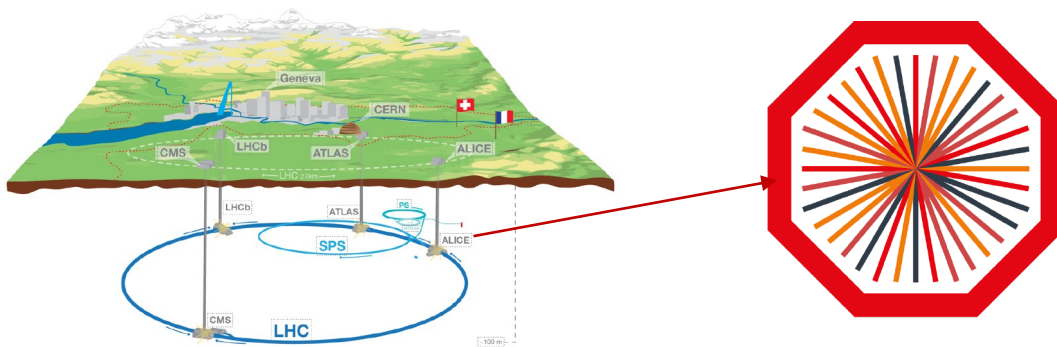


# Magnetic Monopole and HIP searches with TPCs at the LHC: First results from ALICE

Mesut Arslanok  
Yale University



Next Frontiers in Magnetic Monopole Searches, Institute of High Energy Physics, CAS, Beijing, China  
14 September 2026

Yale



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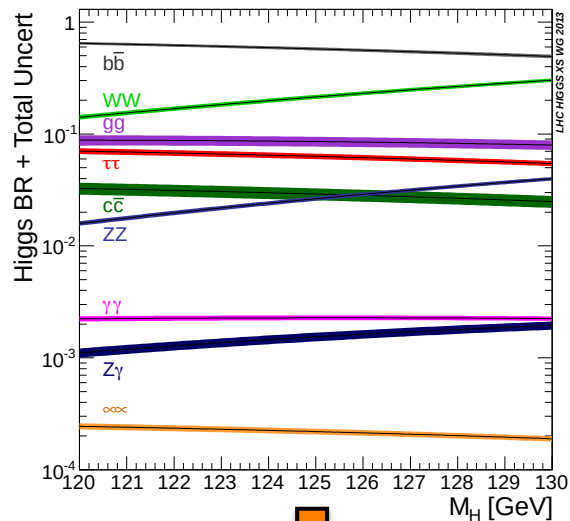
# Outline

- How to design a detector—and what we do differently
- A short introduction to **A Large Ion Collider Experiment (ALICE)**
  - Is ALICE only a heavy-ion experiment? Unique features
- New BSM program in ALICE
  - **A new approach/trigger to measure HIPs:** hybrid detection logic
  - **Configurable detector setups** for unconventional signatures
- What are the perspectives beyond Run 3-4?
  - ALICE3: A next generation heavy ion experiment at the LHC (CERN-LHCC-2022-009 ; LHCC-I-038)

How to design a collider experiment?

# Physics motivation → E.g. Higgs boson

## Main decays channels



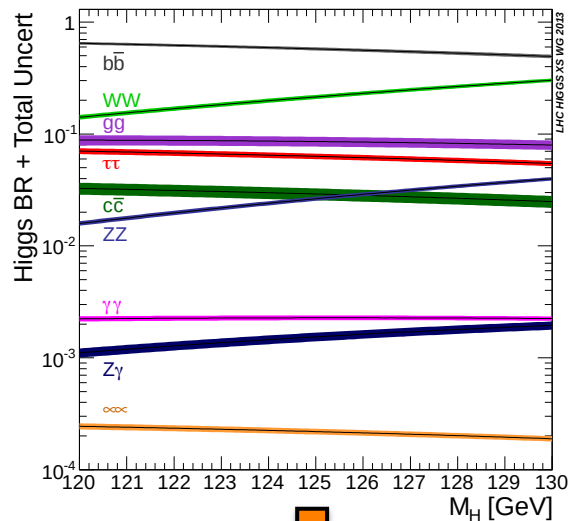
## Sensitive channels

| Decay channel                                                             | Mass resolution | BR                   | Acceptance (A) | $A \times \text{BR}$         |
|---------------------------------------------------------------------------|-----------------|----------------------|----------------|------------------------------|
| $H \rightarrow \gamma\gamma$                                              | 1-2%            | $2.3 \times 10^{-3}$ | 0.4-0.6        | $(0.9 - 1.4) \times 10^{-3}$ |
| $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$              | 1-2%            | $1.2 \times 10^{-4}$ | 0.3-0.5        | $(0.4 - 0.6) \times 10^{-4}$ |
| $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu_\ell \ell^- \bar{\nu}_\ell$ | $\sim 20\%$     | $2.1 \times 10^{-1}$ | 0.1-0.3        | $(2 - 6) \times 10^{-2}$     |
| $H \rightarrow b\bar{b}$                                                  | $\sim 10\%$     | $5.8 \times 10^{-1}$ | 0.05-0.1       | $(3 - 6) \times 10^{-2}$     |
| $H \rightarrow \tau^+ \tau^-$                                             | $\sim 15\%$     | $6.3 \times 10^{-2}$ | 0.1-0.3        | $(6 - 19) \times 10^{-3}$    |



# Physics motivation → E.g. Higgs boson

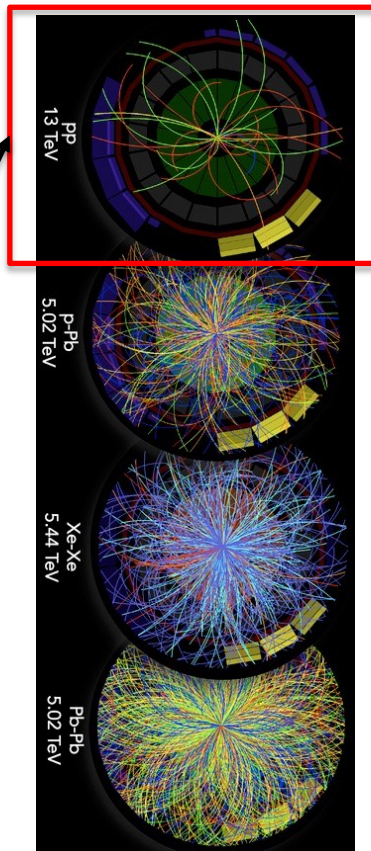
## Main decays channels



## Sensitive channels

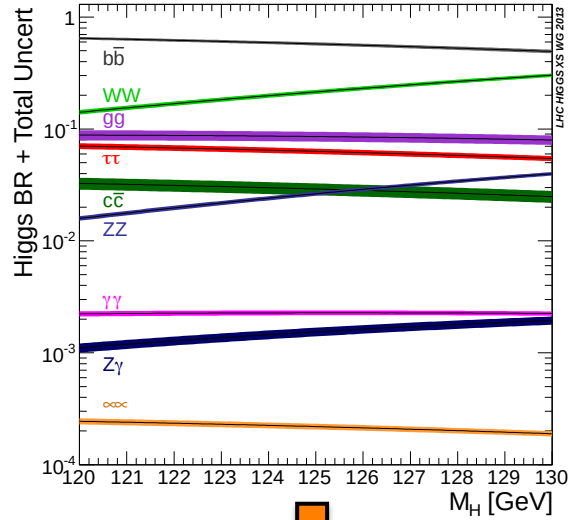
| Decay channel                                                             | Mass resolution | BR                   | Acceptance (A) | $A \times BR$                |
|---------------------------------------------------------------------------|-----------------|----------------------|----------------|------------------------------|
| $H \rightarrow \gamma\gamma$                                              | 1-2%            | $2.3 \times 10^{-3}$ | 0.4-0.6        | $(0.9 - 1.4) \times 10^{-3}$ |
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## pp collisions



# Physics motivation → E.g. Higgs boson

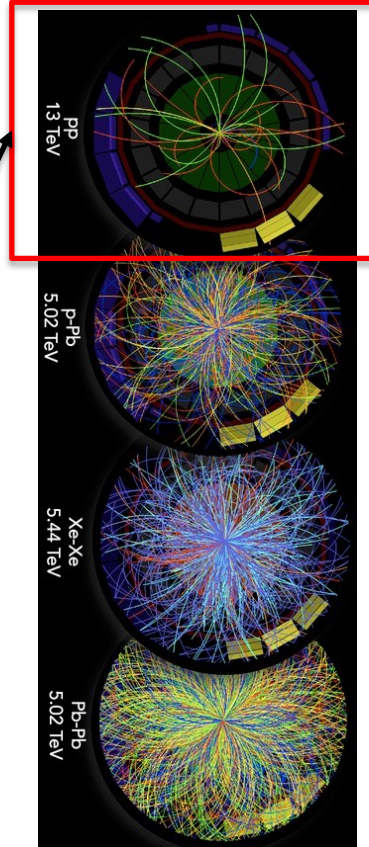
## Main decays channels



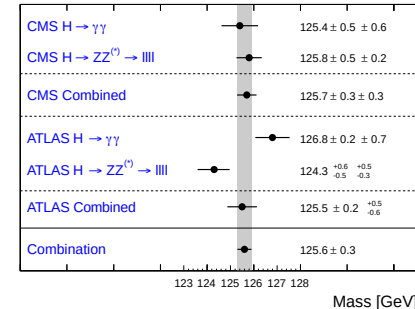
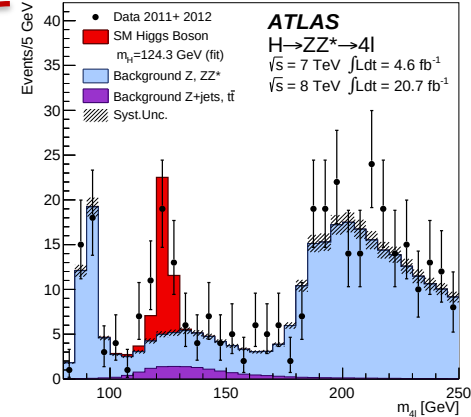
## Sensitive channels

| Decay channel                                                             | Mass resolution | BR                   | Acceptance (A) | $A \times BR$                |
|---------------------------------------------------------------------------|-----------------|----------------------|----------------|------------------------------|
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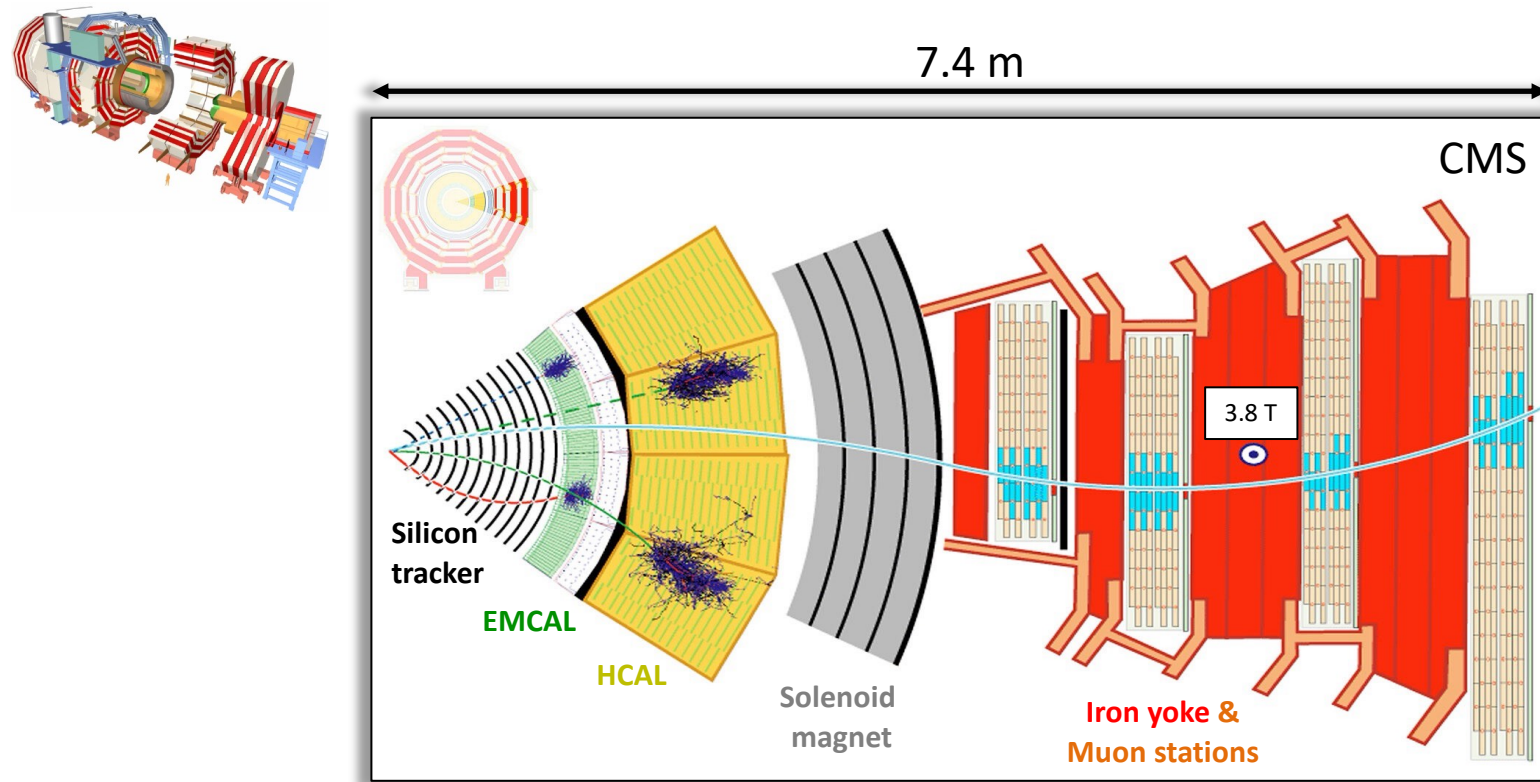
## pp collisions



## Nobel Prize



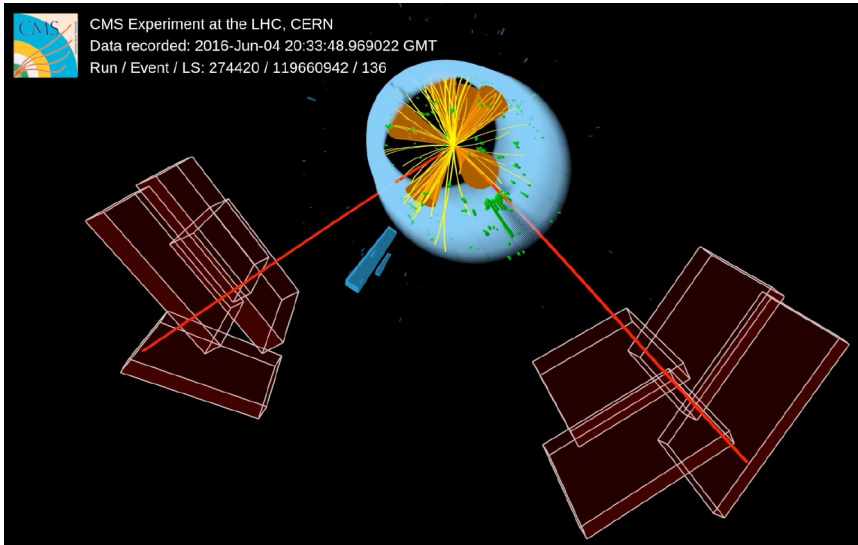
# Higgs boson → How to detect → E.g. Compact Muon Solenoid (CMS)



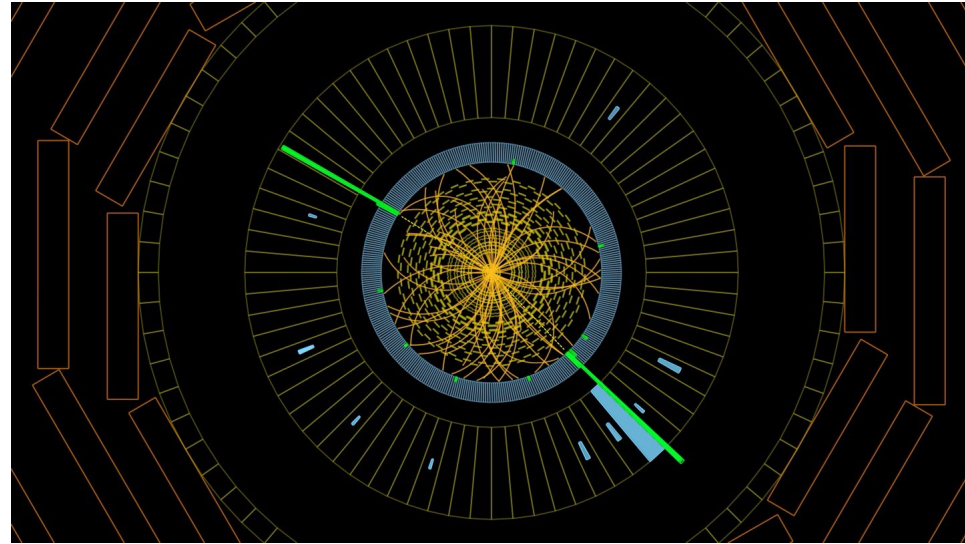
14 Si layers + EMCAL + HCAL + Muon stations

# Higgs candidate events in CMS

## Two muon decay



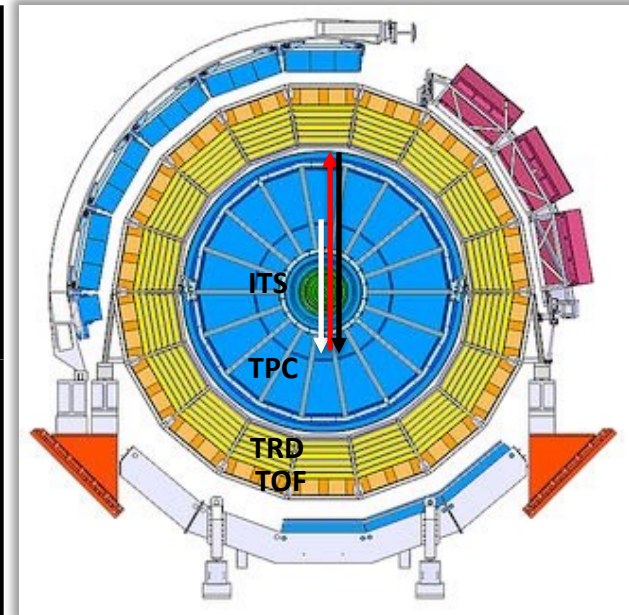
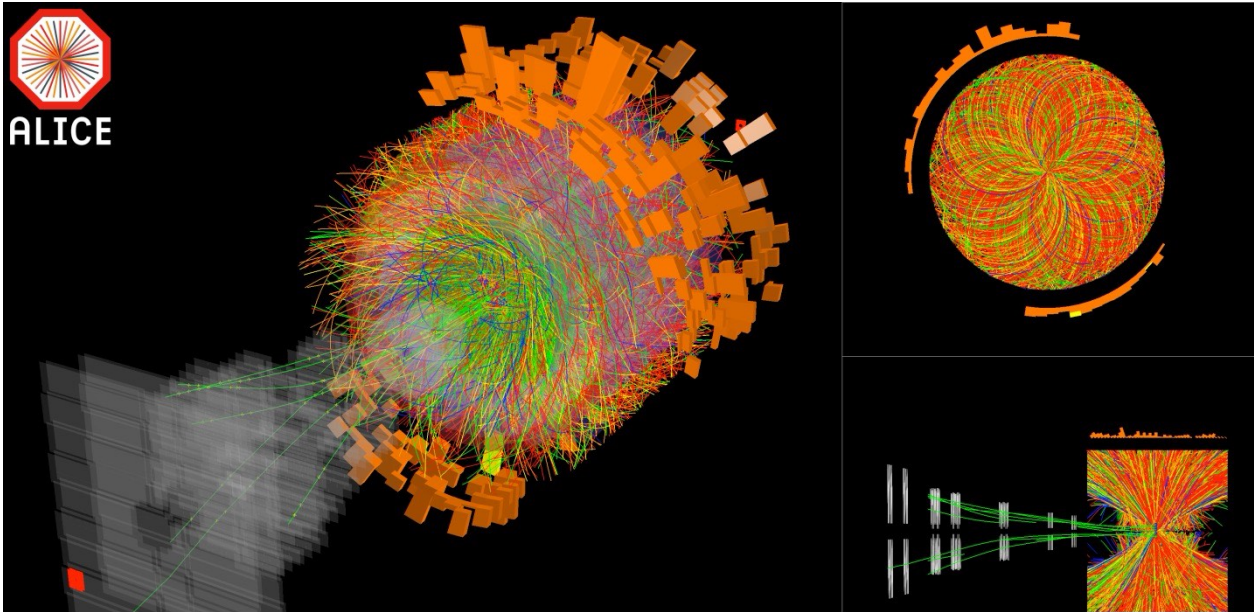
## Two photons



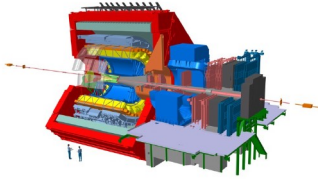
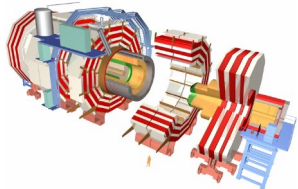
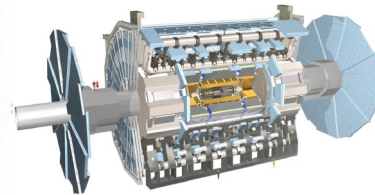
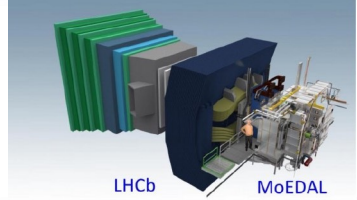


# An event display of a Pb-Pb collision in ALICE

“A dedicated heavy-ion experiment”



# ALICE vs OTHERS

| Detector                               | ALICE (ITS3 + TPC)                                                                                             | CMS                                                                                | ATLAS                                                                               | MoEDAL                                                                              |
|----------------------------------------|----------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Schematic                              |                               |  |  |  |
| Tracking concept                       | ITS (pixel) + large-volume TPC (gas) + TOF (time-of-flight)<br>(TPC: configurable gain and common-mode signal) | All-silicon tracker (pixel + strip)                                                | Silicon (pixel + SCT) + TRT (straw tubes)                                           | Passive NTDs + trapping detectors                                                   |
| Tracking layers / hit points (typical) | ITS: 3 pixel layers (ITS3) + 4 pixel layers (outer ITS2) + up to 159 TPC clusters                              | 4 pixel + 10 strip ( $\approx 14$ Si layers)                                       | 4 pixel + 4 SCT + <b>~30–36</b> TRT hits                                            | NTD etch-pit trajectory (no per-event hit information)                              |
| Inner pixel material (per layer)       | <b>0.09% <math>X_0</math></b><br>(ITS3 inner layers)                                                           | <b>~1% <math>X_0</math></b><br>(order of magnitude)                                | <b>~1–2% <math>X_0</math></b><br>(order of magnitude)                               | —                                                                                   |
| Solenoidal / magnetic field            | <b>0.5 T</b>                                                                                                   | <b>3.8 T</b>                                                                       | <b>2.0 T</b> (inner solenoid)                                                       | <b>No dedicated magnetic field</b>                                                  |
| Active dE/dx information               | <b>Yes</b> — TPC (configurable gain, common-mode signal)                                                       | <b>Yes</b> — silicon (can saturate for very high ionization)                       | <b>Yes</b> — pixel/SCT/TRT (can saturate for very high ionization)                  | <b>No</b> (passive)                                                                 |
| Timing / event information             | <b>Yes</b> (TOF + event information)                                                                           | <b>Yes</b>                                                                         | <b>Yes</b>                                                                          | <b>No</b> (mostly passive, no event-by-event timing for NTDs)                       |

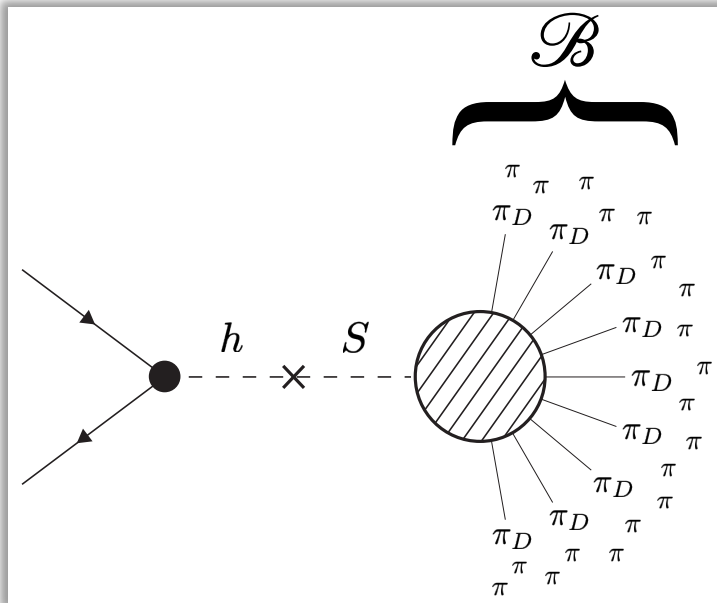
# What makes ALICE special for HIP searches (and in general for BSM)?

| Unique/unusual features                              | Why it matters for HIPs / monopoles                                                                                                      |
|------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Tracking up to 2.5 m                                 | Up to <b>159 (+7 from ITS) spatial + ionization samples</b> along the track trajectory; excellent topology and dE/dx information.        |
| Configurable TPC gain                                | Extending the dynamic range from roughly <b>0.5–50 MIPs</b> → <b>10–5000 MIPs</b> .                                                      |
| TPC common-mode (CM) signal (solution to saturation) | <b>Hybrid detector approach: Independent PID signal</b> , even when conventional clusters saturate.                                      |
| Lowest material budget                               | Lowest material budget (highest efficiency) at the LHC. ITS3 pushes the innermost layers to only <b>~0.09%X<sub>0</sub> per layer</b> .  |
| Lowest magnetic field: 0.5/0.2 T                     | Access to very low- $p_T$ particles; much less bending of the MMs in the magnetic field.                                                 |
| ITS pixel multiplicity/topology                      | Independent silicon confirmation of an unusual trajectory; and PID via pixel-hit multiplicity and cluster shape                          |
| TOF                                                  | Independent velocity information: slow massive HIPs can have anomalous $\beta$ /time of flight.                                          |
| Continuous readout and PID                           | Full event information is available: E.g. event multiplicity, centrality, event shape and spectra ...                                    |
| Detector and reconstruction configurability          | <b>Change the TPC operating point and reconstruction settings for BSM searches.</b> E.g.: TPC with low gain and increased collision rate |

**Drawbacks:** **Low pp luminosity:**  $\sim 1/2000$  of ATLAS/CMS and  $\sim 1/200$  of MoEDAL.  
**Limited acceptance:**  $|\eta| \lesssim 1.5$ , compared with  $|\eta| \lesssim 2.5$  for ATLAS/CMS (partly compensated by much lower B field)

# How to overcome the luminosity drawback? E.g.: SUEPs

$$pp \rightarrow h \rightarrow S \rightarrow \mathcal{B} + X$$



Higgs production is the “portal” to the hidden sector

## Production mechanism:

1. Higgs production at LHC
2. Portal through scalar mixing or rare decay ( $h = S$ )
3. ‘Dark shower’ in hidden sector (many dark pions)
4. Dark pions decay back to SM pions

## Experimental signature: High soft particle multiplicity

- $\langle n(Q) \rangle \sim \left( \frac{Q}{\Lambda_D} \right)$   $Q$  = energy available in the shower (roughly  $m_H$  or  $m_S$ )  
 $\Lambda_D$  = hidden confinement scale (analogous to  $\Lambda_{QCD}$ )
- If  $Q = 125$  GeV and  $\Lambda_D = 1$  GeV  $\Rightarrow n \sim 100$

Signature would be high multiplicity of soft tracks  
(isotropic event dominated by mesons)

S. Knapen et. Al., JHEP 08 (2017) 076

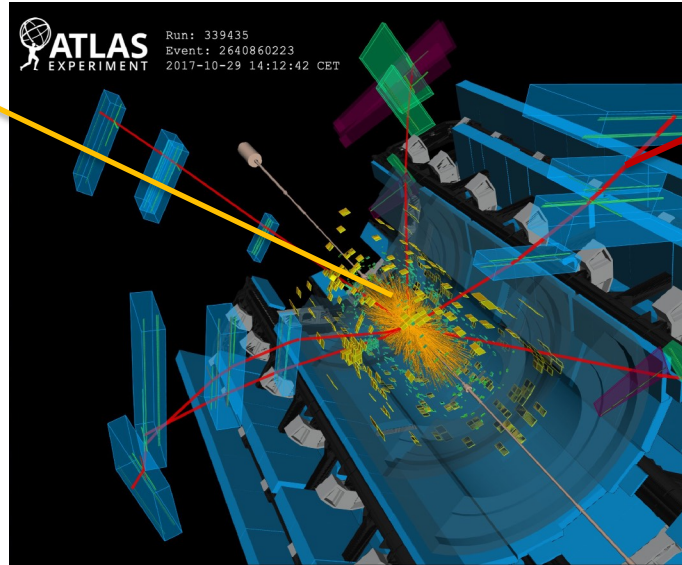


# How to overcome the luminosity drawback? E.g.: SUEPs

What ALICE triggers?

BR = 100%

Signal-tagging eff. = 98%



What ATLAS triggers?

BR = 10%

Signal tagging eff. = 0.4%

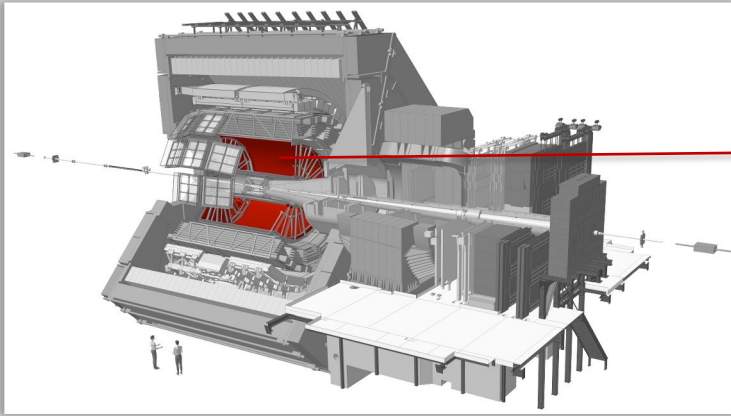
ATLAS, 1612.00850

ATLAS net trigger efficiency  $\approx 0.4\% \Rightarrow 2000\times$  luminosity gap is reduced to  $\approx 8\times$  in signal yield

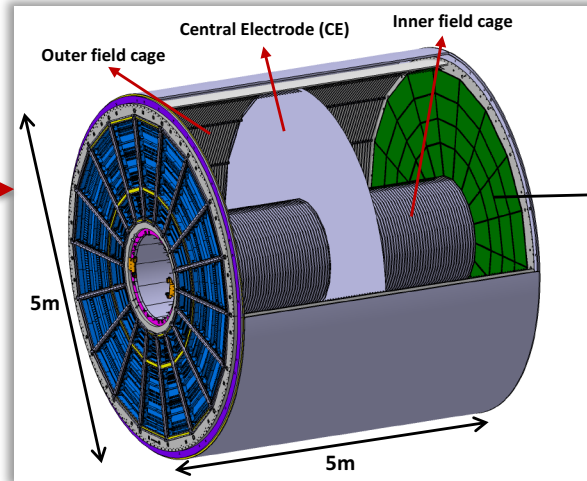
TPC as the monopole tracker

# Introduction to ALICE TPC

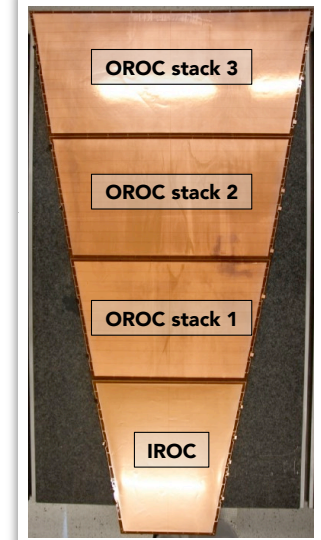
## ALICE



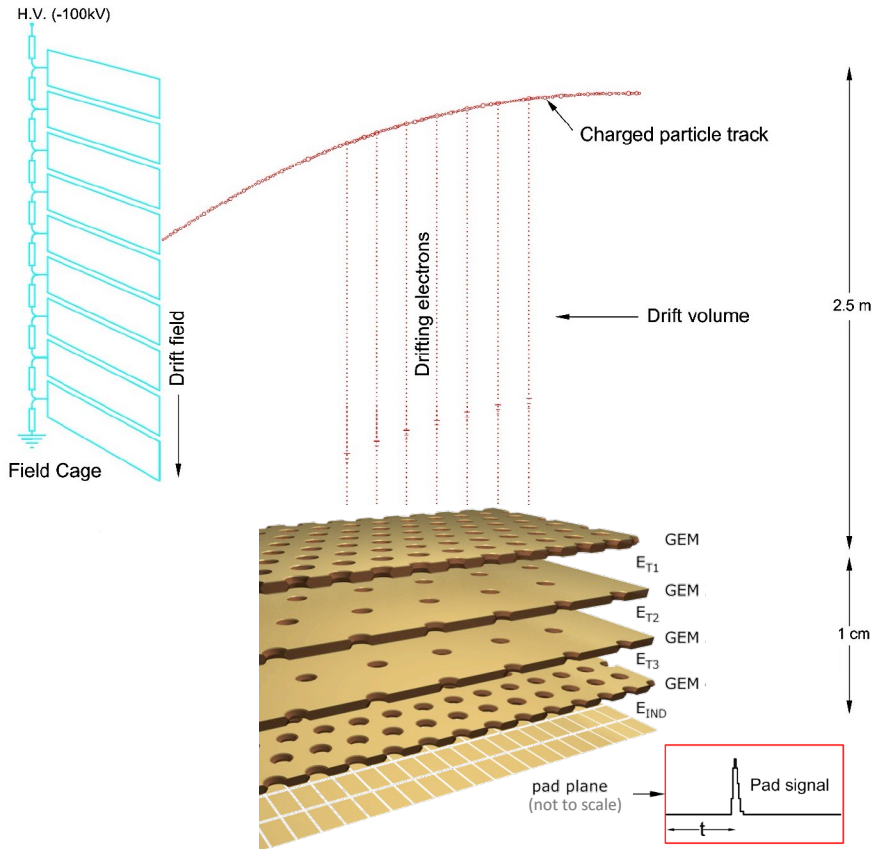
## ALICE TPC



## TPC readout sector



# Working principle



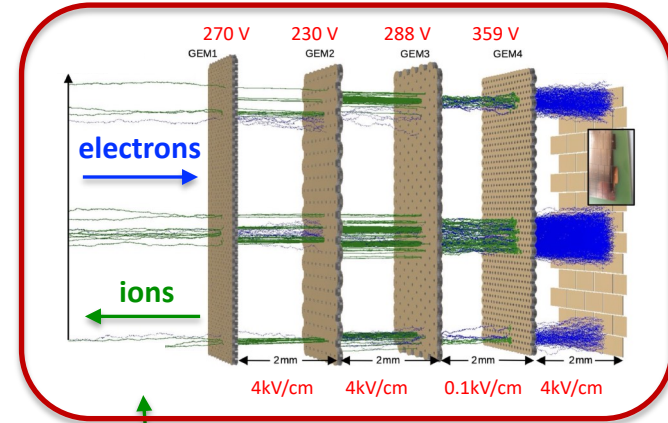
➡ **Ionization**

➡ **Electron Drift**

➡ **Gas Amplification**

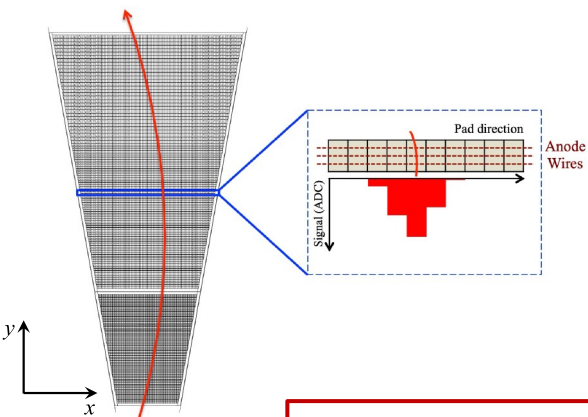
- Electrons with **~1000 larger drift velocity**
- Original charge is multiplied by a factor of **about 2000**
- **Intrinsic ion blocking with ~0.7% ion backflow**

➡ **Signal Generation**

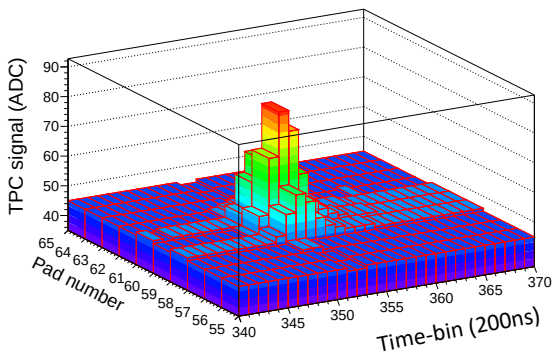


# Signal creation to particle identification

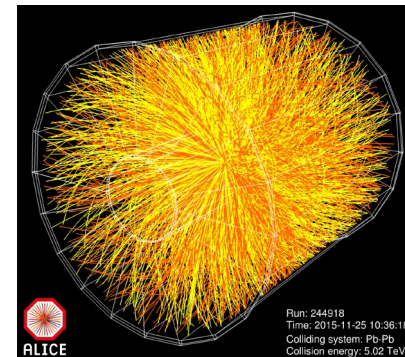
## Track projection



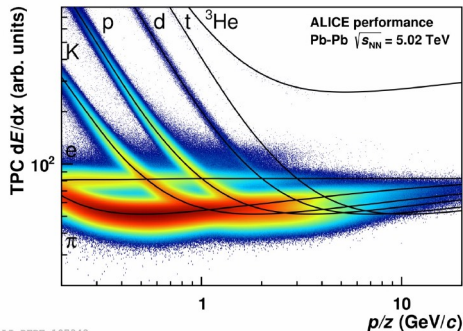
## Clustering



## Time projection & Tracking



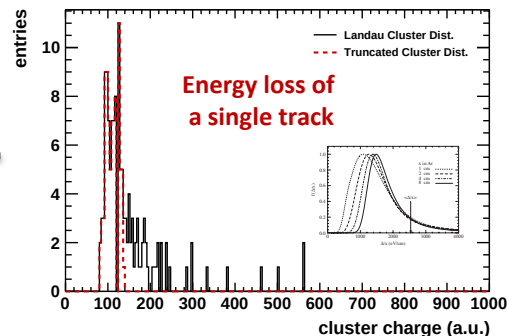
## Particle identification (PID) (Production of expected $dE/dx$ (splines))



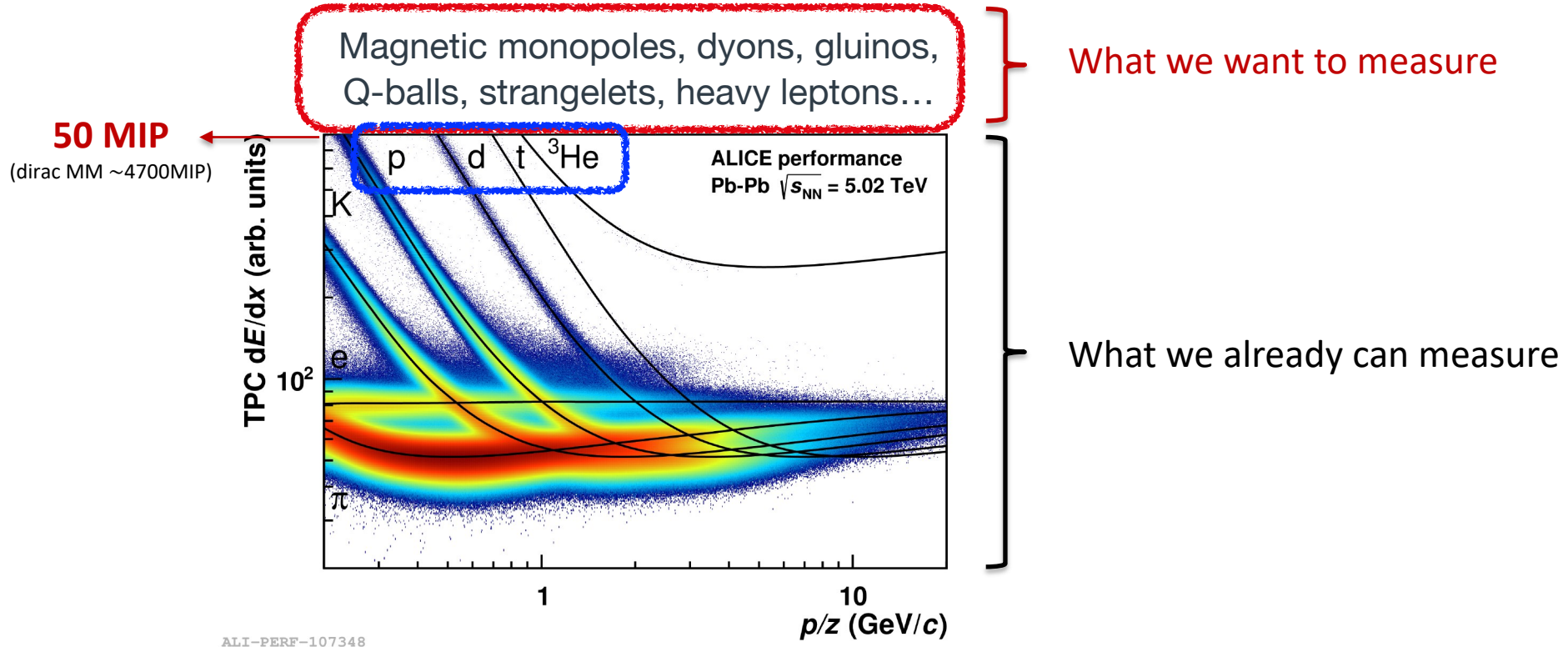
ALI-PPRF-107348

$dE/dx + p$

## $dE/dx$ calculation: Truncated mean

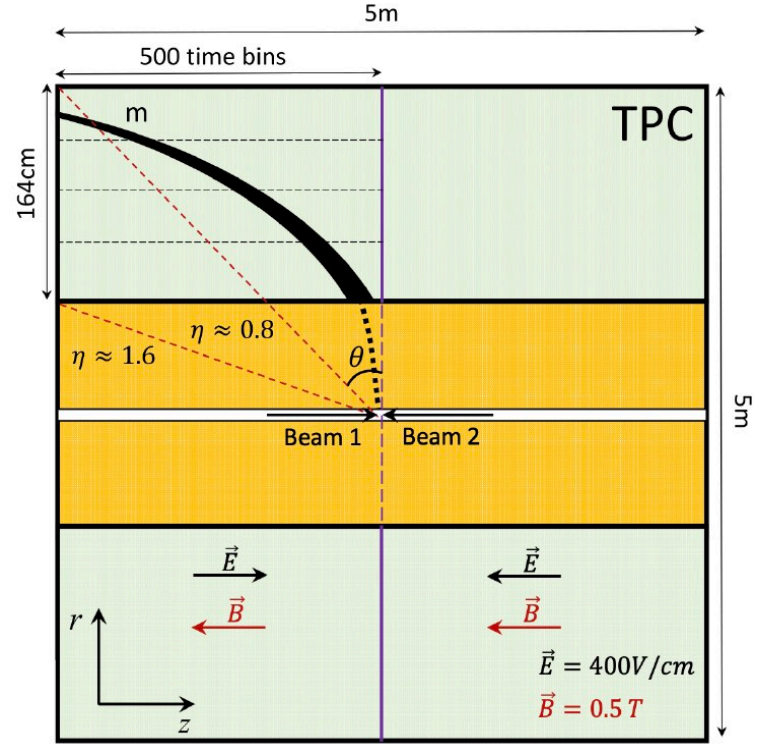
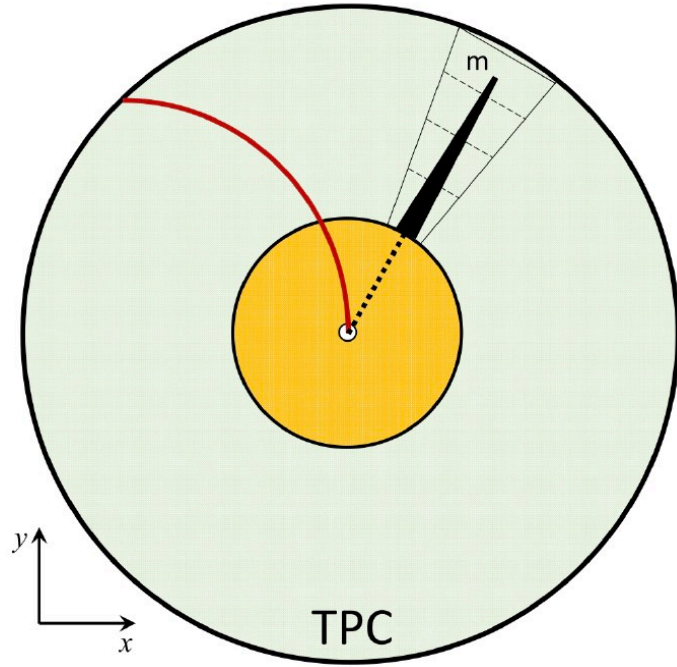


# Goal: Undiscovered territories in TPC





## How does a monopole track look like in the TPC?



M. Arslanđok, H. Caines and M. Ivanov  
Phys. Rev. D 110, 032013 (2024)

# What is new?

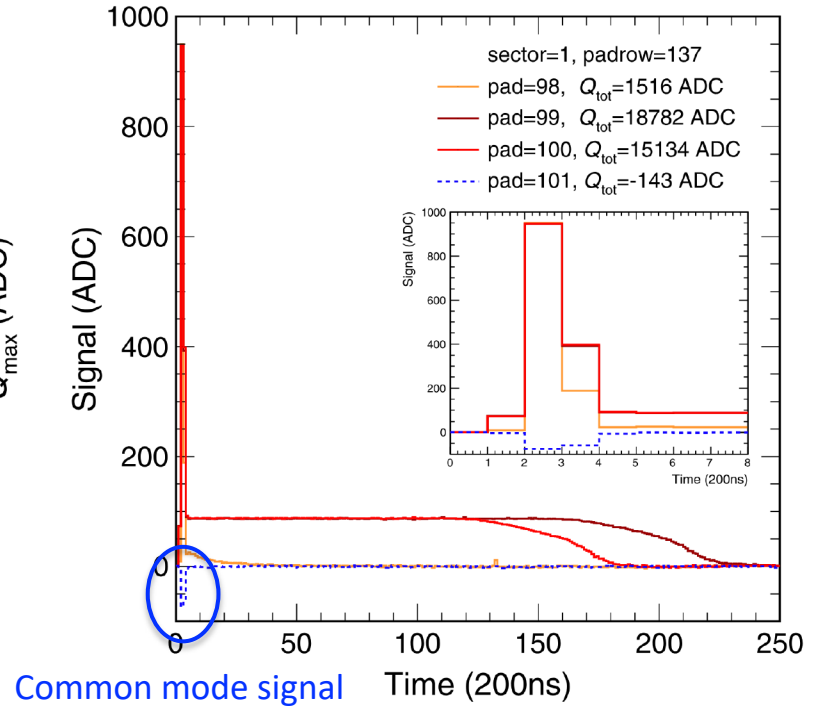
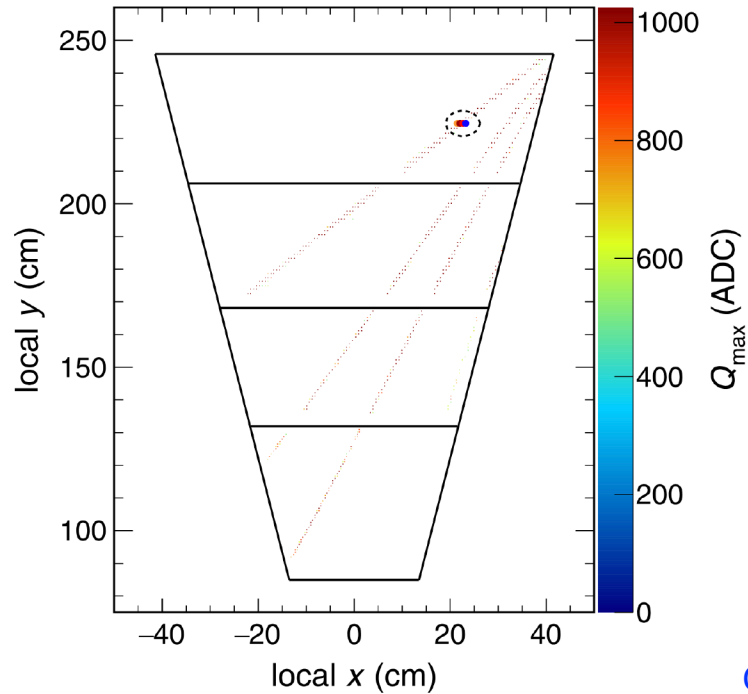
## 1) Hybrid detector approach

M. Arslanok, H. Caines and M. Ivanov, Phys. Rev. D 110, 032013 (2024)

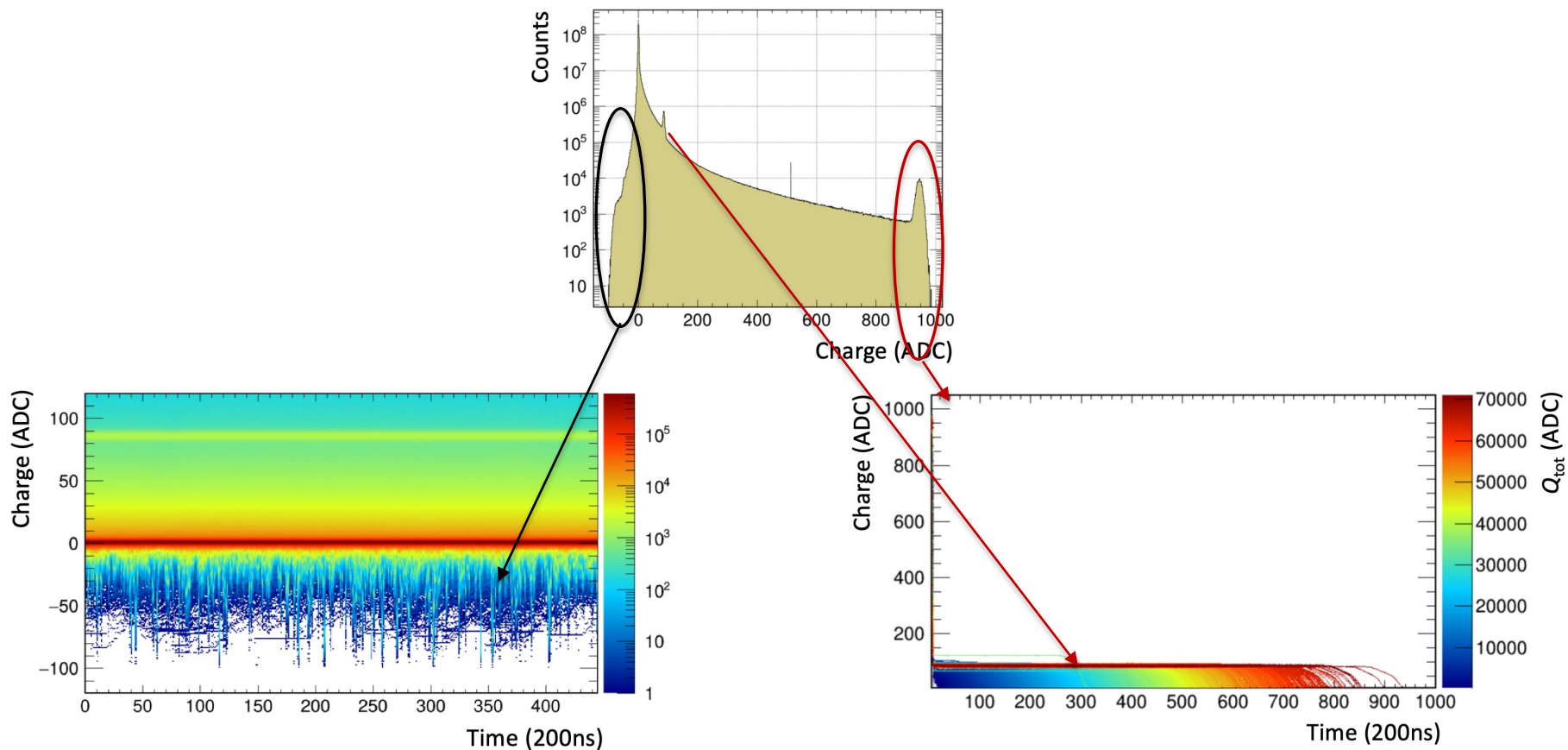
# Signal saturation: Limitation in the TPC?

M. Arslandok, H. Caines and M. Ivanov

Phys. Rev. D 110, 032013 (2024)

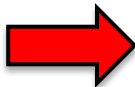
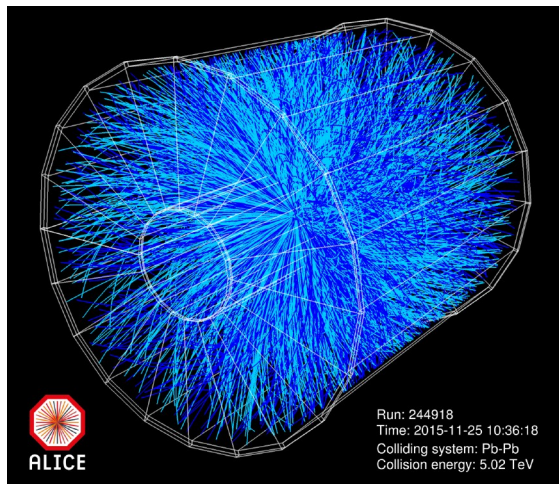


# Charge spectra within the dynamic range

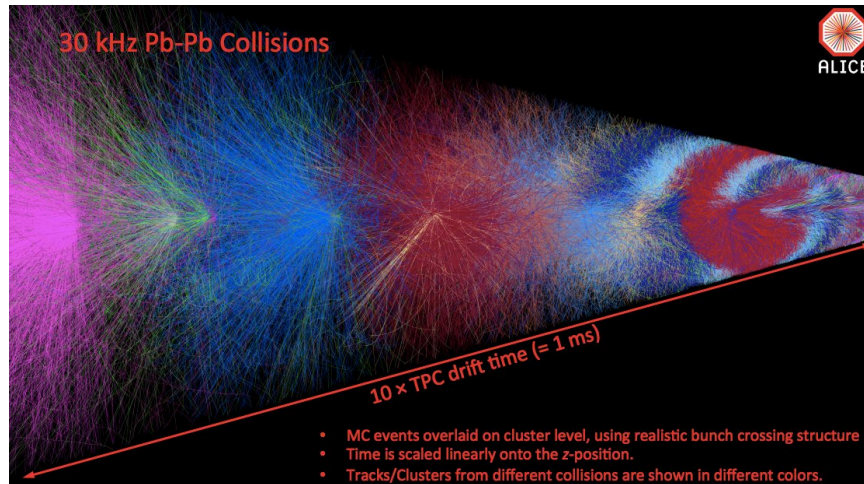


# Readout with GEM TPC

Triggered

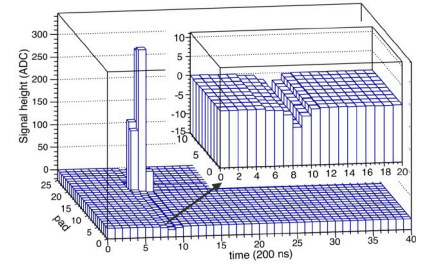
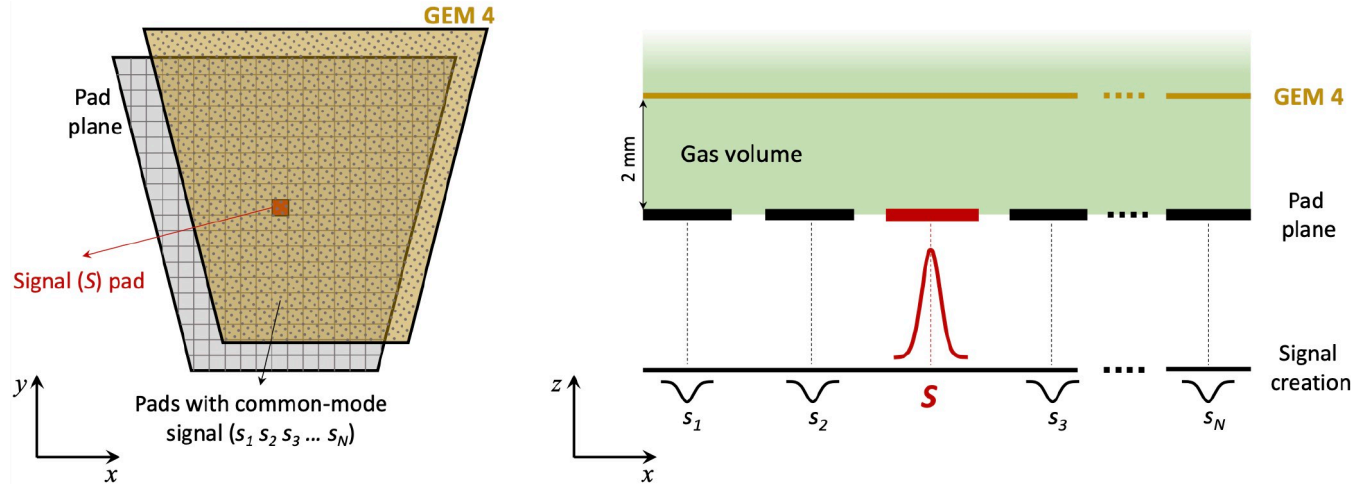


Continuous



- **Continuous readout**  
→ **~50 times more collisions** → **higher chance to SEE Monopoles**
- **Instead of events, “Time frames” (~15 ms) containing ~150 collisions**  
→ **~15000 samples in time direction** → **higher chance to DETECT Monopole signals**

# Unwanted Common-mode signal as the HIP trigger



$$\sum_{i=1}^{N_{\text{pads}}} |s_i| \approx 0.5 \times S$$

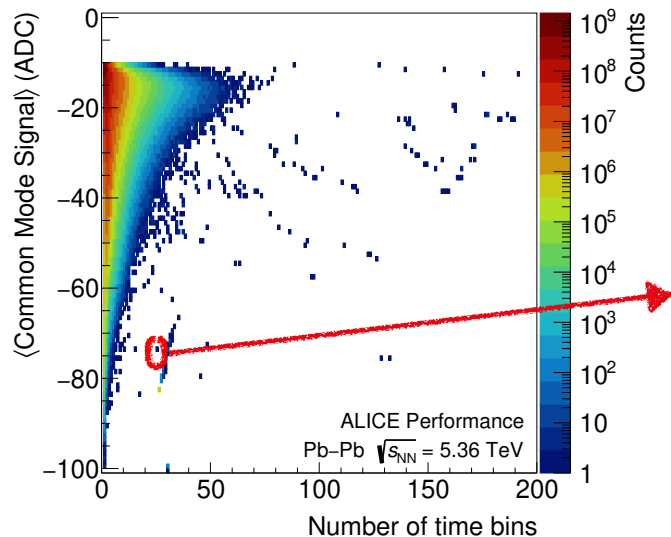
$$N_{\text{pads}} = 3000 - 5000$$

- **Common-mode (CM) signal:**
  - Negatively polarized signal below the baseline caused by capacitive coupling between **GEM4** electrode and **readout pads**
- **What makes CM so special?:**
  - CM signal is **several thousand times smaller** than the original signal
  - The CM signal is very fast and can therefore be detected before the TPC malfunctions due to a **hardware trip**



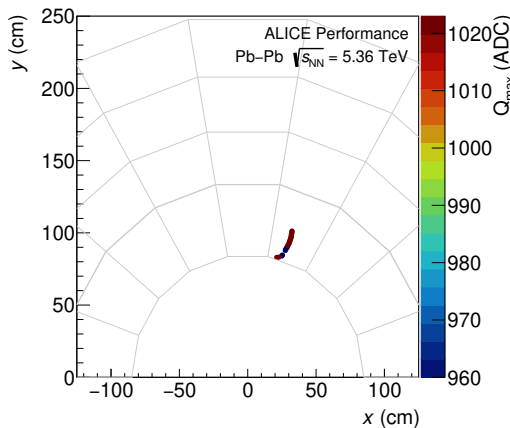
# First look at common-mode-triggered Pb–Pb 2026 data

Trigger the candidate in FPGA using the CM signal  $\Rightarrow$  Track it in the TPC  $\Rightarrow$  Propagate to the ITS

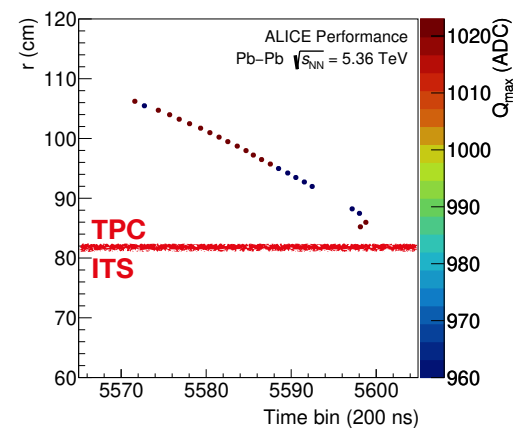


ALI-PERF-637742

Trigger candidate:  $dE/dx \sim 9000$  MIP



ALI-PERF-637747



ALI-PERF-637752

- Candidates with energy losses of up to 9000 MIPs equivalent have been identified
- Analysis is ongoing

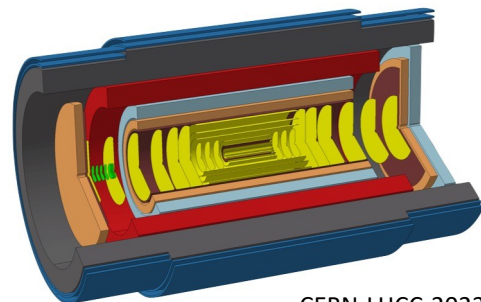
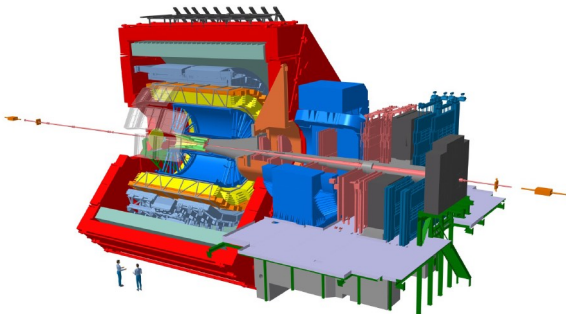
# Summary: Hybrid detector logic

## Novel Idea

- **Hardware trigger** based on the common-mode signal in the TPC to tag HIPs during online processing in the FPGA
  - Passive comp.: Save triggered raw data **online** without any compression for any HIP in any collision system, even for cosmics
    - **Even if the TPC (and/or ITS) is not stable**, there will be enough time to save the trigger decision and thus full raw data information
  - Active comp.: **Special offline track reconstruction** of the raw data
    - Mainly combined information from ITS and TPC, complemented by other subdetectors

## Advantages

- **Run 3 - Run 4 (2021-2033)**
  - Triggering via common-mode signal by the TPC
  - Small B field of 0.5 T
  - New GEM-based TPC → continuous readout
  - Significantly low material budget
- **Run 5 (2036-2041): ALICE 3**
  - TOF and/or ITS as the trigger detectors
  - TOF at  $r=19\text{cm}$  and ITS layers inside the beam pipe
  - Higher luminosities compare to Runs 3 and 4
  - Even lower material budget



CERN-LHCC-2022-009 ; LHCC-I-038

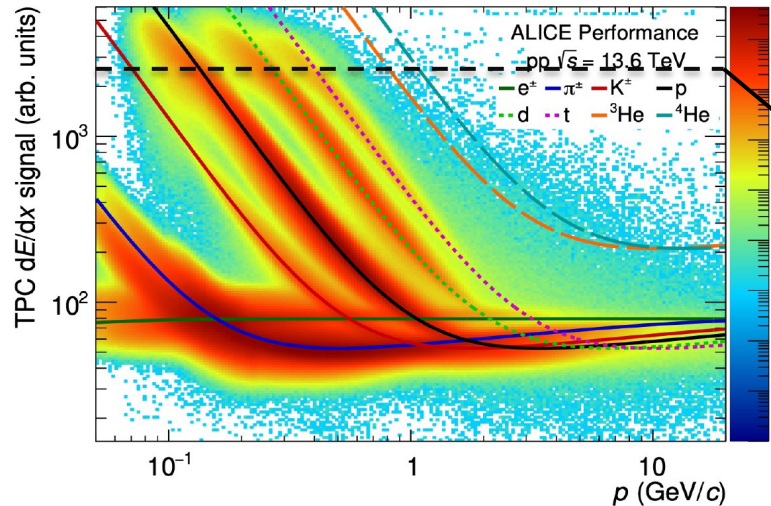
What is new?

2) Low-gain configuration of the TPC

# First look at the uncalibrated low gain data

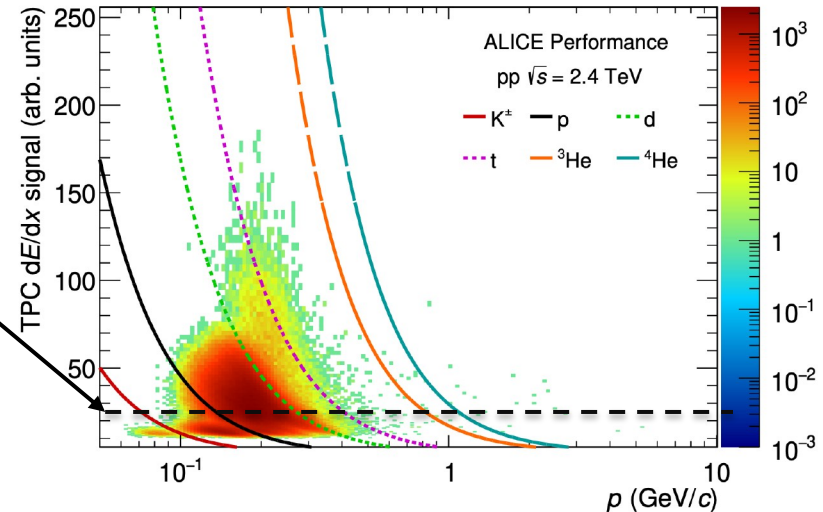
- We collected data at  $\sqrt{s} = 2.4$  and 13.6 TeV, pp using the low-gain configuration of the TPC
- Approximately 100 billion events were recorded during a dedicated 17-hour run
- Dirac magnetic monopole with  $g_D=1$  has an energy loss equivalent of 4700 MIPs
  - $n \cdot g_D \rightarrow n^2 \times 4700 \text{ MIP} \Rightarrow \mathbf{2.5M \text{ MIP corresponds to } 23 g_D}$

Nominal gain dynamic range ~1-50 MIPs  
(using CM signal it goes up to 25000 MIP)



ALI-PERF-630333

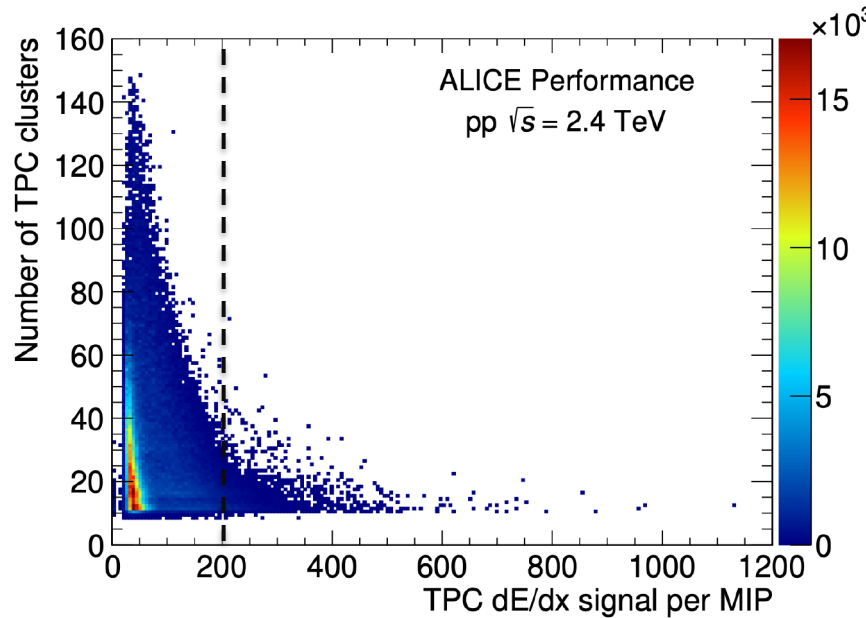
Low gain dynamic range ~20-5000 MIPs  
(using CM signal it goes up to 2.5M MIP)



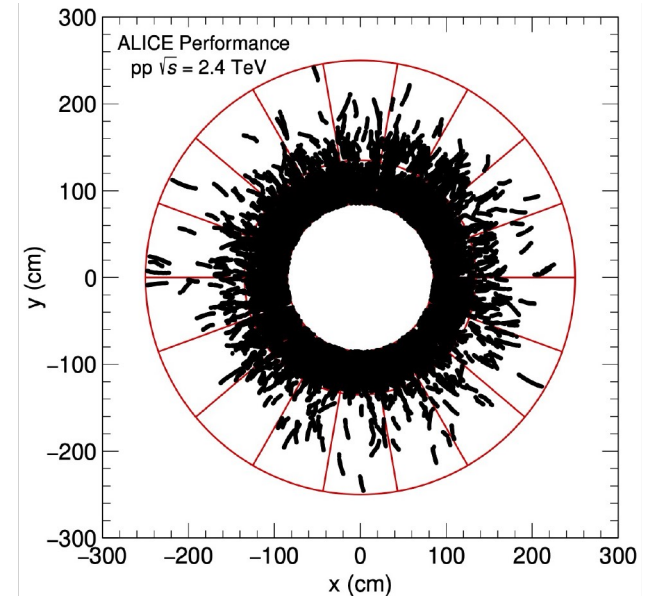
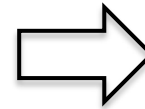
ALI-PERF-630338

# Highly ionizing particle search in the TPC

- Spallation product reconstruction using 4.3 million events → candidates up to 1150 MIP
- Candidates will be traced down to the ITS to match tracks with large clusters in the ITS

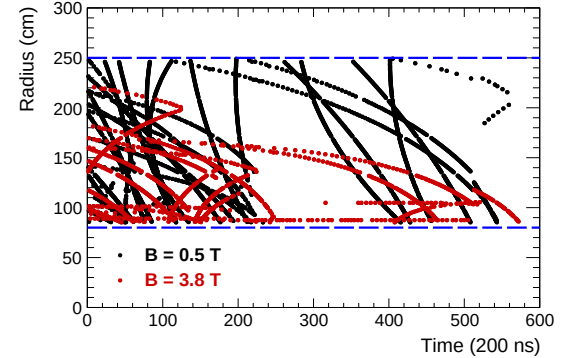
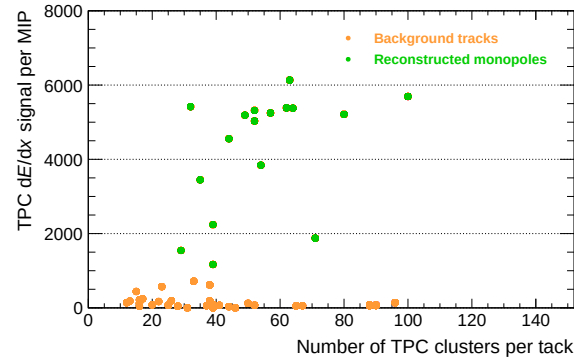
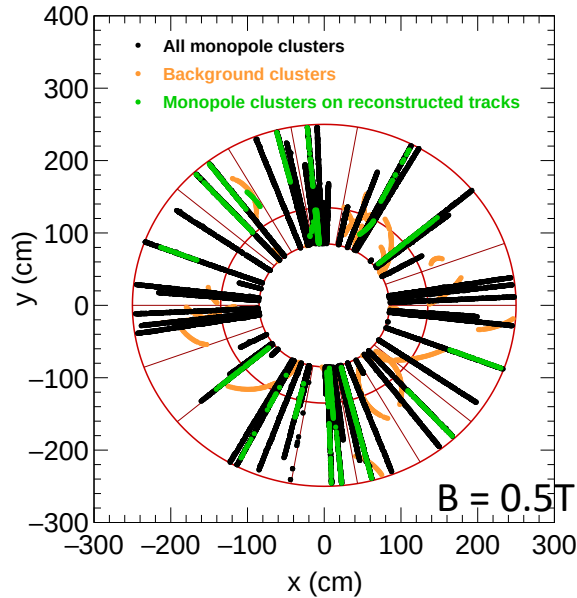


ALI-PERF-630348



ALI-PERF-630343

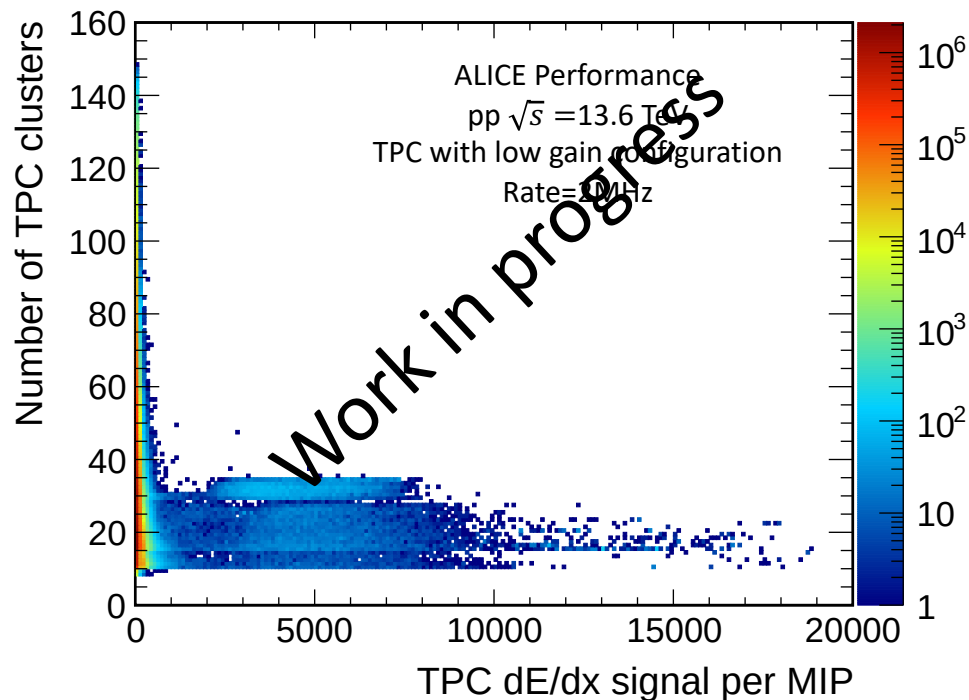
# Highly ionizing particle search in the TPC



- $g_D = 1$  monopoles from Schwinger production are within the detector's dynamic range.
- Tracks are found only partially due to parabolic trajectory
- Next steps:
  - Modification of the TPC clusterizer and tracking algorithms to reconstruct parabolic trajectories.
  - Study of the ITS response to highly ionizing particles



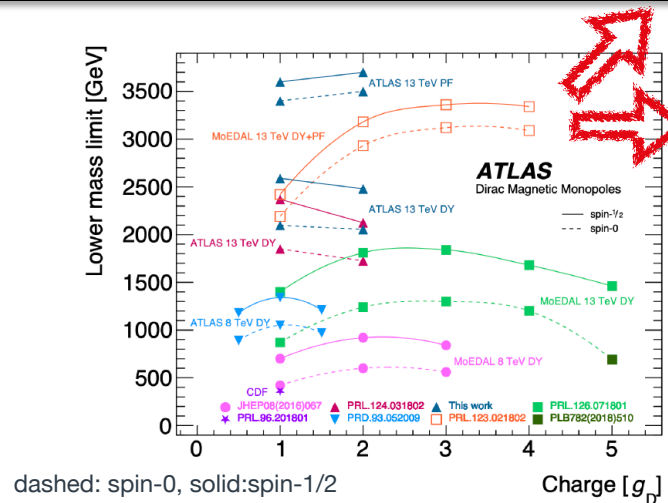
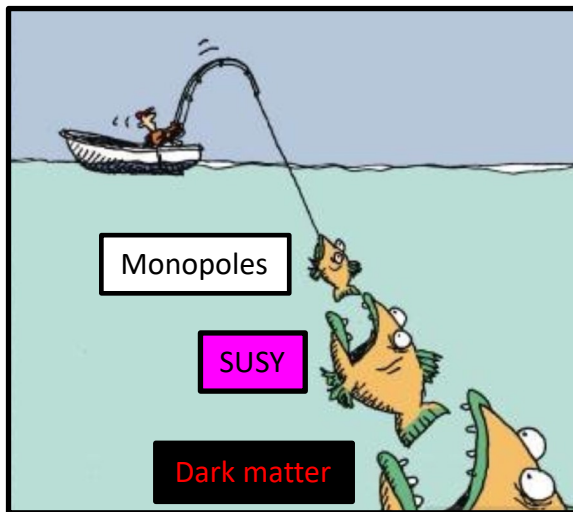
# First results from special reconstruction of low-TPC-gain data



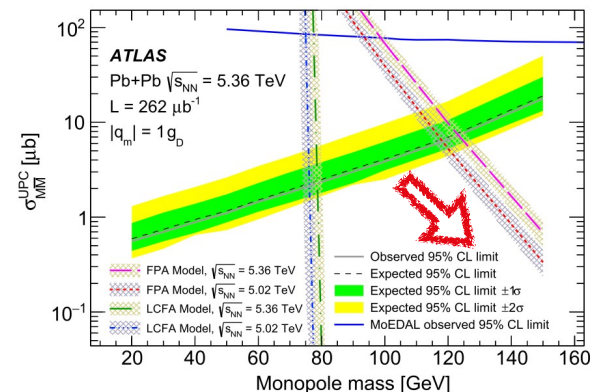
- Candidates up to 20,000 MIPs, mainly low- $p_T$  carbon nuclei ( $Z=6$ )
- 0.05% of tracks have signals above 2,000 MIPs

# Summary: HIP search in ALICE

- Trigger for any HIP in any collision system
- If approved, run with the low-gain mode of the TPC



dashed: spin-0, solid: spin-1/2



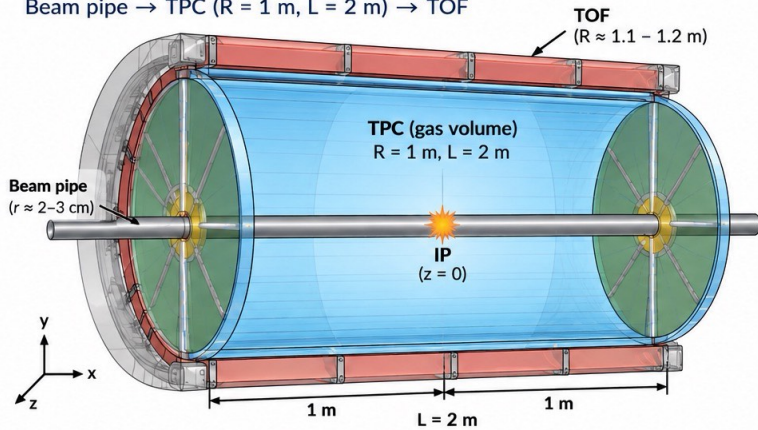
Nature (London) 602, 63 (2022)  
J. Phys. Conf. Ser. 2375, 012002 (2022)

# Dream TPC for MM searches at the ALHC

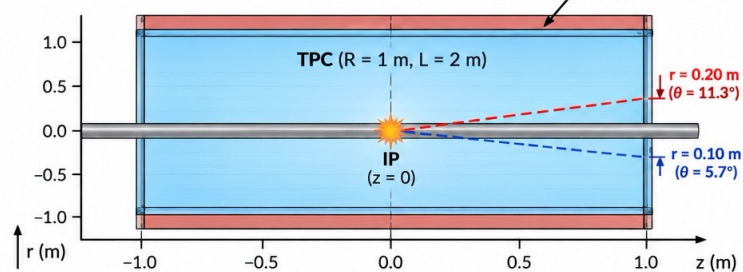
Chatgpt + I

## Simplified ALICE TPC geometry (collision at center)

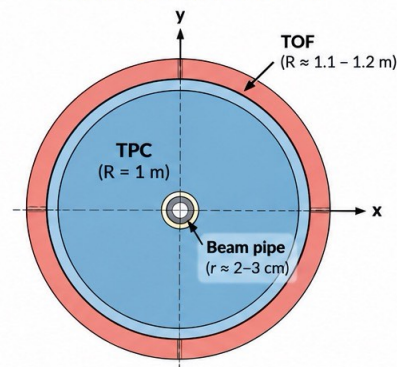
Beam pipe  $\rightarrow$  TPC ( $R = 1$  m,  $L = 2$  m)  $\rightarrow$  TOF



## Longitudinal (r-z) view (collision at center)



## Transverse (x-y) view (z = 0)



## $\eta$ acceptance from minimum transverse length

For a track from the origin reaching transverse radius  $r_{\min}$  at the endcaps ( $|z| = L/2$ ):

$$\tan \theta_{\min} = \frac{r_{\min}}{L/2}, \quad \eta_{\max} = -\ln \left[ \tan \left( \frac{\theta_{\min}}{2} \right) \right]$$

Results for  $L = 2$  m ( $L/2 = 1.0$  m)

| Minimum transverse length $r_{\min}$ | $\theta_{\min}$ | $\eta_{\max}$ |
|--------------------------------------|-----------------|---------------|
| 0.20 m (20 cm)                       | 11.3°           | 2.31          |
| 0.10 m (10 cm)                       | 5.7°            | 3.13          |

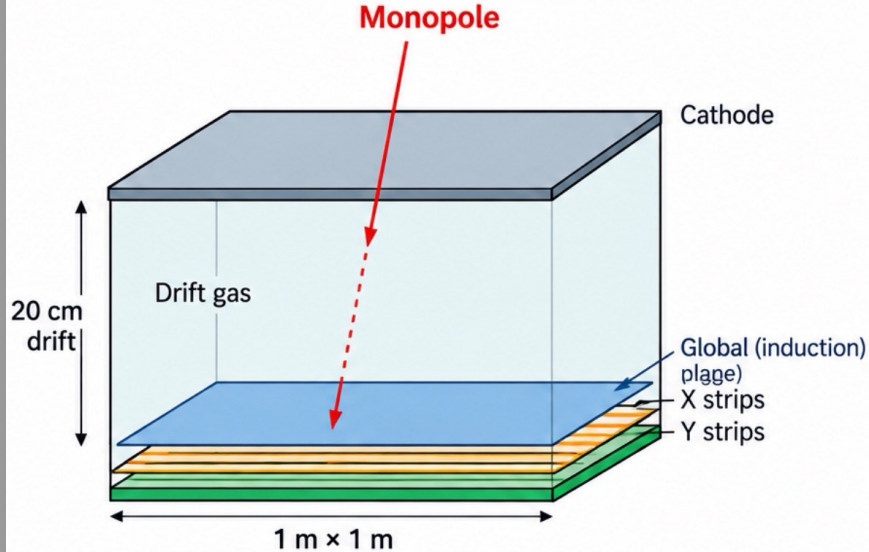
With a minimum transverse length of 10 cm:

$$|\eta| \lesssim 3.13$$

+  
Low gain  
+  
Large dynamic range

# Dream TPC for MM searches with cosmic rays

Chatgpt + I



2000 tiles ( $1 \text{ m}^2$  each)  $\rightarrow 2000 \text{ m}^2$   
41 channels per tile (20 X + 20 Y + 1 global)  
Total channels: 82,000

## Estimated cost for $2000 \text{ m}^2$ (no amplification)

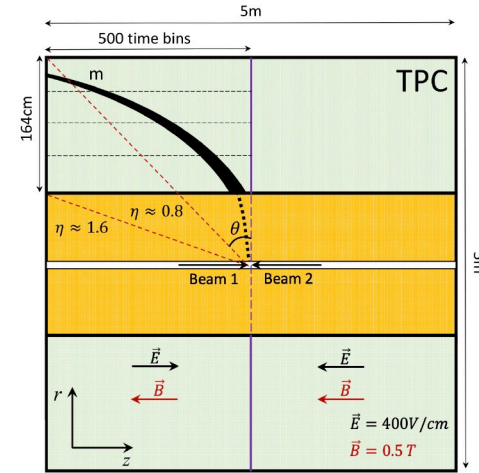
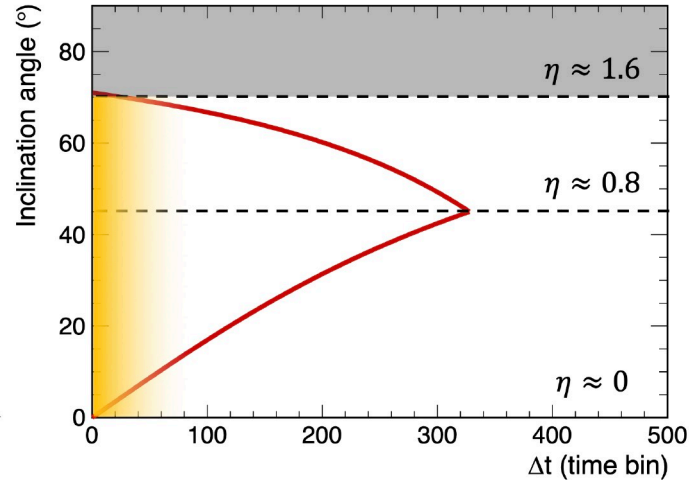
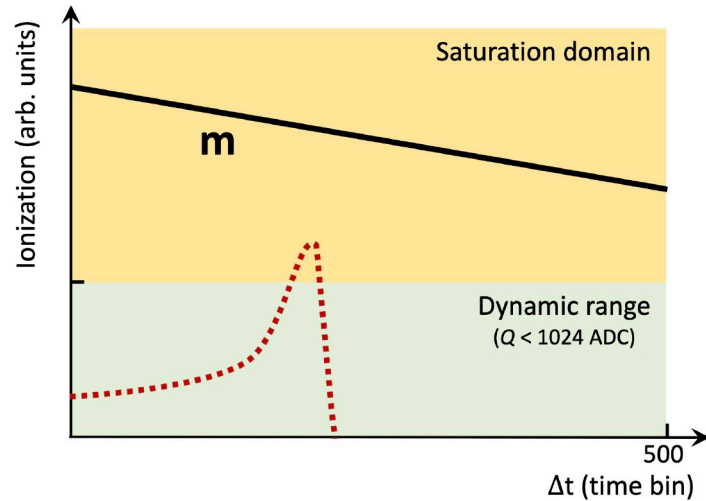
| Item                      | Cost (M€)  |
|---------------------------|------------|
| Cathodes + field cages    | 0.4 – 0.8  |
| Induction (global) planes | 0.2 – 0.4  |
| X/Y strip readout planes  | 0.4 – 0.8  |
| Front-end electronics     | 0.2 – 0.6  |
| Trigger electronics       | 0.05 – 0.1 |
| DAQ                       | 0.2 – 0.4  |
| Gas system                | 0.1 – 0.3  |
| HV/LV and services        | 0.1 – 0.3  |
| Mechanics and enclosures  | 0.4 – 0.8  |
| Assembly, QA, spares      | 0.2 – 0.5  |

**Total ( $2000 \text{ m}^2$ )      ~ 2.3 – 5.1 M€**

**Target (aggressive): ~ 3 M€**

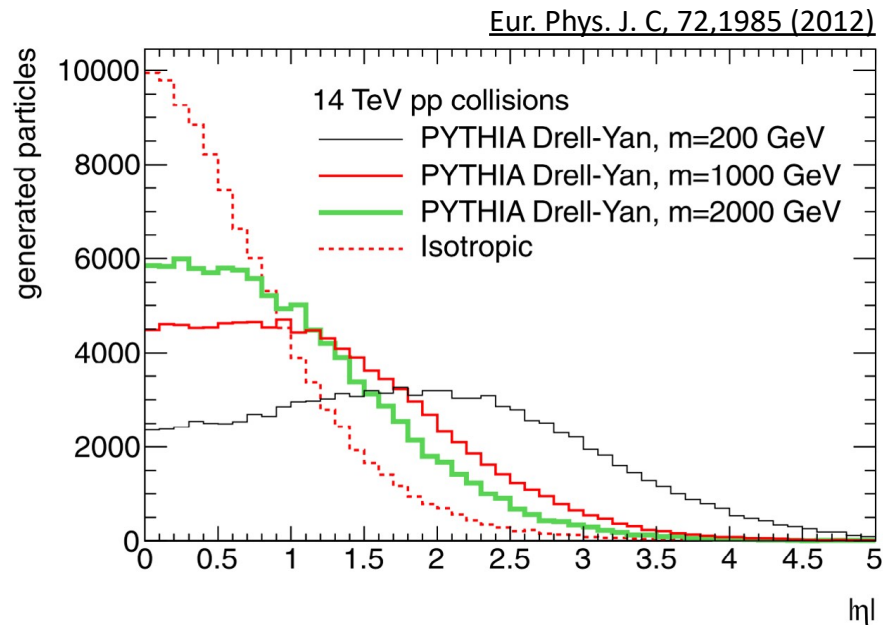
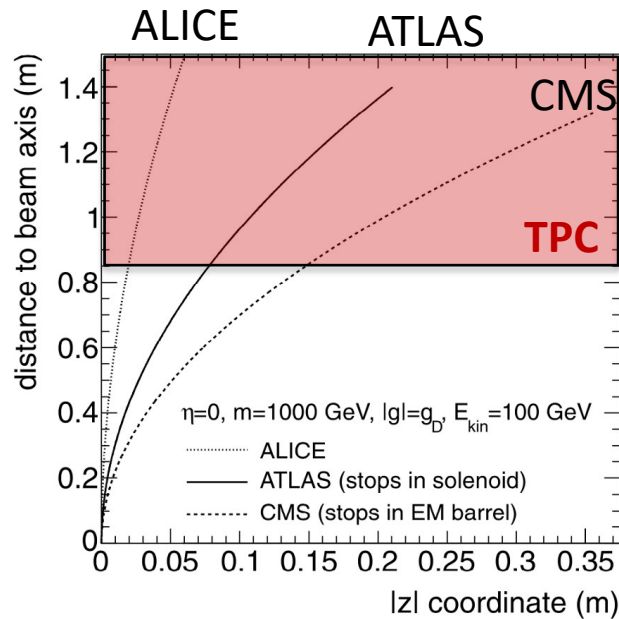
BACKUP

# How does a monopole track look like in the TPC?



- Main observable is the time spent in the active zone of the TPC
- Monopoles will be visible up to about  $|\eta| < 1.5$

# Advantage of low B field

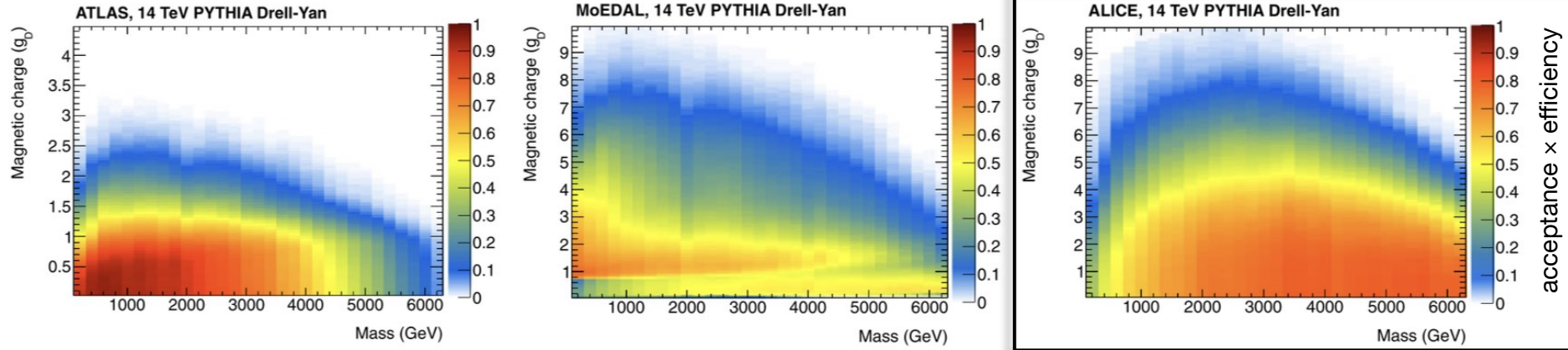


➤ Large kinematic coverage at midrapidity



# Advantage of TPC as the MM tracker

Eur. Phys. J. C, 72,1985 (2012)

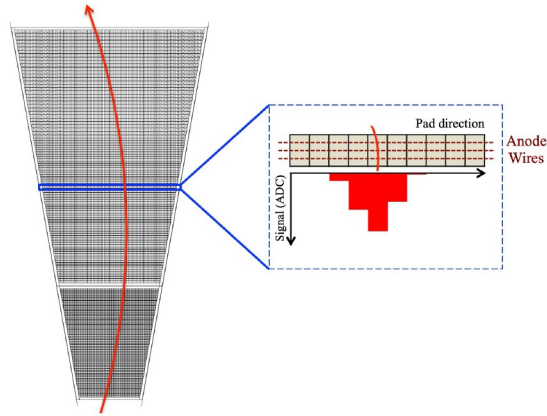


## ➤ Assumptions in the paper vs current setup:

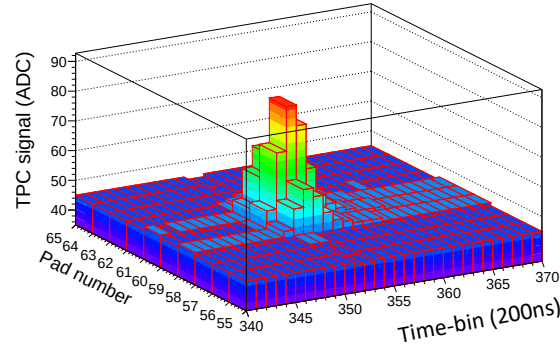
- ✓ Identification of HIPs in the TPC → possible with our current approach
- ✓  $|\eta| < 0.8$  → will be extended to  $|\eta| < 1.5$
- ✓ Material budget of Run 1 setup → much lower in Run 3-5

# Conventional PID?

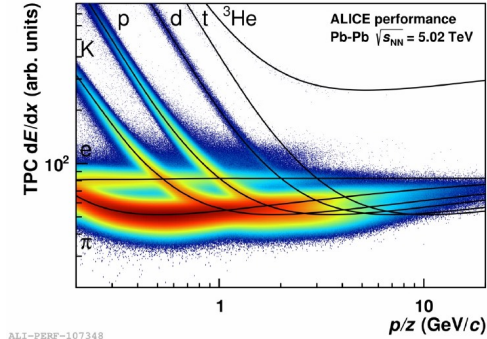
Cluster creation on a single row out of 152



A typical cluster: "hit point" in TPC



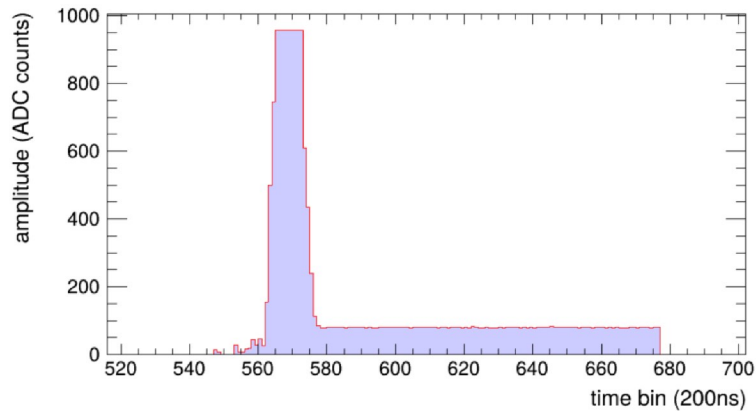
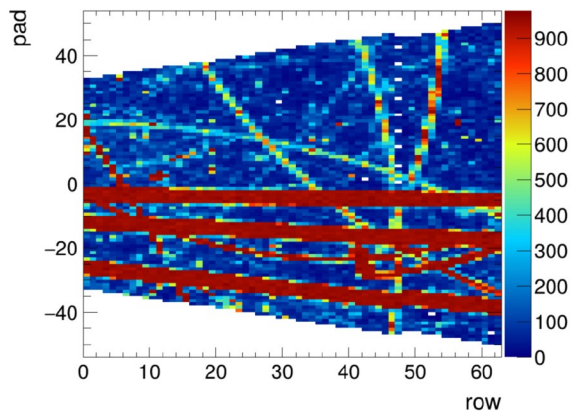
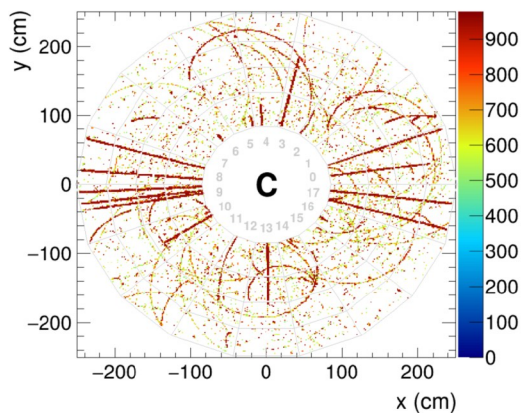
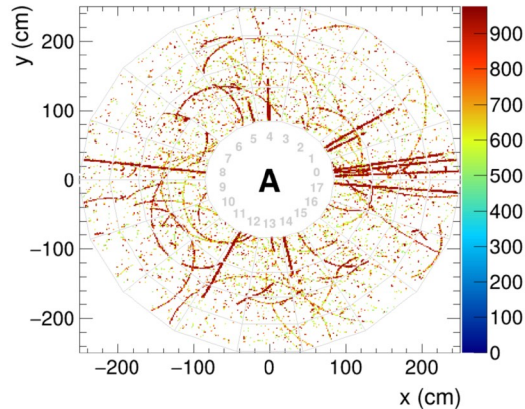
Particle identification



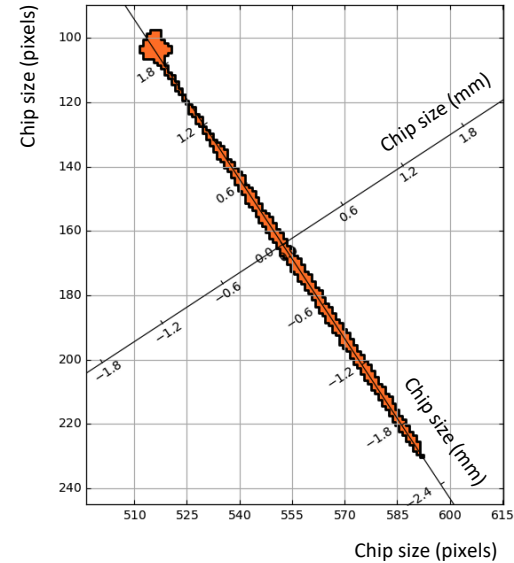
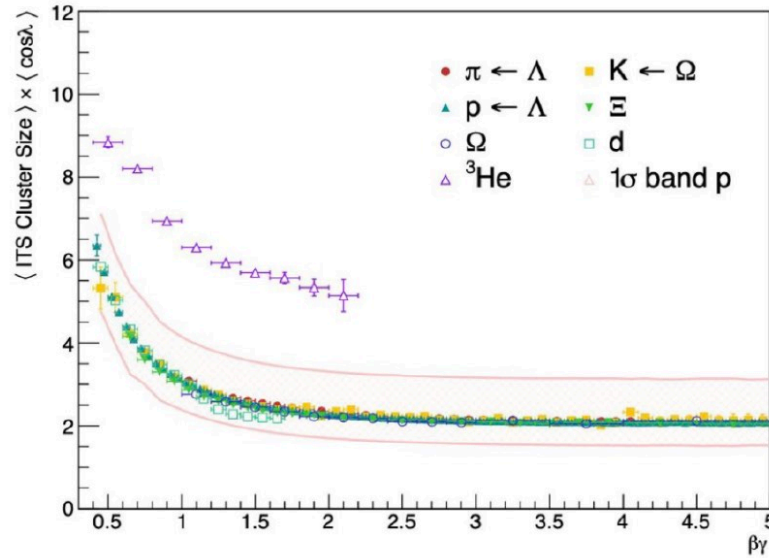
- Max charge that TPC measures is  $\sim 1000$  ADC  
 $\Rightarrow 1\text{MIP} \sim 20$  ADC  $\rightarrow$  Monopole candidate with 4700 MIP  $\gg 1000$  ADC  
 $\Rightarrow$  **Conventional PID with current reconstruction will fail**

# First magnetic monopole simulations at nominal TPC gain

The cluster finder fails at nominal gain due to signal saturation and excessively wide clusters.

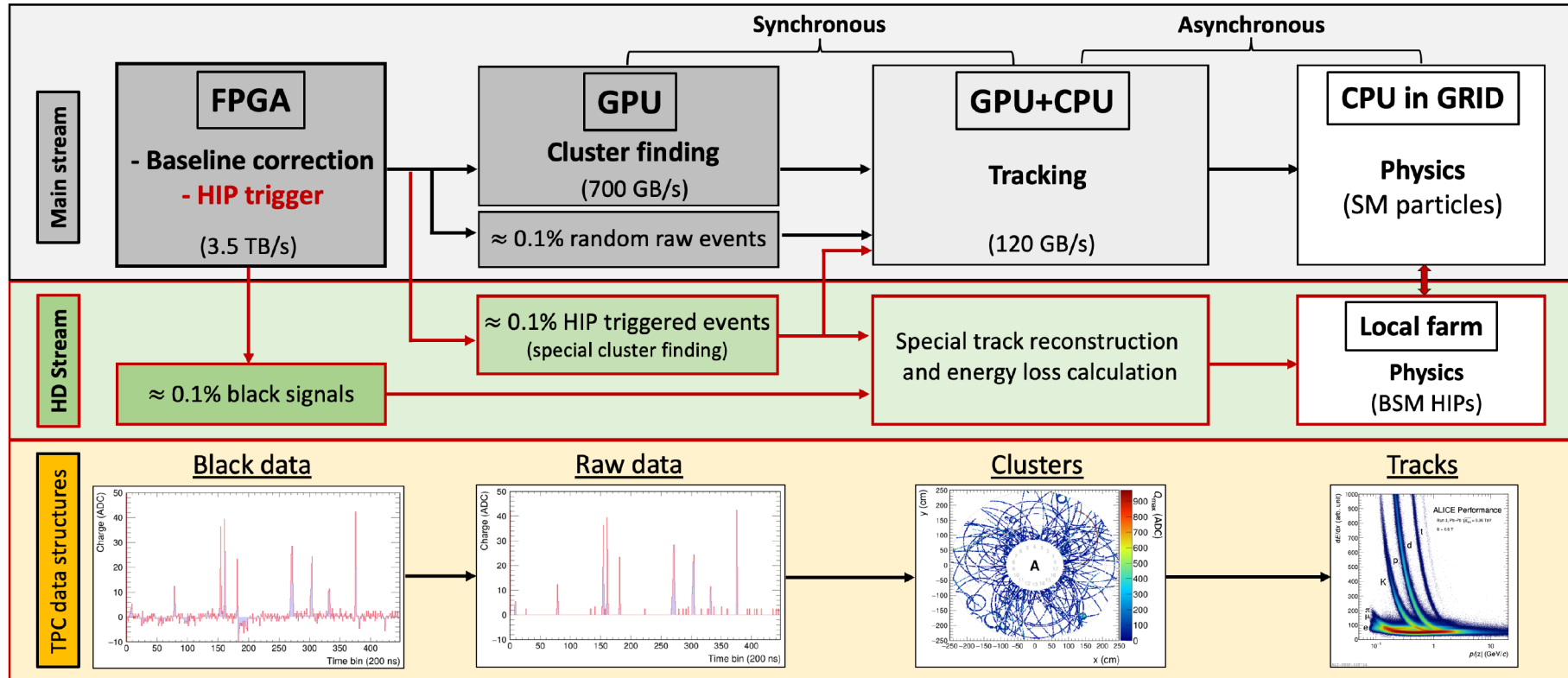


# Propagation to ITS



- Cluster sizes up to **an order of magnitude above SM background** observed in raw data
- These clusters serve as a **software trigger**
- TPC signal can be correlated **even if ITS chips reboot**

# Hybrid detector approach: Data stream



# Limits of the TPC?

- 1) “Critical charge density  $Q_{\text{critical}}$  which leads to a discharge in a GEM hole for  $\text{NeCO}_2$  is  $(7.3 \pm 0.9) \times 10^6$ ”
- 2) “In **multi-GEM systems** the total gain can be shared between several foils building a stack, and thus increasing its stability against electrical discharges.”

[P. Gasik et. al. https://doi.org/10.1016/j.nima.2017.07.042](https://doi.org/10.1016/j.nima.2017.07.042)

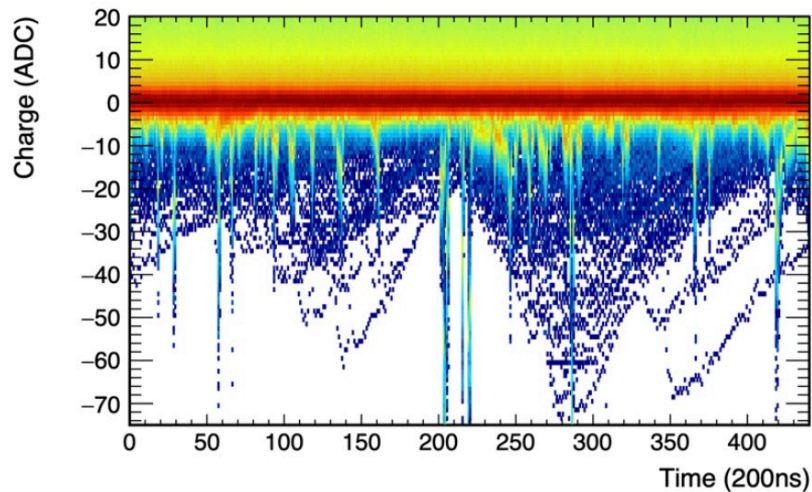
- Number of electrons per hole in case of Monopole
  - ⇒  $4700 \text{ (MIP)} \times 40 \text{ (} N_{\text{El}}/\text{MIP)} \times 2000 \text{ (gain)}$
  - ⇒  $3 \times 10^8$  electrons per cm ending on pad plane  
(Diffusion - 2.5 mm & flat diffusion assumption → electrons in  $\pm 1$  sigma)
  - ⇒  $3 \times (10^8) \times (140 \text{ (pitch)}/5000 \text{ (diffusion)}) \times (140 \text{ (pitch)}/10000 \text{ (pad length)})$
  - ⇒  $1 \times (10^5)$  electrons per hole

**Even if the TPC is not stable, there will be enough time to see the CM signal**

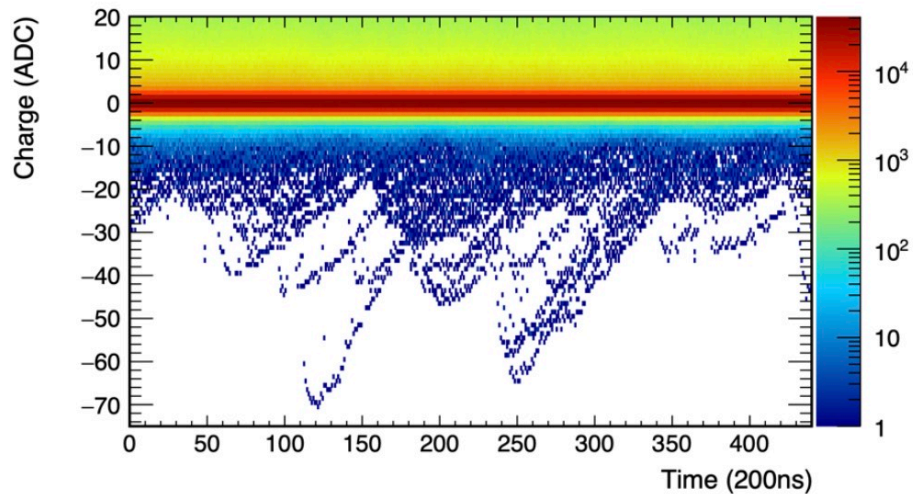


# Common-mode signal → Curse or blessing?

Before CM correction

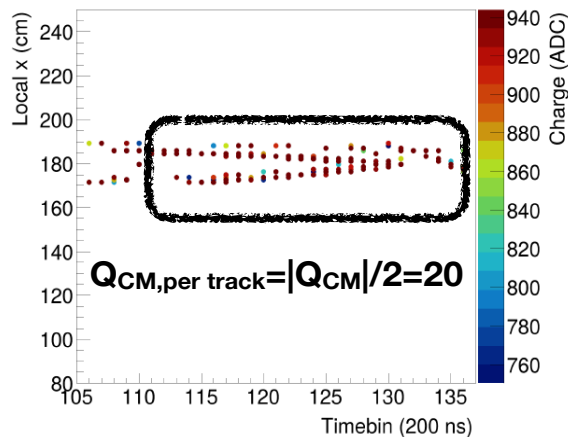
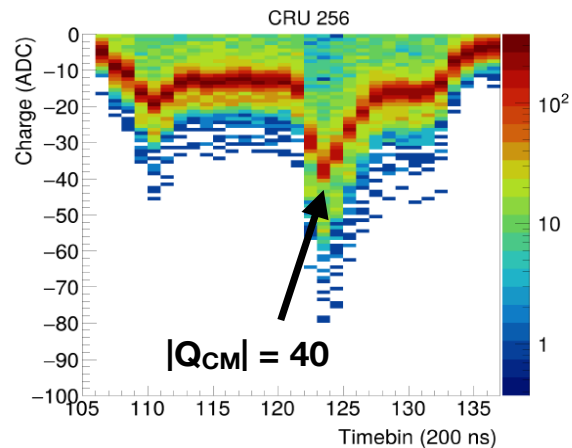


After CM correction

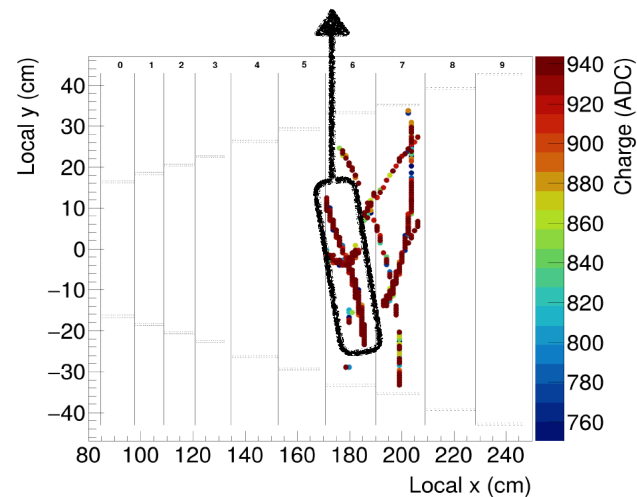




# Spallation product example (1)

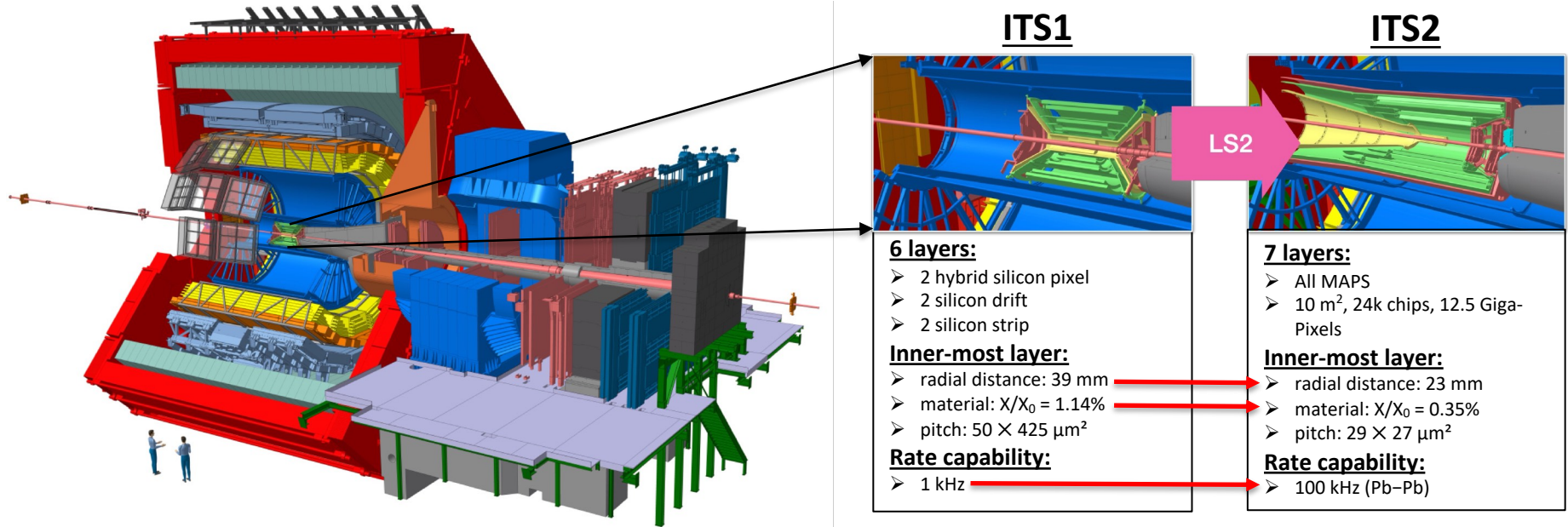


$$Q_{max,HIP} = [(20 \times 3200)/30] \times (1/0.5) \\ = 4267 \text{ ADC} = 214 \text{ MIPs}$$



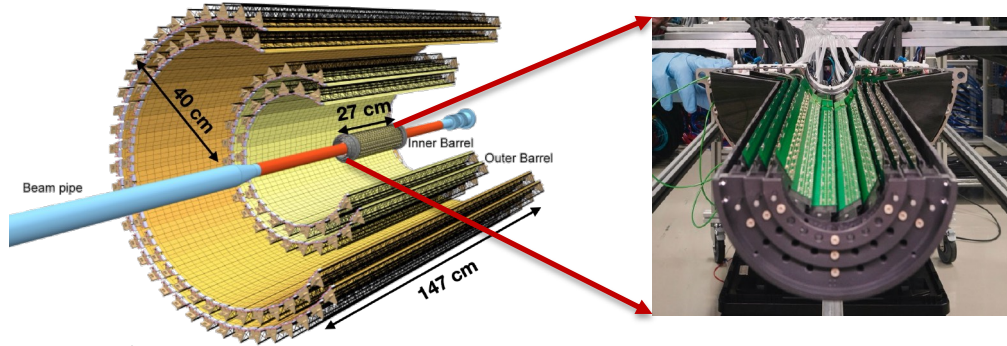
Such short tracks are rejected  
in the current framework

# ITS2 in Run 3



# ITS3 in Run 4

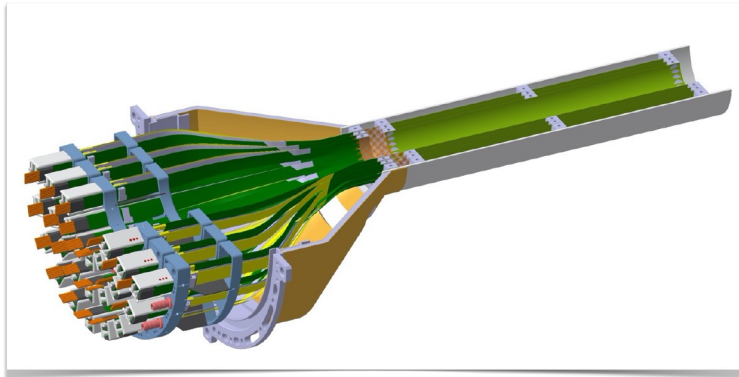
ITS2



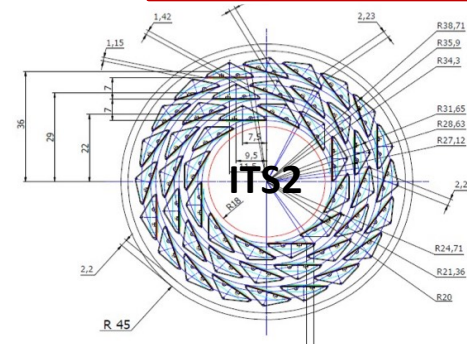
Get closer to the IP  
and  
reduce the material

Ultra-thin, wafer-scale, bent MAPS around the beam pipe

ITS3



**Extremely low material budget**  
**Homogeneous material distribution**



Material:  $X/X_0 = 0.35\%$

$X/X_0 = 0.1\%$

