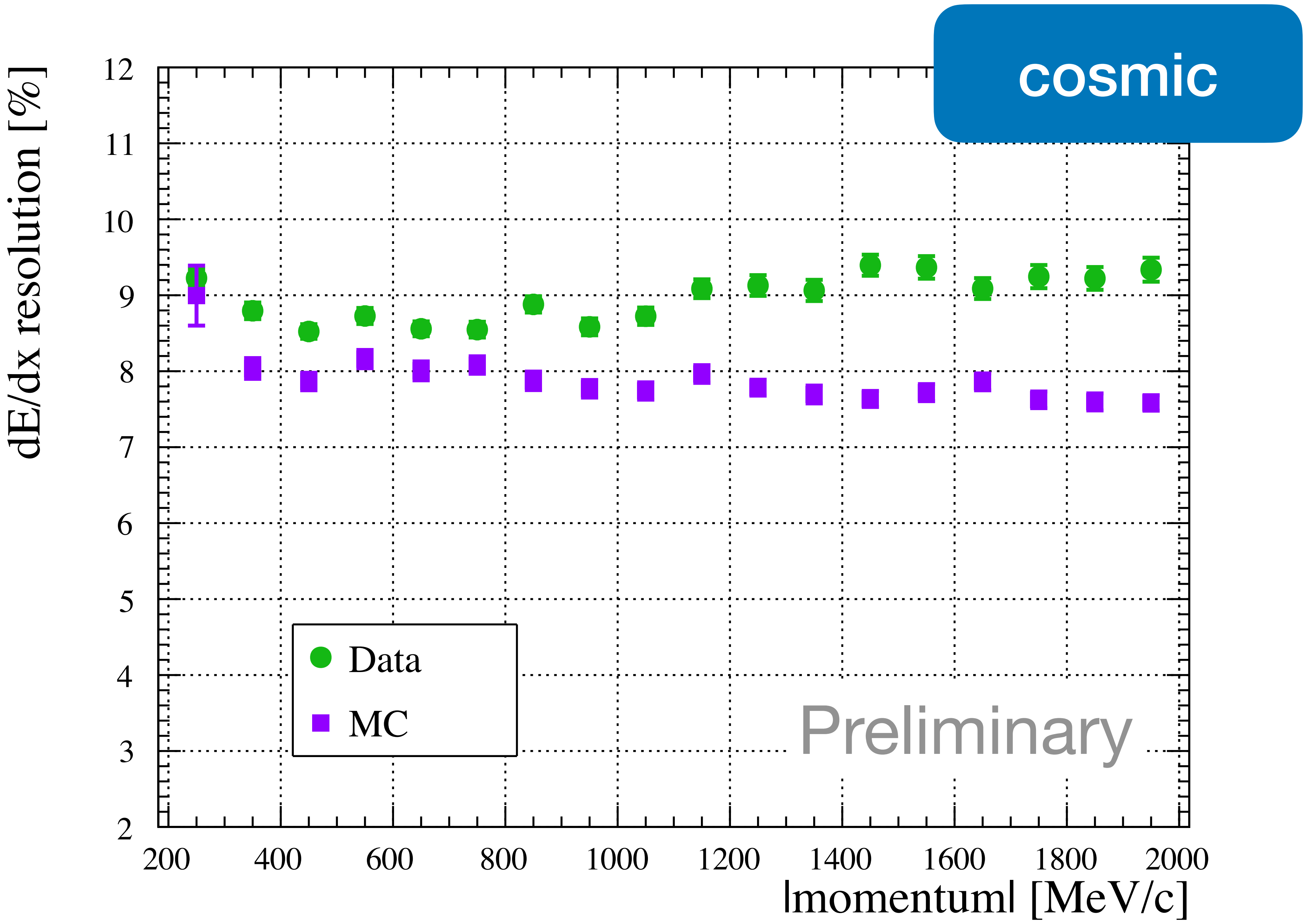


- **compatibility** with what we expect to have in both **negative** and **positive tracks**

dE/dx resolution

beam and cosmic: data and MC comparison

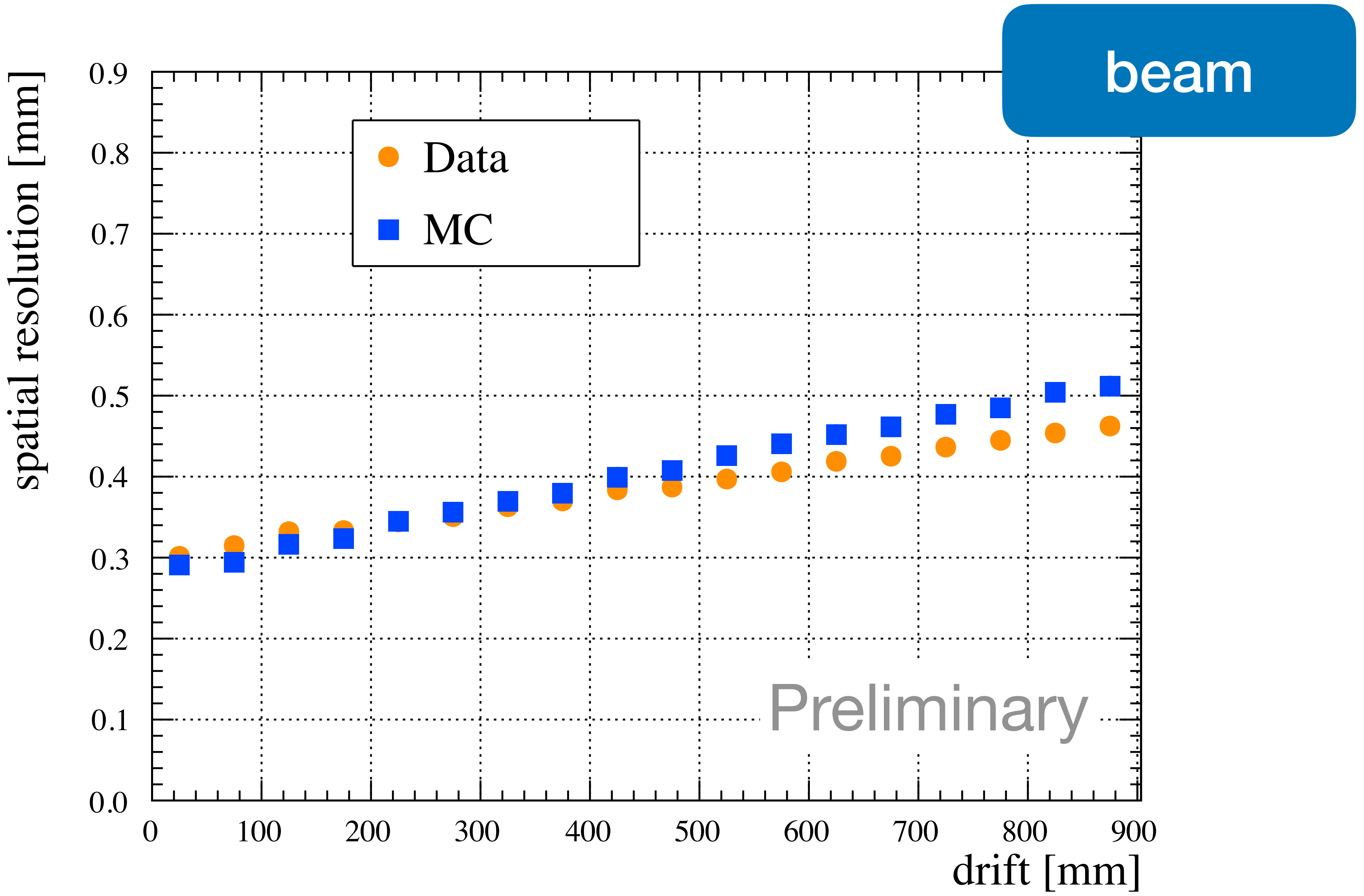


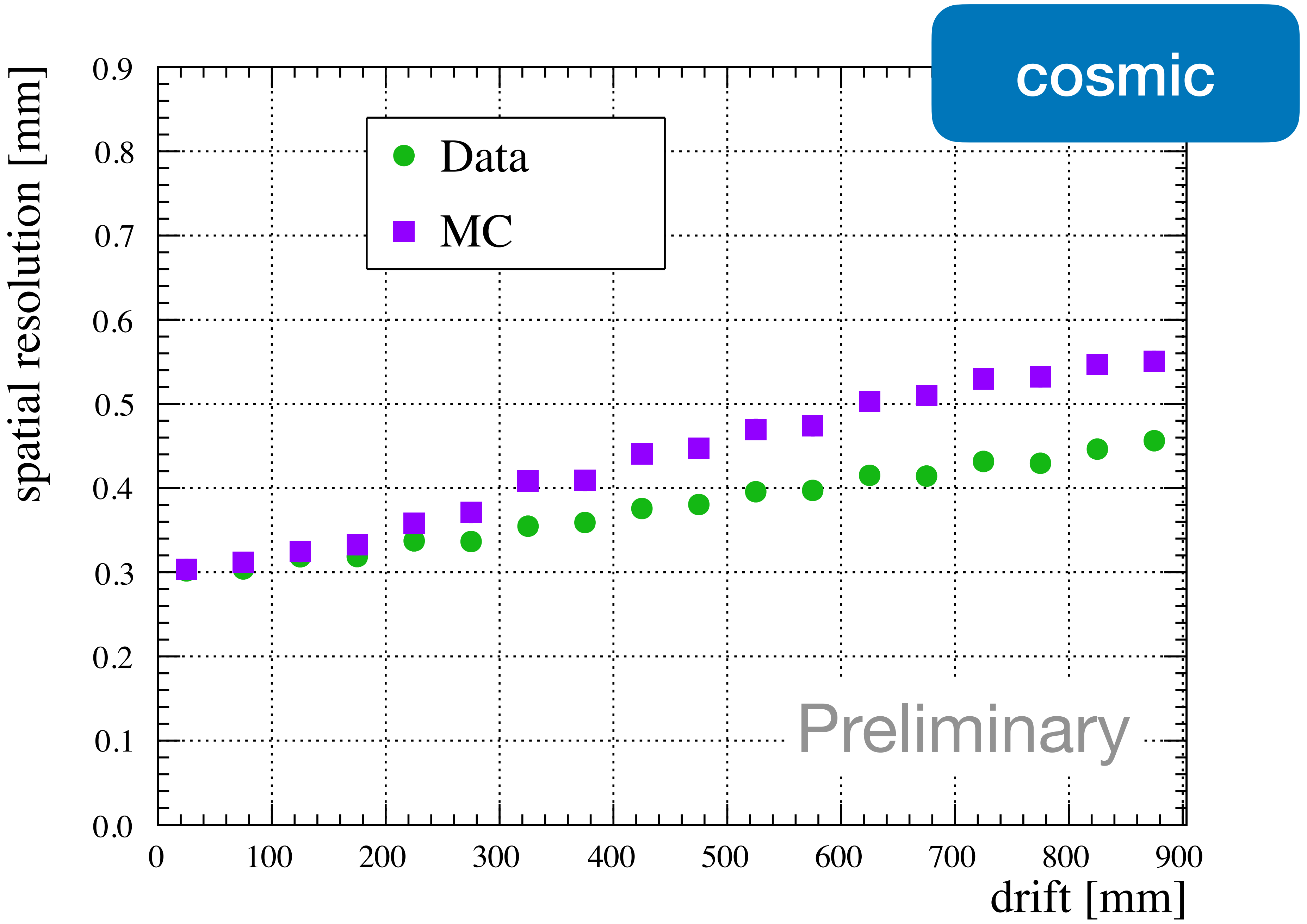


- **beam** (horizontal tracks, longer) have **better** resolution than **cosmic** (vertical, shorter)
- general trend: dE/dx resolution gets better with |momentum|
- **discrepancy** between data and MC (max 17%)
- both cosmic and beam **meet** the **requirements** (10%)

spatial resolution vs drift distance

beam and cosmic: data-MC comparison



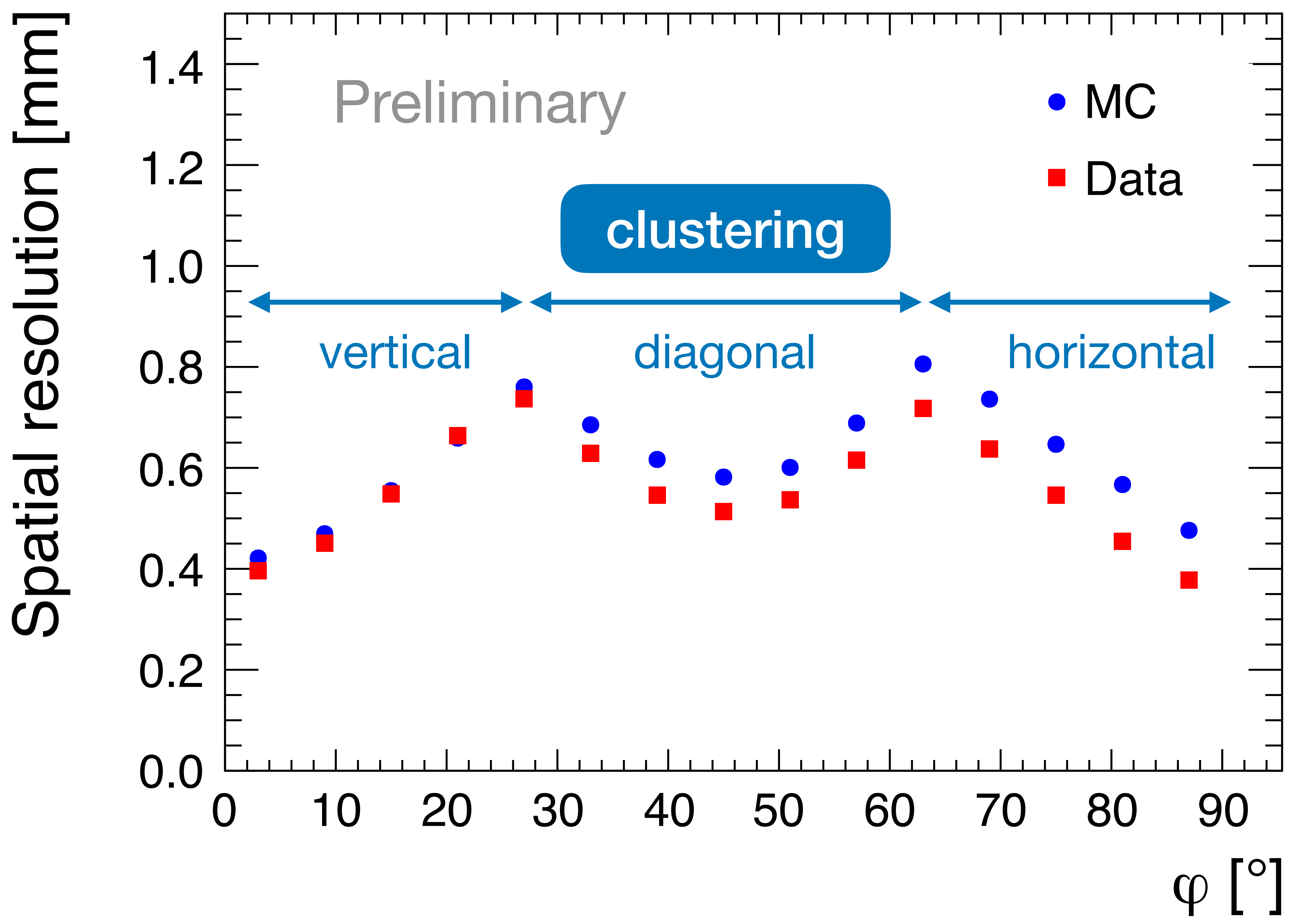


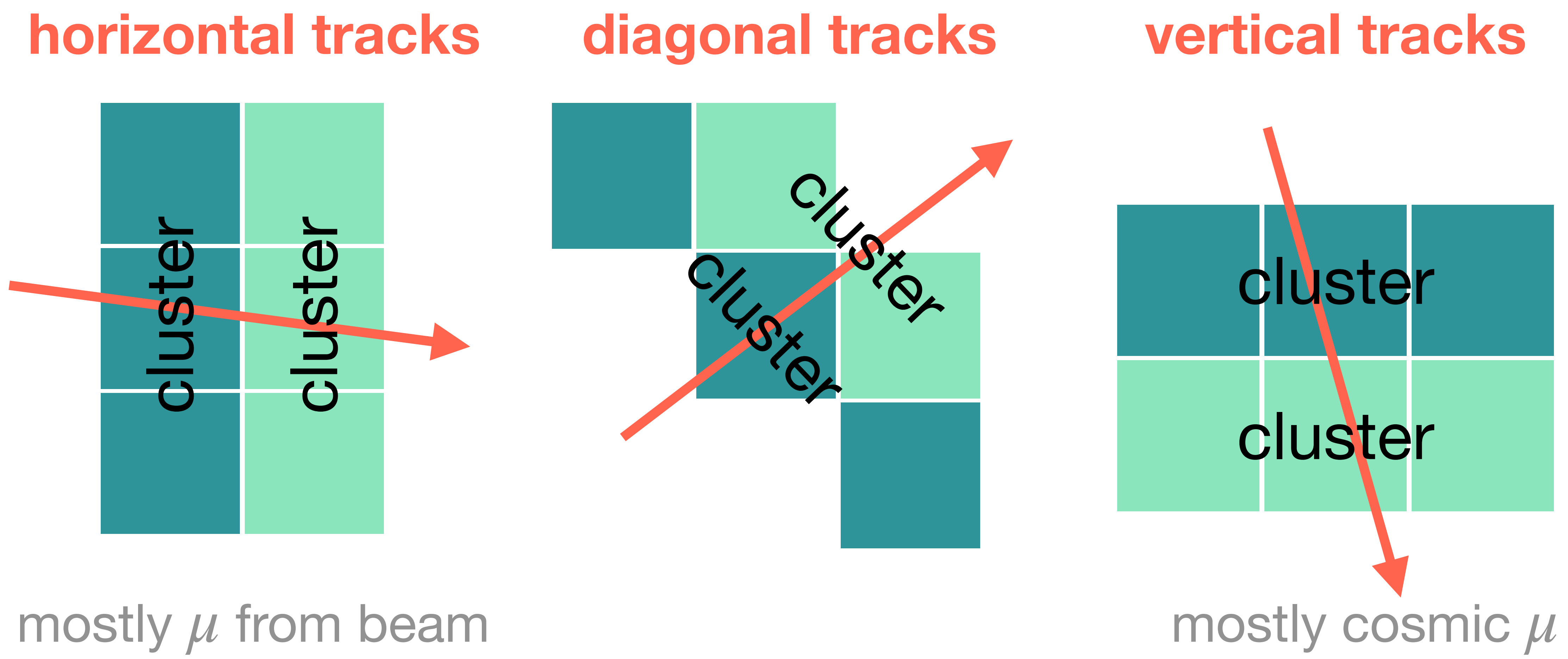
- expected **dependence** on **drift** (diffusion effects)
- **low drift** distance: good agreement between data and MC in both beam and cosmic
- **high drift** distance: **MC overestimates** the spatial resolution (bigger effect in the cosmic case)
- spatial resolution in data better than 0.5 mm → **meet** the **requirements** (0.6 mm)

spatial resolution vs angle

data-MC comparison

- to better determine the initial deposit position we group pads into **clusters** (leading pad + its neighbours)
- different track **orientation** ⇒ different **clustering**
- vertical clustering is optimised for horizontal tracks: the less a track is horizontal, the less the clustering is adapted
- in general the **best clustering** is the one more **perpendicular** to the track





Electric and magnetic field non uniformities in the HA-TPCs

The $\overrightarrow{E} \times \overrightarrow{B}$ effect

- $\overrightarrow{B}$ is **<u>nominally</u>** (0.2T, 0, 0), $\overrightarrow{E}$ is **<u>nominally</u>** (275V/cm, 0, 0): the electrons drift in the X-direction, the charged particles have a **curvature** in the **(Z,Y) plane**

- $\overrightarrow{E}$ and $\overrightarrow{B}$ **non-uniformities** have been observed: E_y, E_z, B_y and B_z are **<u>actually</u>** different from zero

- these non-uniformities **affect the electrons' drift** through the anode plane

$$\overrightarrow{V}_d = \frac{\mu}{1+(\omega\tau)^2}\left(\overrightarrow{E} + (\omega\tau)\frac{\overrightarrow{E}\times\overrightarrow{B}}{|\overrightarrow{B}|} + (\omega\tau)^2\frac{(\overrightarrow{E}\cdot\overrightarrow{B})\overrightarrow{B}}{|\overrightarrow{B}|^2}\right)$$

The $\overrightarrow{E} \times \overrightarrow{B}$ effect
the $\overrightarrow{B}$ non-uniformities

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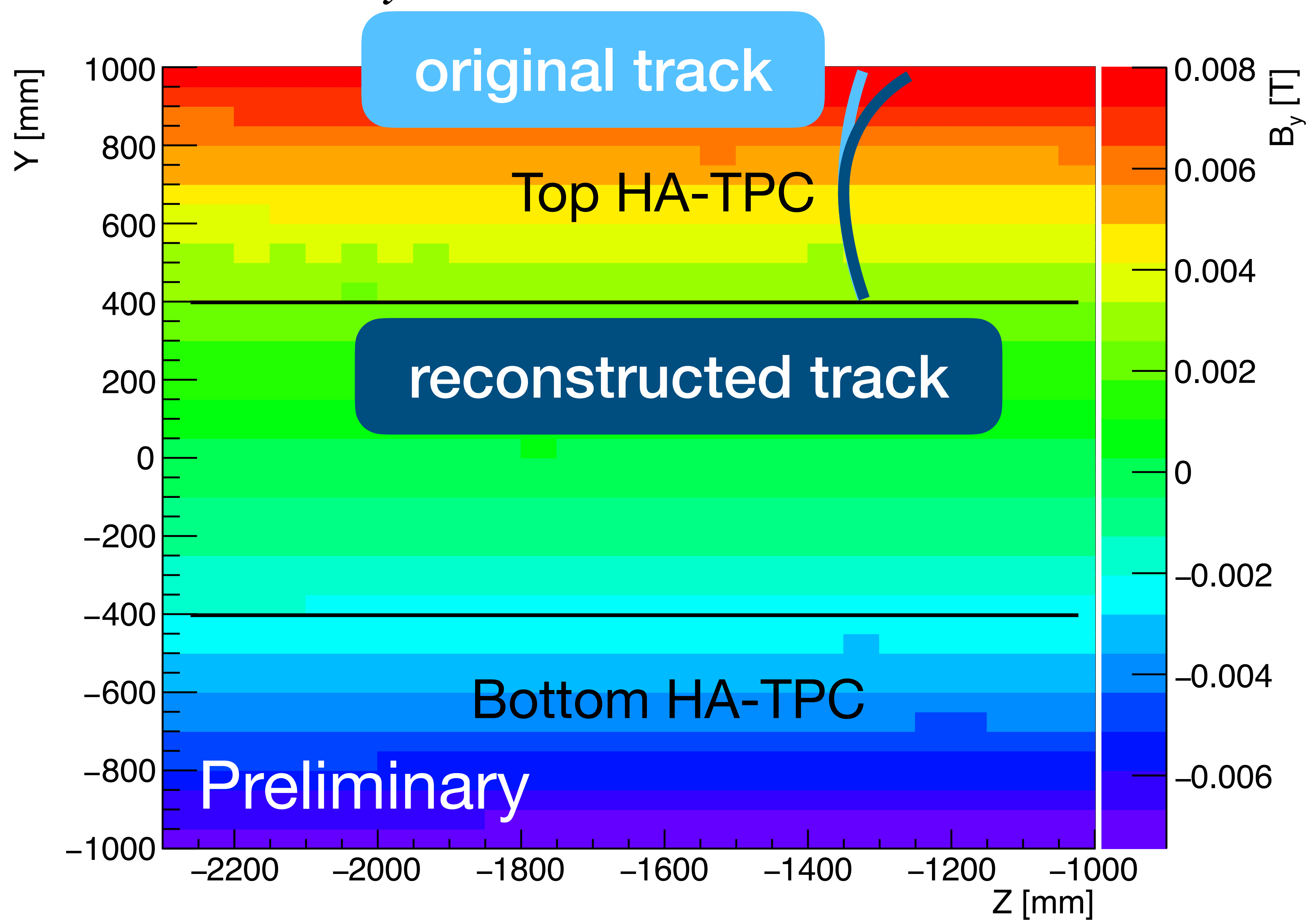
B_y **on the (Z,Y) plane**



- in this case the **reconstructed track** image on the anode plane is **more curved** than the **original track** in the interaction plane

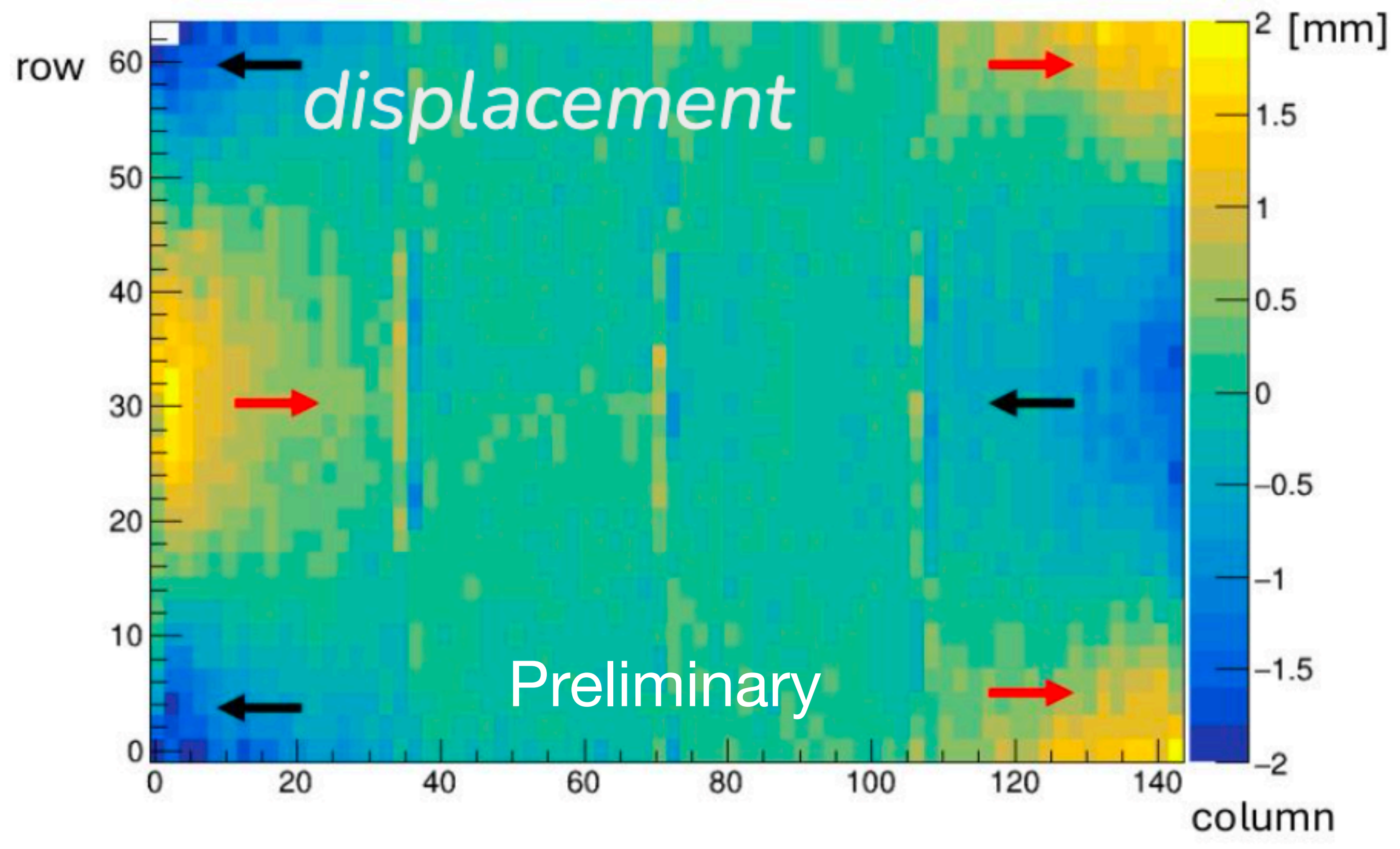
- in order to **correct** for the $\overrightarrow{E} \times \overrightarrow{B}$ effect, the collected electrons on the anode plane are *drifted back in the past* in the interaction plane using already existing $\overrightarrow{B}$ maps

The $\overrightarrow{E} \times \overrightarrow{B}$ effect

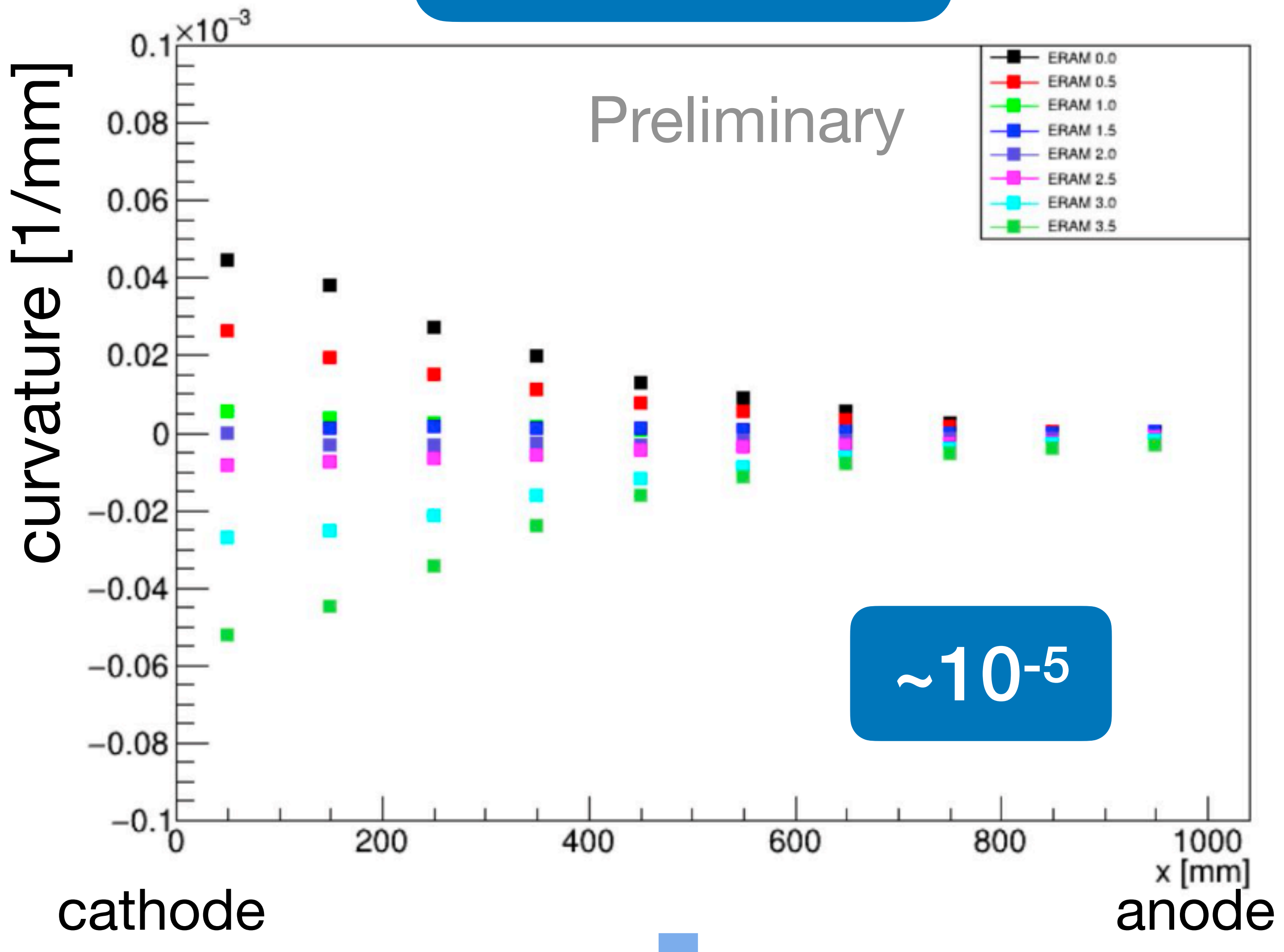
the $\overrightarrow{E}$ non-uniformities

- even **without** $\overrightarrow{B}$ field the tracks were **still curved**
- assumptions: homogeneous $\overrightarrow{E}$ field, cage gaps not modelled
- the actual geometry has been implemented in COMSOL and $\overrightarrow{E}$ maps have been produced
- **corrections** were performed using $\overrightarrow{E}$ **maps**

displacement

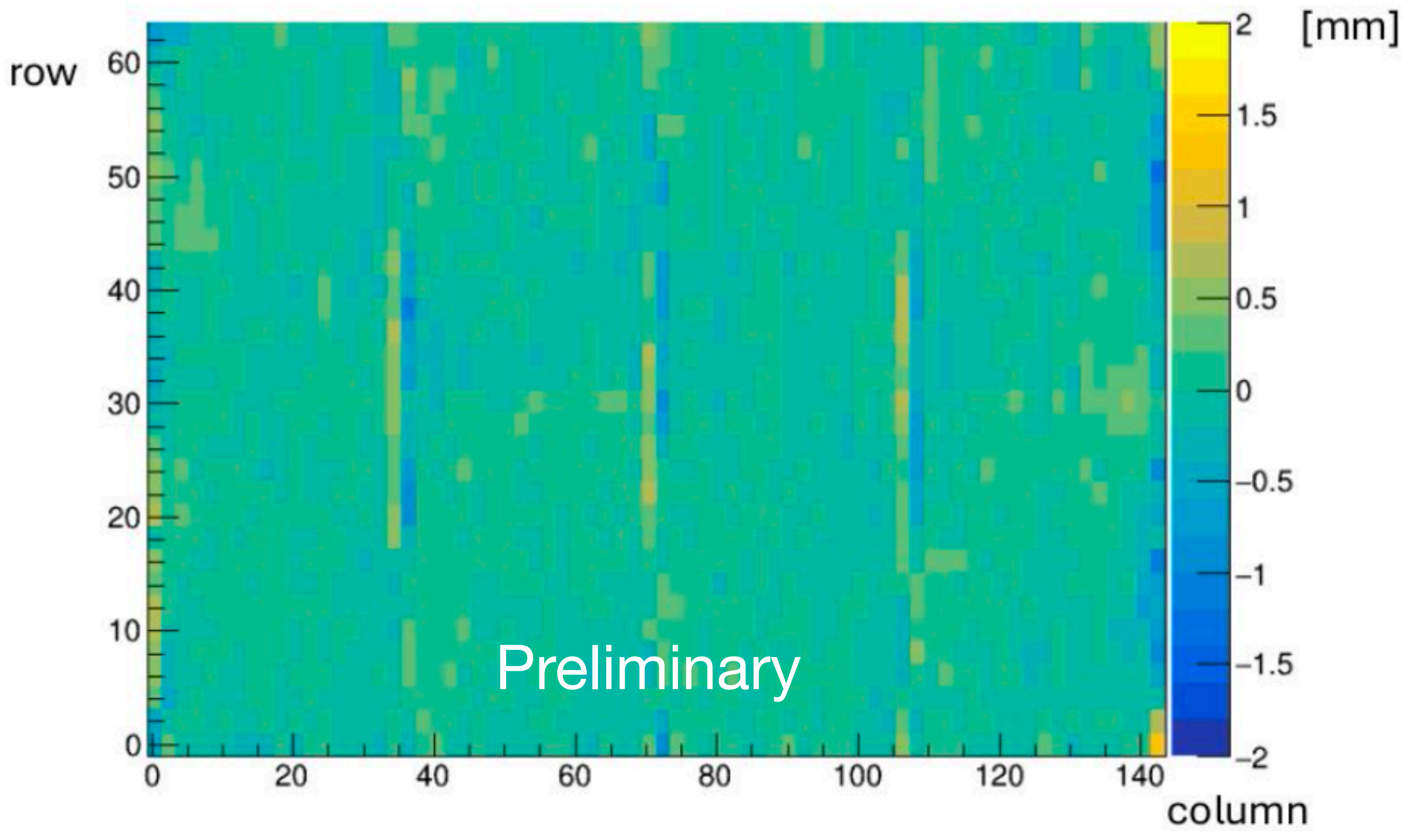


curvature

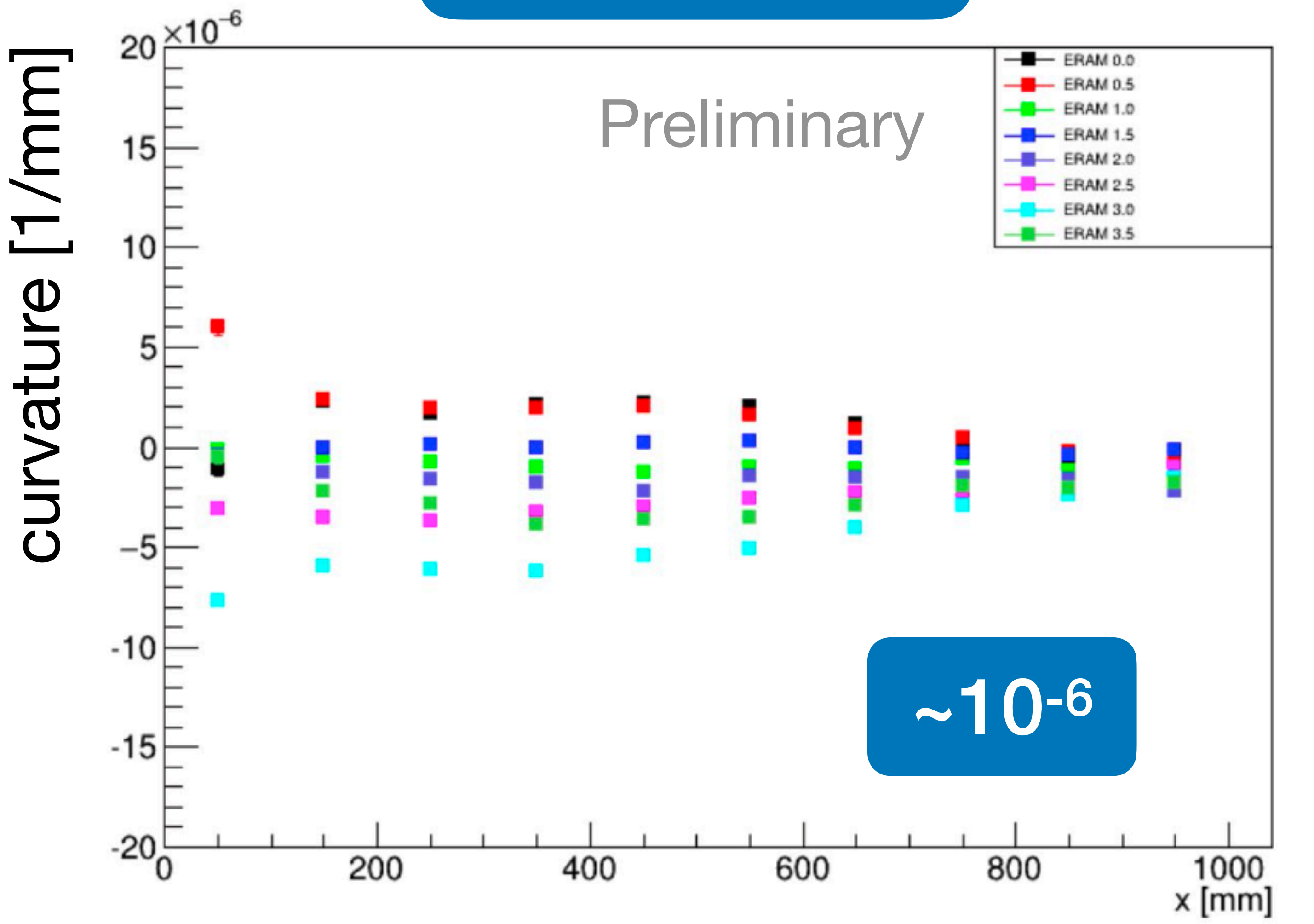


$\overrightarrow{E}$ corrections

displacement



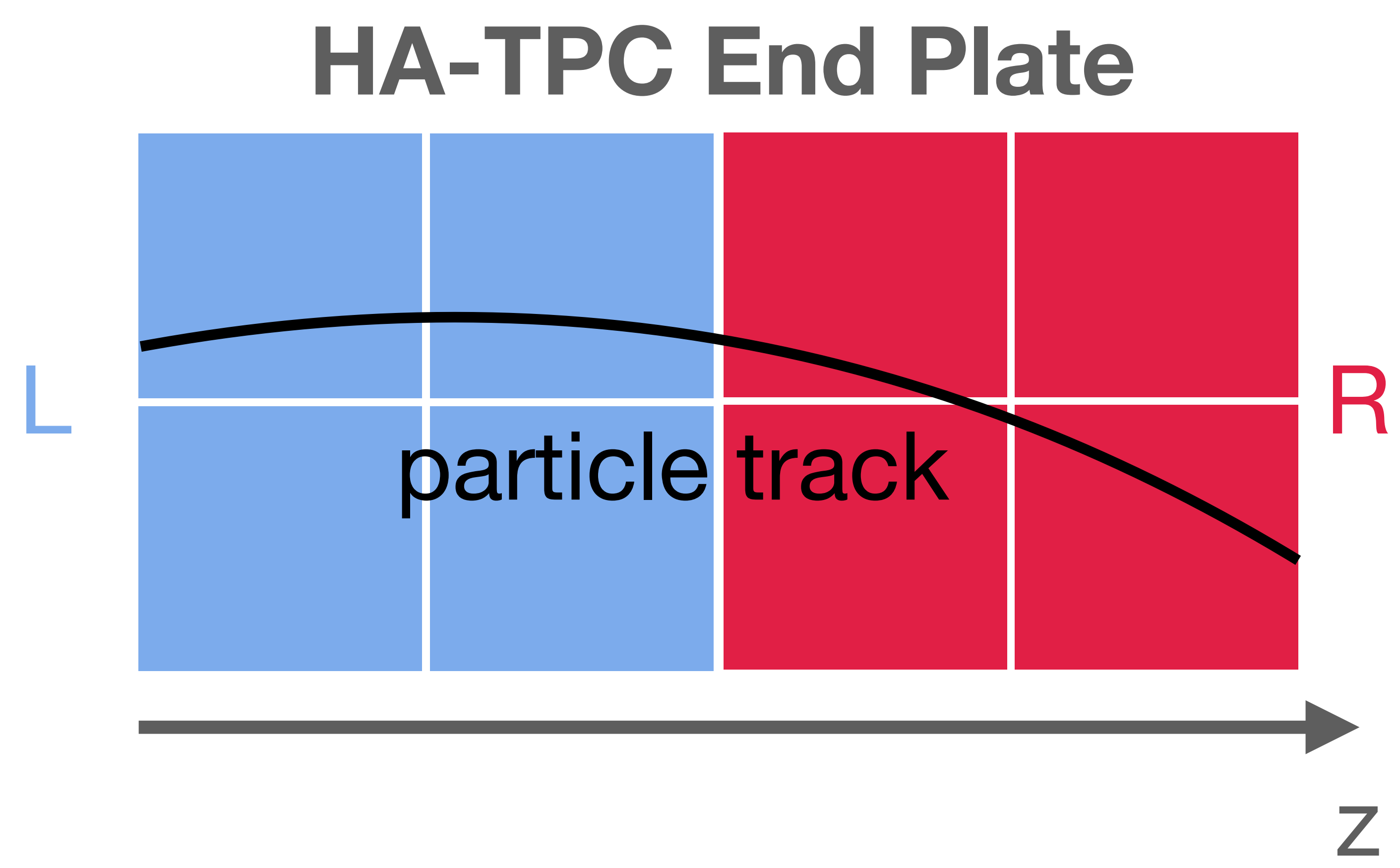
curvature



Systematics on p reconstruction due to distortions in the HA-TPCs

the strategy

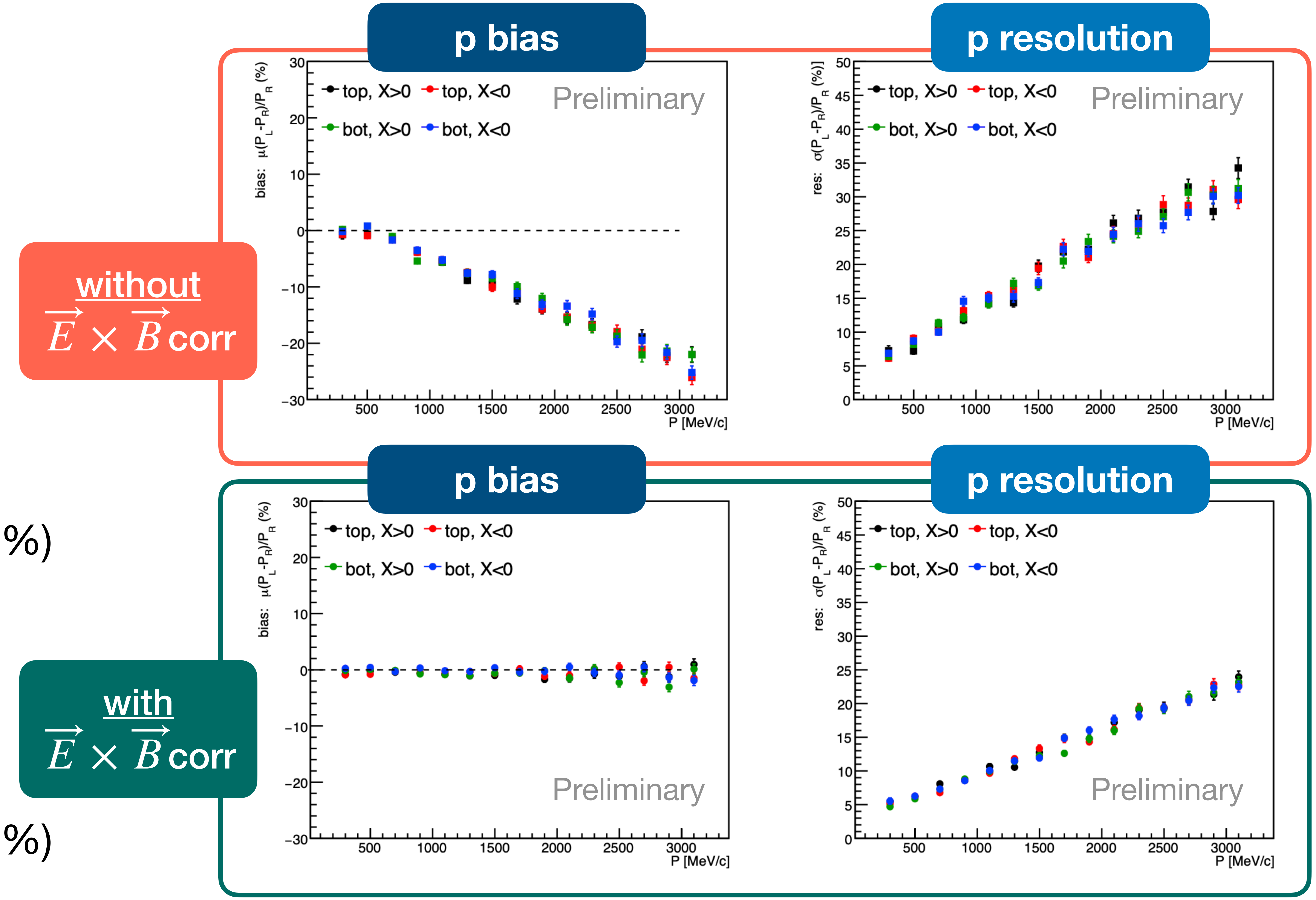
- in order to investigate the effect of $\overrightarrow{E} \times \overrightarrow{B}$ correction a **separate track fit** was implemented for the **first half** and the **second half** of the track $\longrightarrow$ p_L and p_R
- we reconstructed **beam data** and **simulations** selecting long tracks crossing the whole EndPlate and **comparing** p_L and p_R **with** and **without** $\overrightarrow{E} \times \overrightarrow{B}$ **correction**



Systematics on p reconstruction due to distortions in the HA-TPCs

$(p_L - p_R)/p_R$ vs p in MC

- **bias** and **resolution** on $(p_L - p_R)/p_R$ are evaluated in function of p for the **4 EP** (different colours)
- **without** $\vec{E} \times \vec{B}$ corrections:
  - bias has a negative trend
  - p resolution increases with p (up to 35%)
- **with** $\vec{E} \times \vec{B}$ corrections:
  - bias is constantly ~ 0
  - p resolution increases with p (up to 23%)



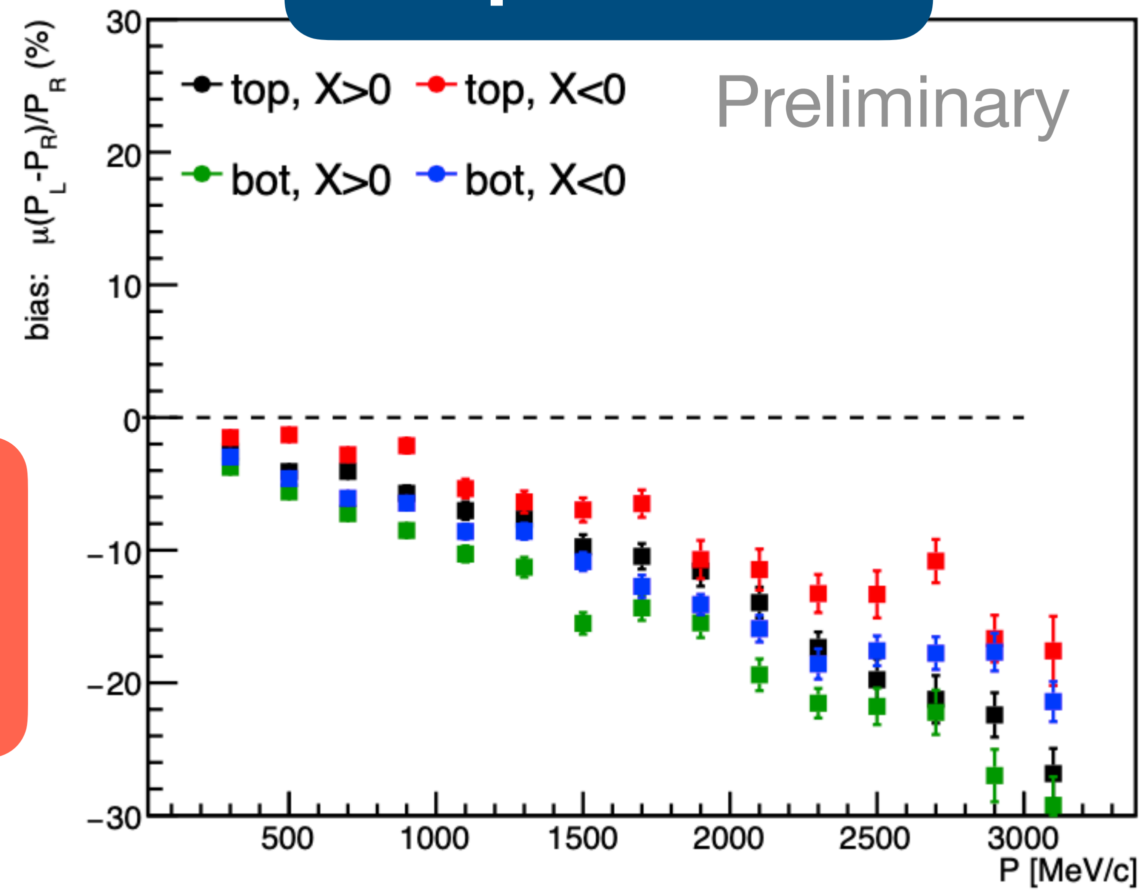
Systematics on momentum reconstruction due to distortions in the HA-TPCs

$(p_L - p_R)/p_R$ vs p in data

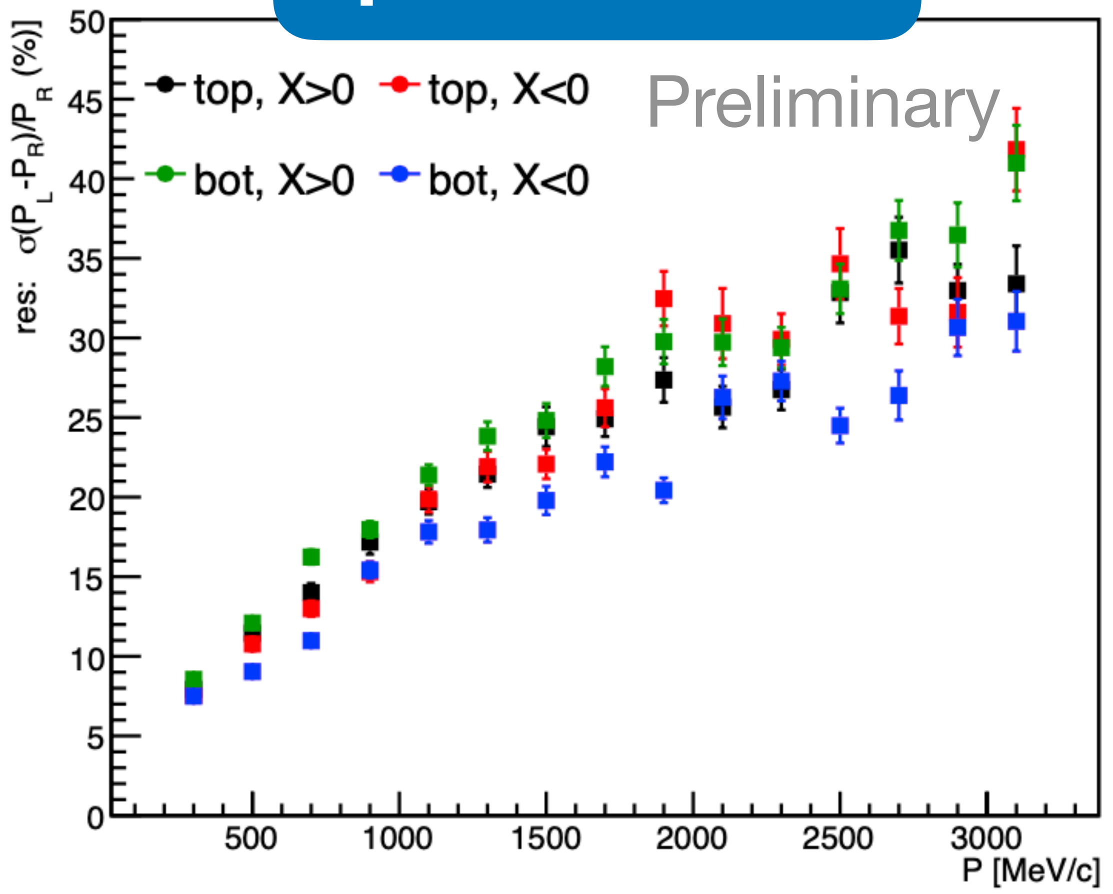
- **bias** and **resolution** on $(p_L - p_R)/p_R$ are evaluated in function of p for the **4 EP** (different colours)
- **without** $\vec{E} \times \vec{B}$ corrections:
  - similar trend seen in MC for both p bias and resolution
- **with** $\vec{E} \times \vec{B}$ corrections:
  - bias is reasonably well corrected for 3 out of 4 EPs, residual bias for top X<0 EP
  - top X<0 EP has the worst p resolution

without $\vec{E} \times \vec{B}$ corr

p bias

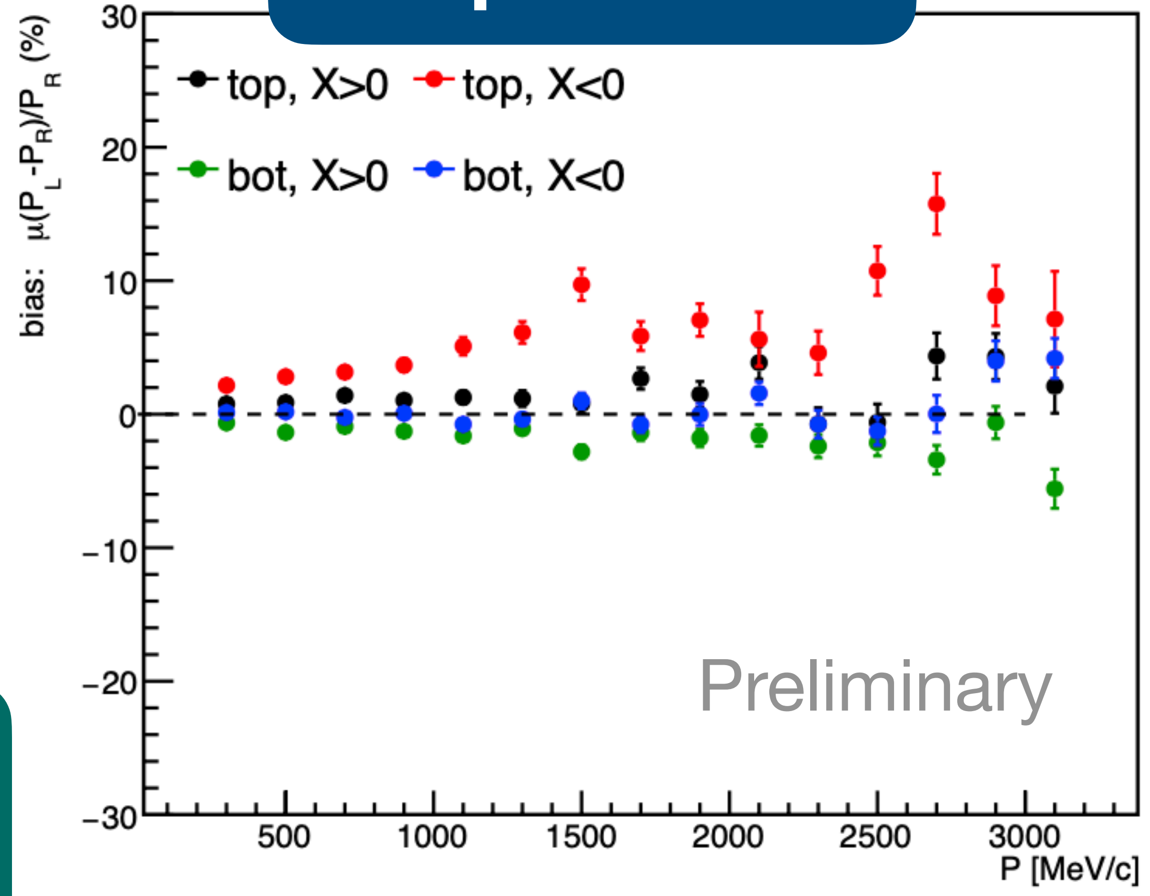


p resolution

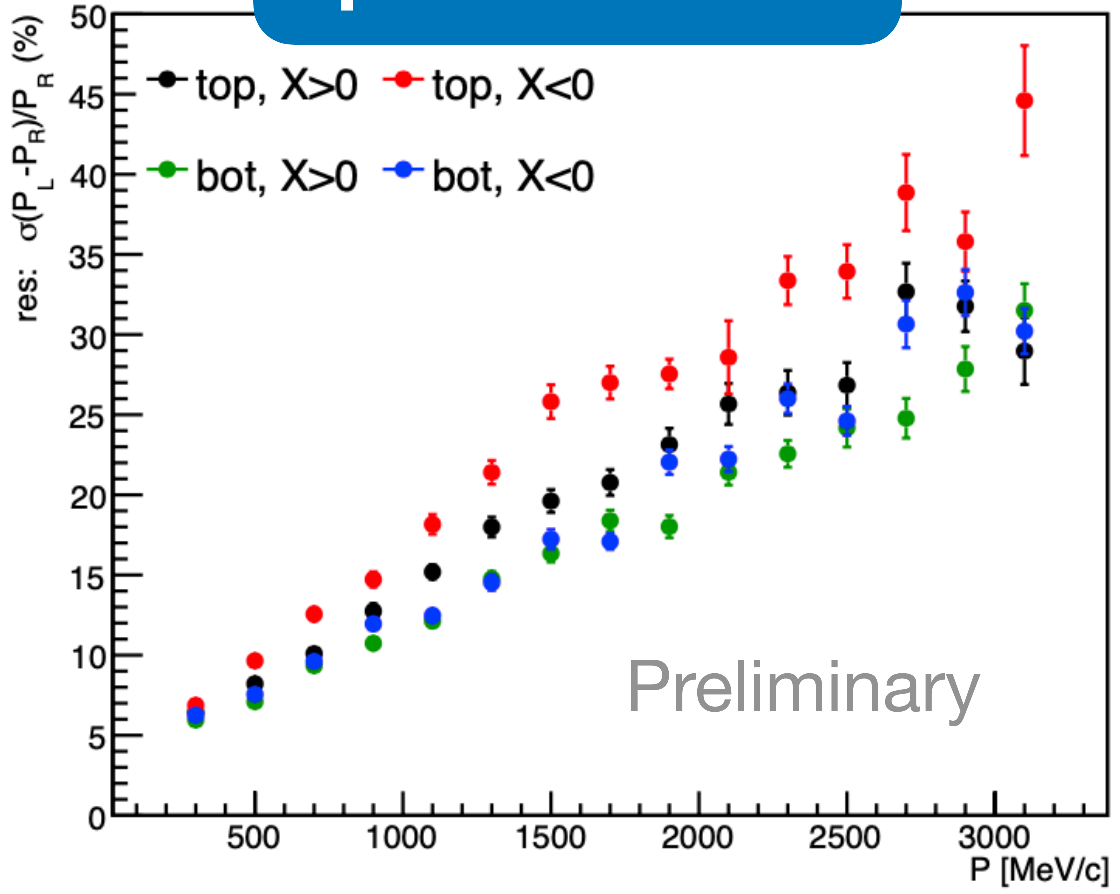


with $\vec{E} \times \vec{B}$ corr

p bias



p resolution



Conclusions

- T2K ND280 Upgrade is installed and fully operational
- High-Angle TPCs' performance :
    - meet the requirements on both spatial resolution and dE/dx resolution
    - little discrepancies in data and MC $\Rightarrow$ room for improvement !
- $\overrightarrow{E}$ and $\overrightarrow{B}$ **fields non-uniformities** in the High-Angle TPCs were observed: lot of work (and improvements) have been made to **correct for** the induced $\overrightarrow{E} \times \overrightarrow{B}$ **effect :**
    - $\overrightarrow{B}$: inhomogeneities from UA1 magnetic field $\Rightarrow$ extrapolation of $\overrightarrow{B}$ maps in the HA-TPC region $\Rightarrow$ correction drifting back electrons in the interaction plane
    - $\overrightarrow{E}$: curvature was observed without $\overrightarrow{B}$ $\Rightarrow$ $\overrightarrow{E}$ maps got from COMSOL $\Rightarrow$ curvature sensitively reduced
    - **studies** on the **systematics** on momentum reconstruction show that the applied **corrections** work reasonably **well**

Grazie per l’attenzione !

Backup slides

The $\vec{E} \times \vec{B}$ effect

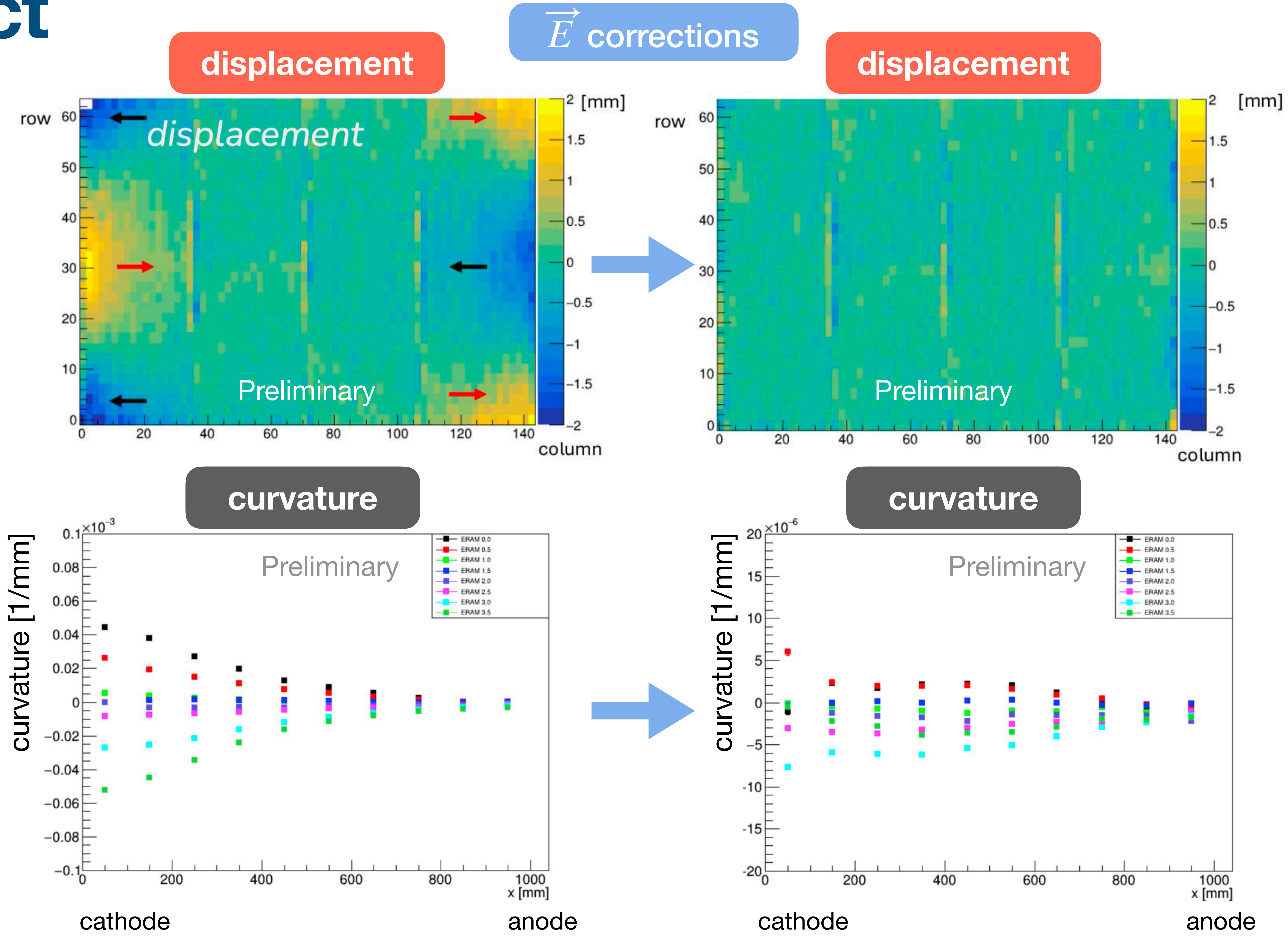
the correction

- in order to correct for the $\vec{E} \times \vec{B}$ effect, the collected electrons on the anode plane are drifted “back in the past” in the interaction plane
- this drift is performed using the detector $\vec{B}$ **map**

The $\vec{E} \times \vec{B}$ effect

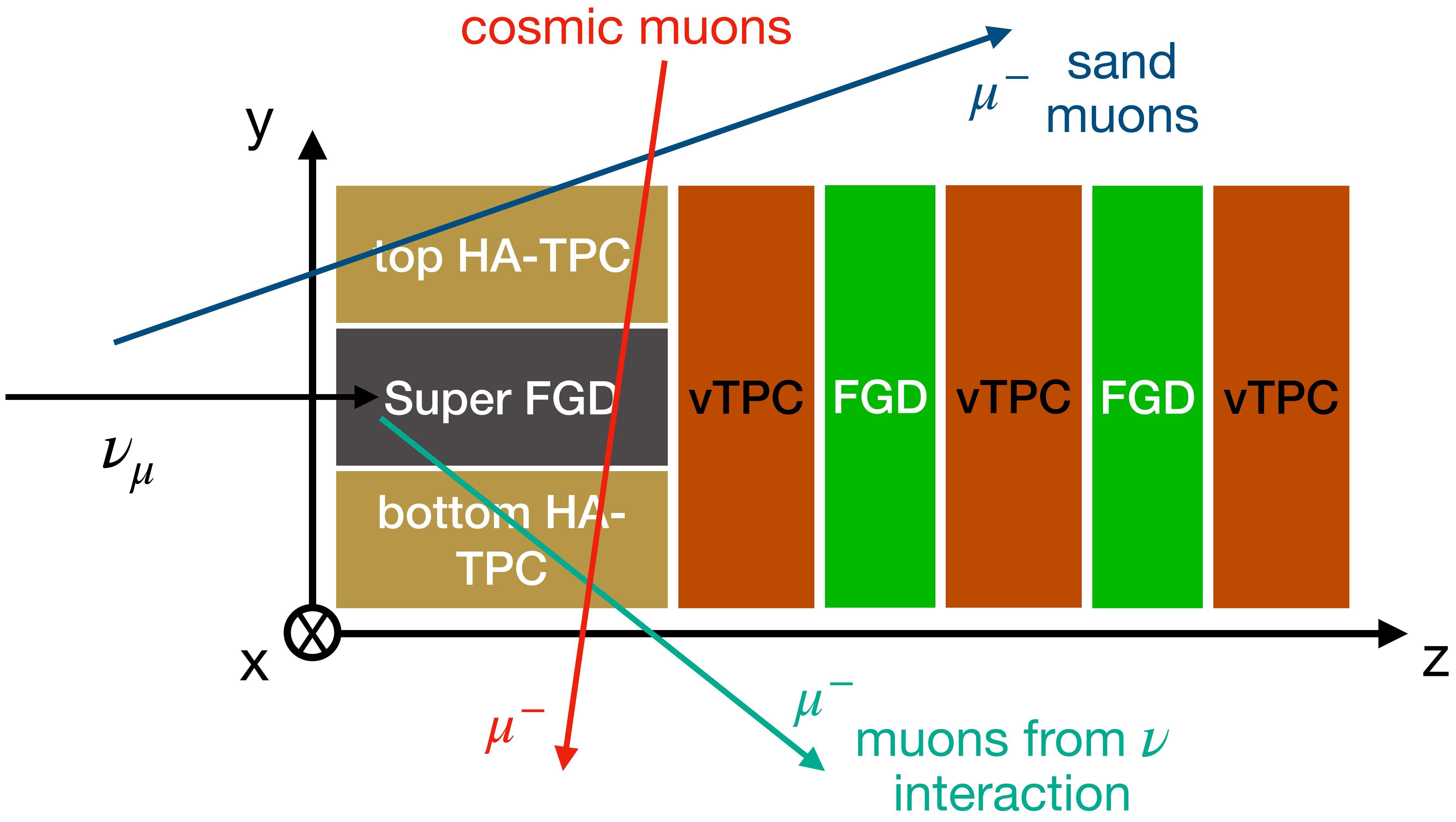
the $\vec{E}$ non-uniformities

- even without $\vec{B}$ field the tracks were still curved
- assumptions: homogeneous $\vec{E}$ field, cage gaps not modelled
- the actual geometry has been implemented in COMSOL and $\vec{E}$ maps have been produced
- corrections were performed using **$\vec{E}$ maps**



HA-TPCs perfomance

collected data tracks types

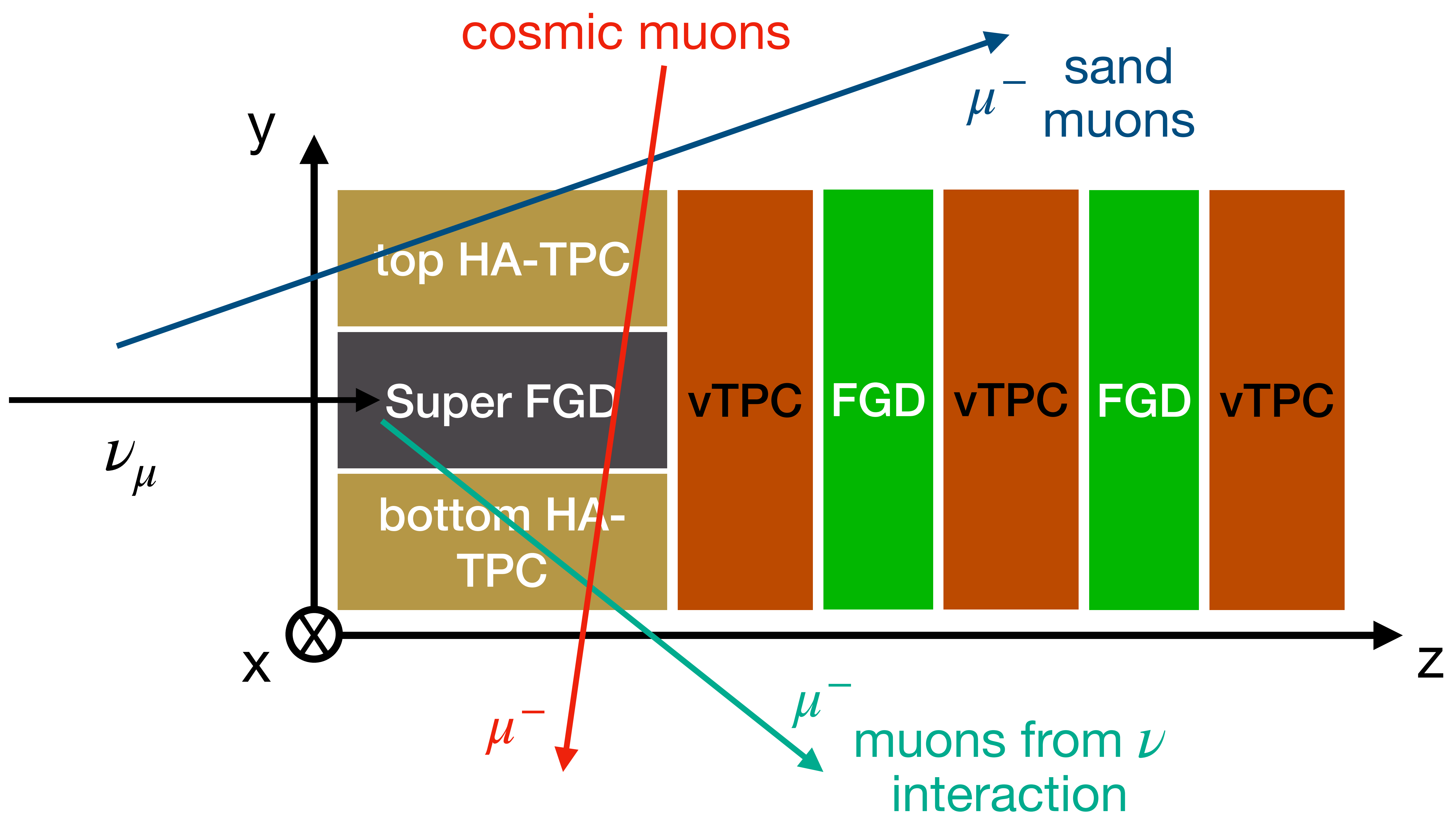


We collect data of 2 types:

- **cosmic data:**
  - cosmic muons
- **beam data:**
  - cosmic muons
  - sand muons
  - muons from neutrino interactions in ND280

HA-TPCs perfomance

collected data tracks types



We collect data of 2 types:

- **cosmic data:**
  - cosmic muons — vertical tracks
- **beam data:**
  - cosmic muons
  - sand muons
  - muons from neutrino interactions in ND280

horizontal tracks

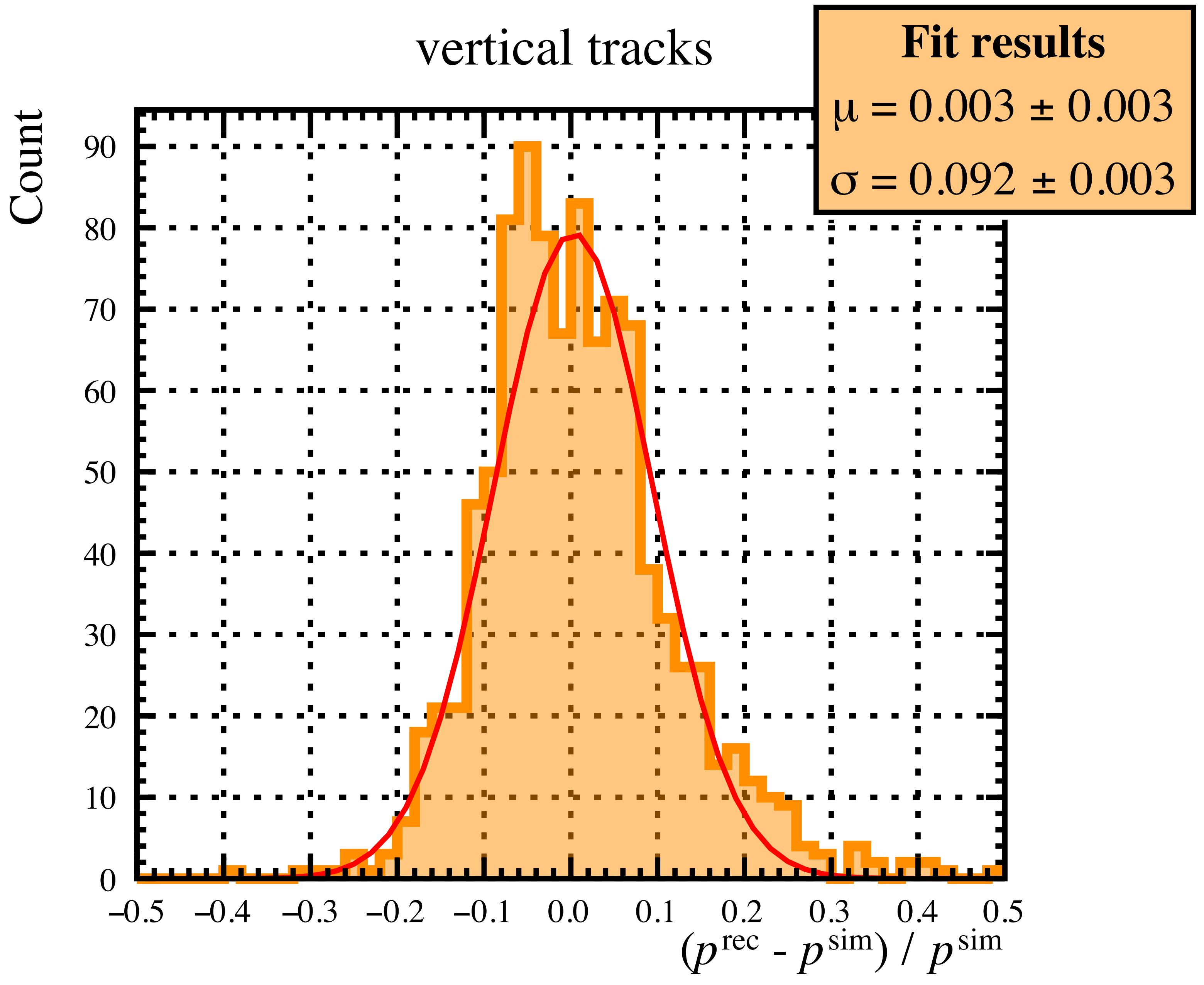
momentum resolution

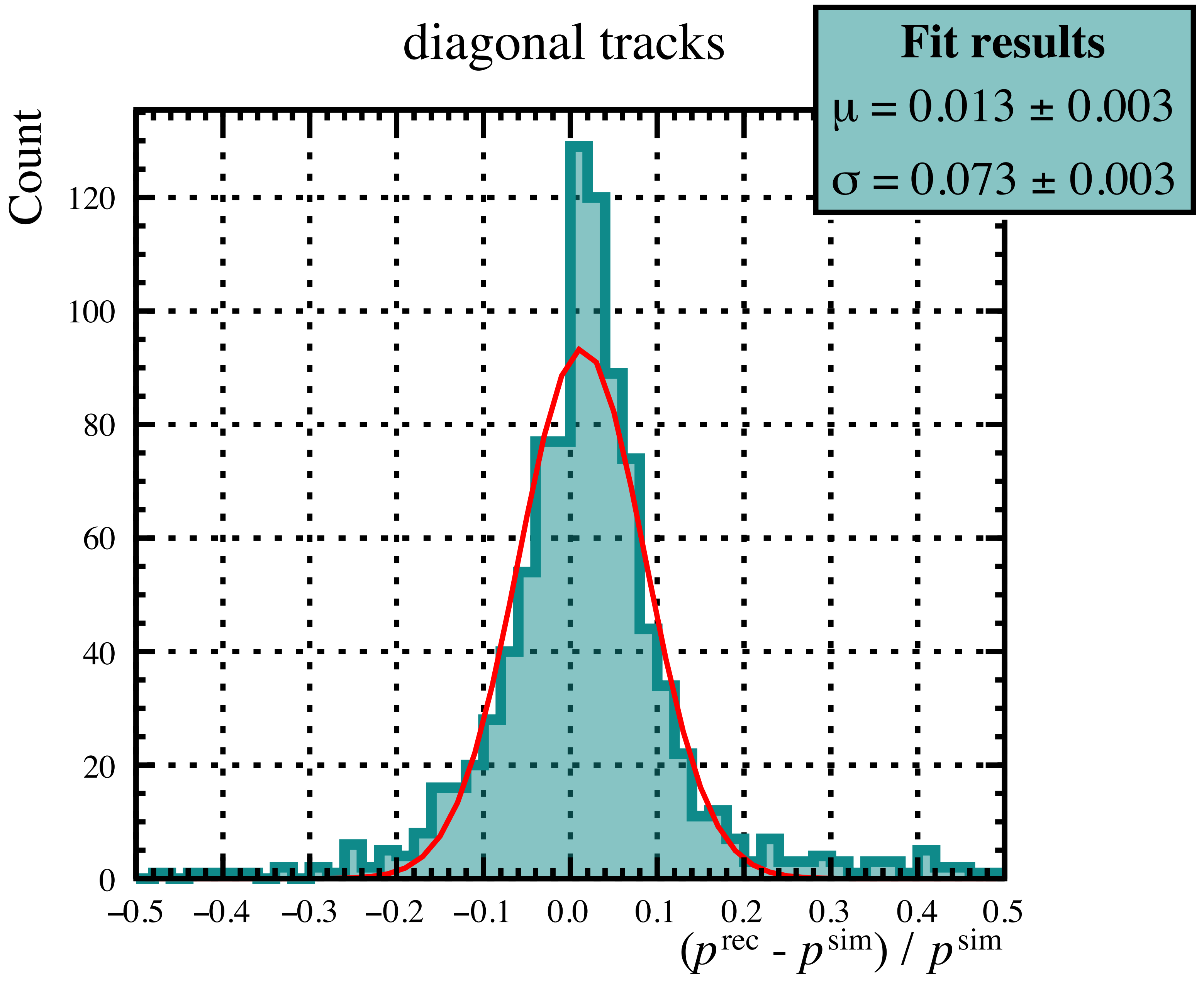
Gluckstern formula

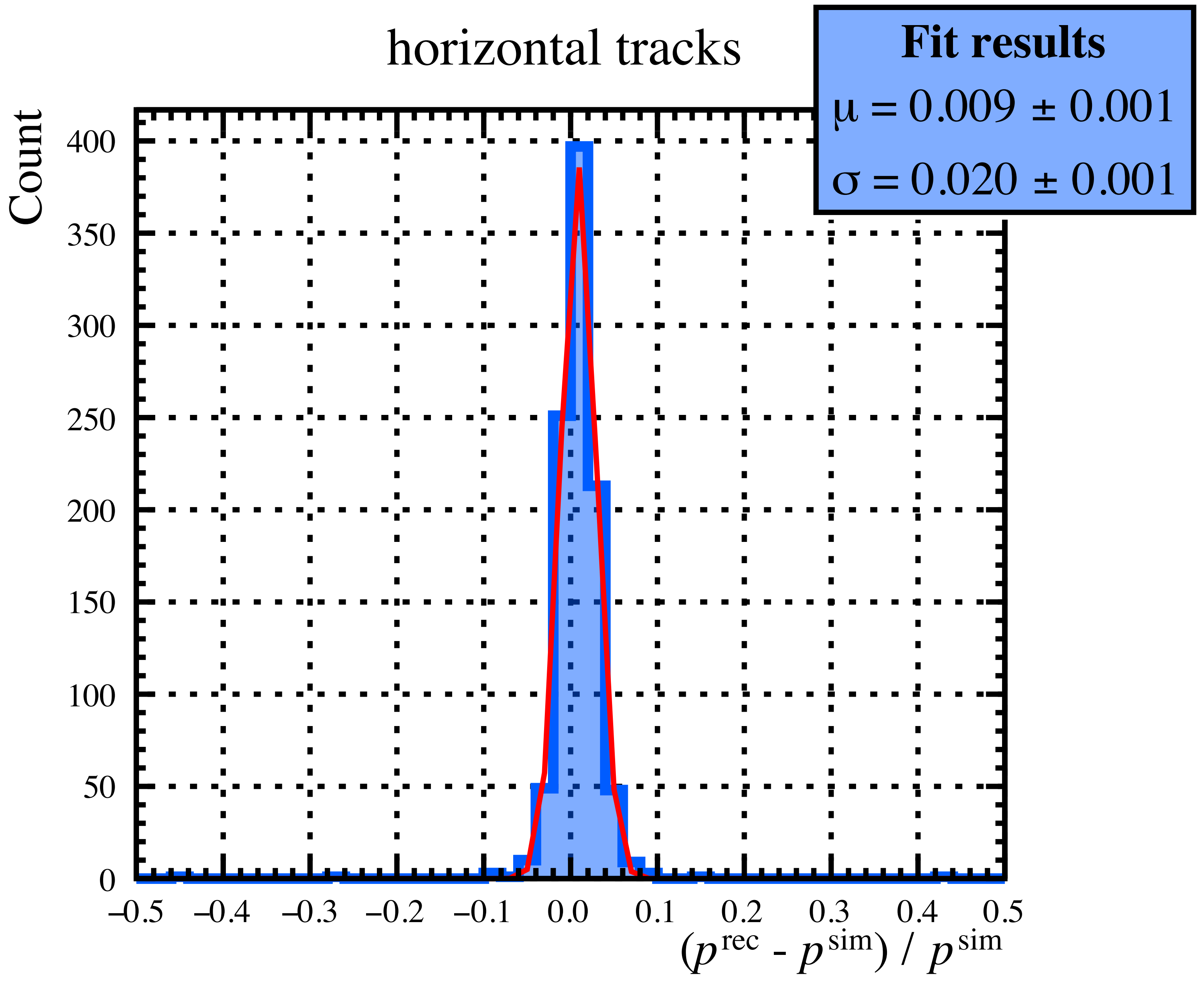
$$\frac{\sigma_{p_t}}{p_t\ [GeV/c]} = \sigma_{xy} \frac{p_t\ [GeV/c]}{e\ B\ [T]\ l^2\ [m^2]} \sqrt{\frac{720}{N_p + 4}}$$

3 type of MC (at p = 1 GeV/c)

- vertical tracks (the shortest)
- diagonal tracks
- horizontal tracks (the longest) → better momentum resolution

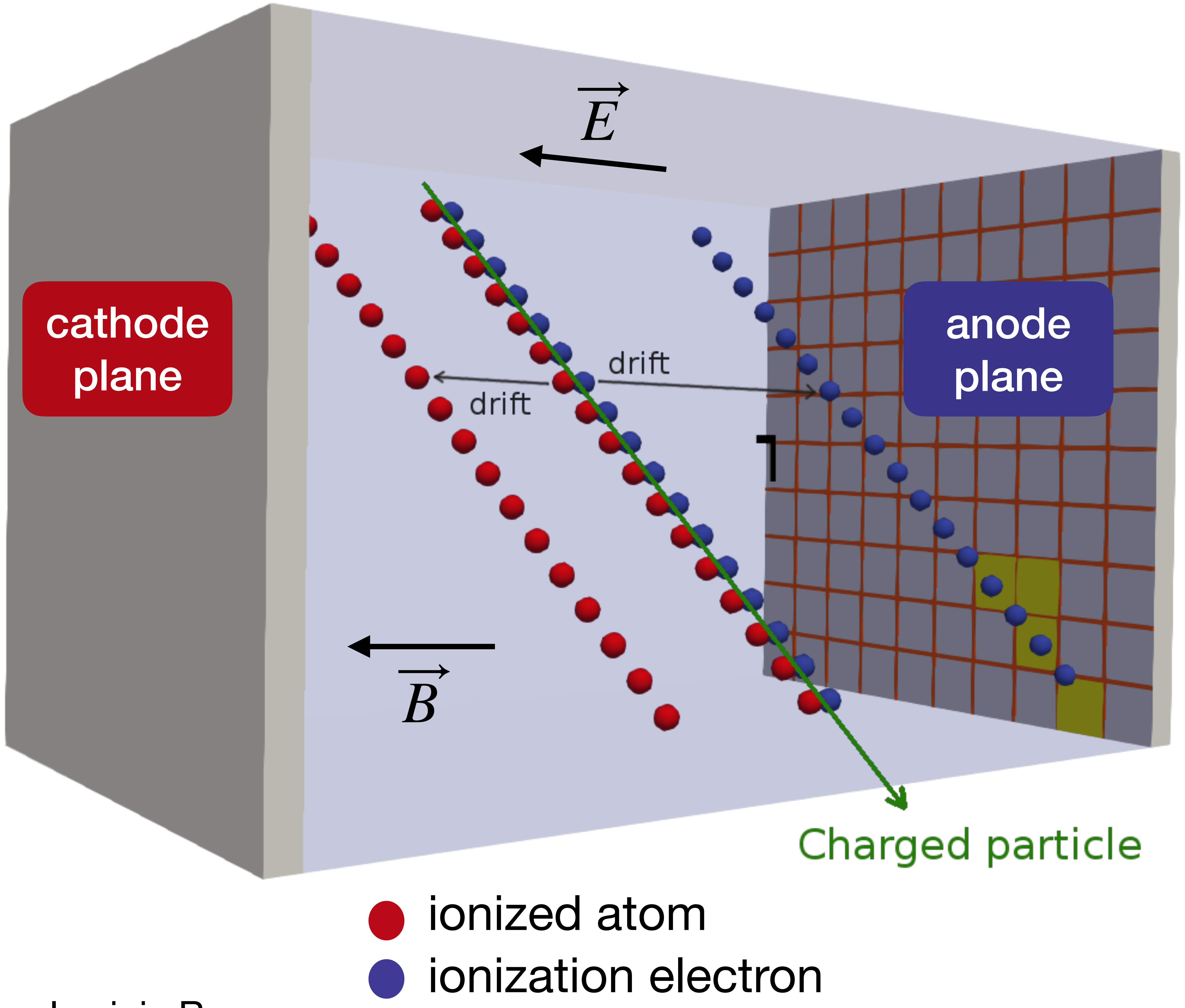






The High-Angle TPC

Time Projection Chamber working principle



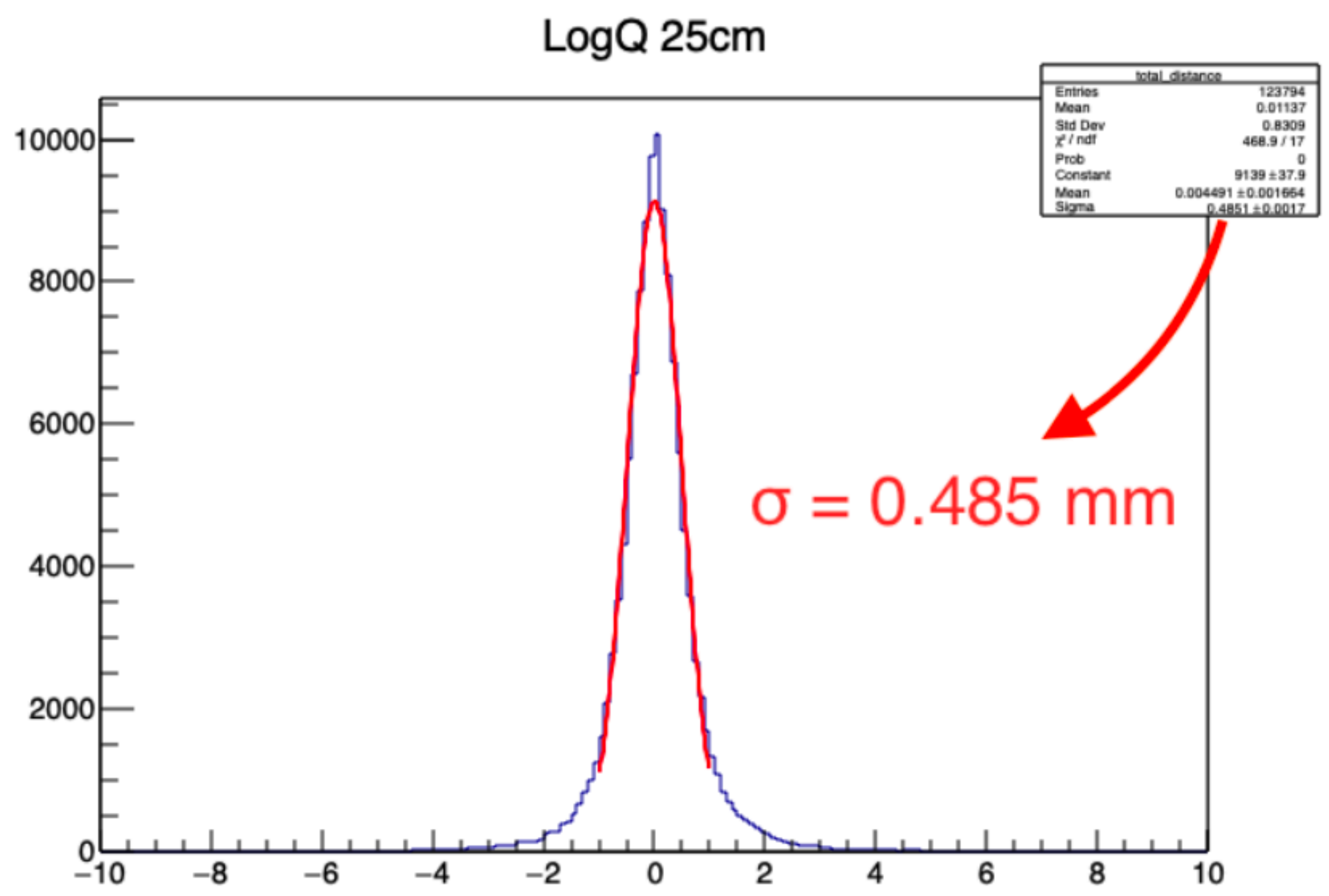
- a **charged particle** crosses the TPC
- it ionizes the gas the **ionization electrons** that **drift** towards the **anode plane**
- a 2D **projection** of the **track** on the **read-out** plane is produced
- the **drift time** can be used to reconstruct the 3rd dimension
- the **momentum** and **charge** can be determined based on the **track curvature** produced by $\vec{B}$

How to get the spatial resolution ?

- each track is fitted with a circle/parabola
- for each cluster in the track compute the residuals:

$$res = \sqrt{(z_{rec}^{cluster} - z^{track\ fit})^2 + (y_{rec}^{cluster} - y^{track\ fit})^2} - R$$

- fill a histogram with res from all the tracks
- fit the histogram with a gaussian
- SR = σ from the fit



How to get the dE/dx resolution ?

from dE/dx binned in |p|

dE/dx resolution vs |p|