# A New Hydrogen-Filled Cherenkov Detector for Kaon Tagging at the NA62 Experiment at CERN

**16th Pisa Meeting on Advanced Detectors**
**La Biodola, Isola d'Elba**

Summary of JINST 19 (2024) 05, P05005

**Chandler Kenworthy, on behalf of the NA62 Collaboration**
**ckenwort@cern.ch**

# NA62 at CERN

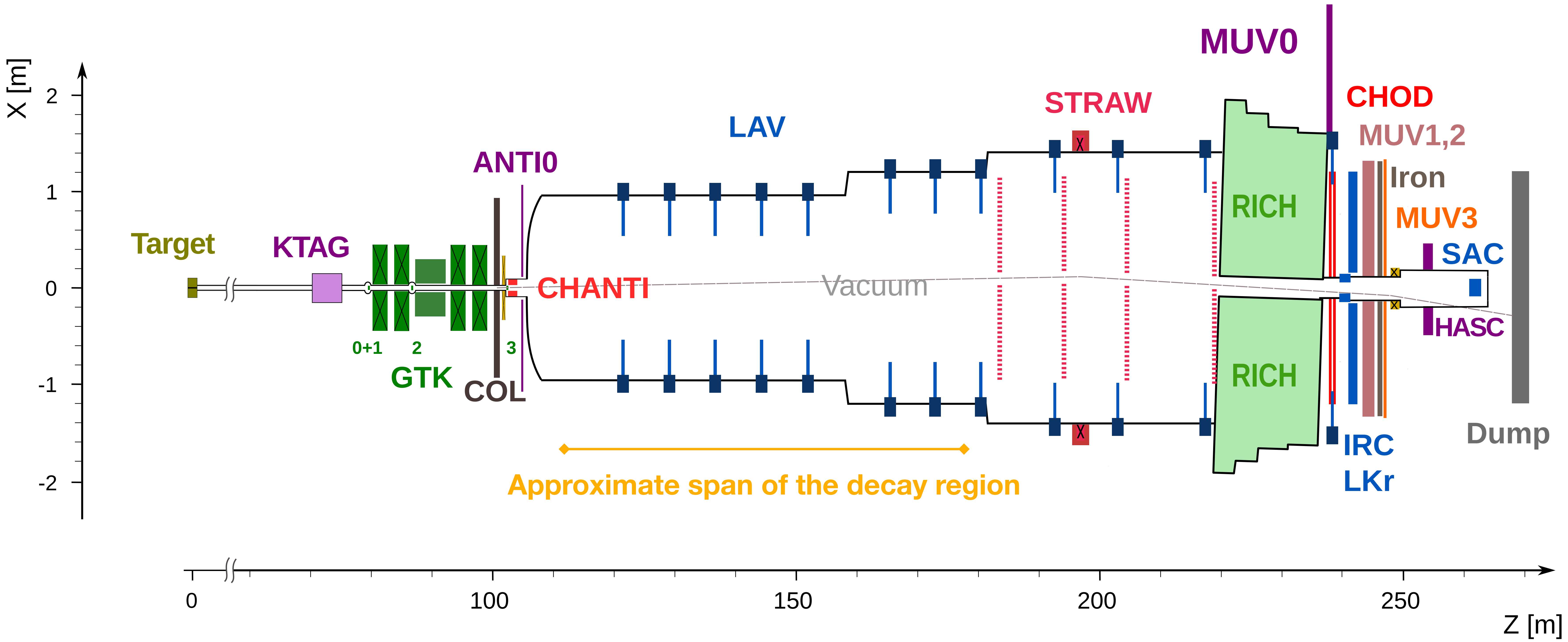
- Fixed target experiment in the CERN North Area (JINST 12.05 (2017), P05025).
- Goal: measure very-rare $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu})$ to a precision of $\mathcal{O}(10\%)$. SM expectation is $(8.4 \pm 1.0) \times 10^{-11}$ (JHEP 11 (2015) 033).
- Result from 2016-2018 data: $(10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9|_{syst}) \times 10^{-11}$ with a $3.4\sigma$ significance (JHEP 06 (2021), p. 093).
- Broad physics programme includes: exotic searches, rare kaon decay measurements and searches for forbidden decays.

# The Detector

- 400 GeV/c protons from the SPS directed onto a beryllium target. Secondary 75 GeV/c charged beam: 6% $K^+$, 70% $\pi^+$ and 23% protons.

- Upstream of decay region $K^+$ tagged by **KTAG** and tracked through **GTK** (silicon pixel detector).

- Downstream of decay region: **STRAW** (charged track spectrometer), PID (**RICH**, **MUVs**, **LKr**), **CHOD** (hodoscope), photon vetoes (**LAV**, **SAC**, **IRC**) and other veto detectors (**MUV0**, **HASC**).



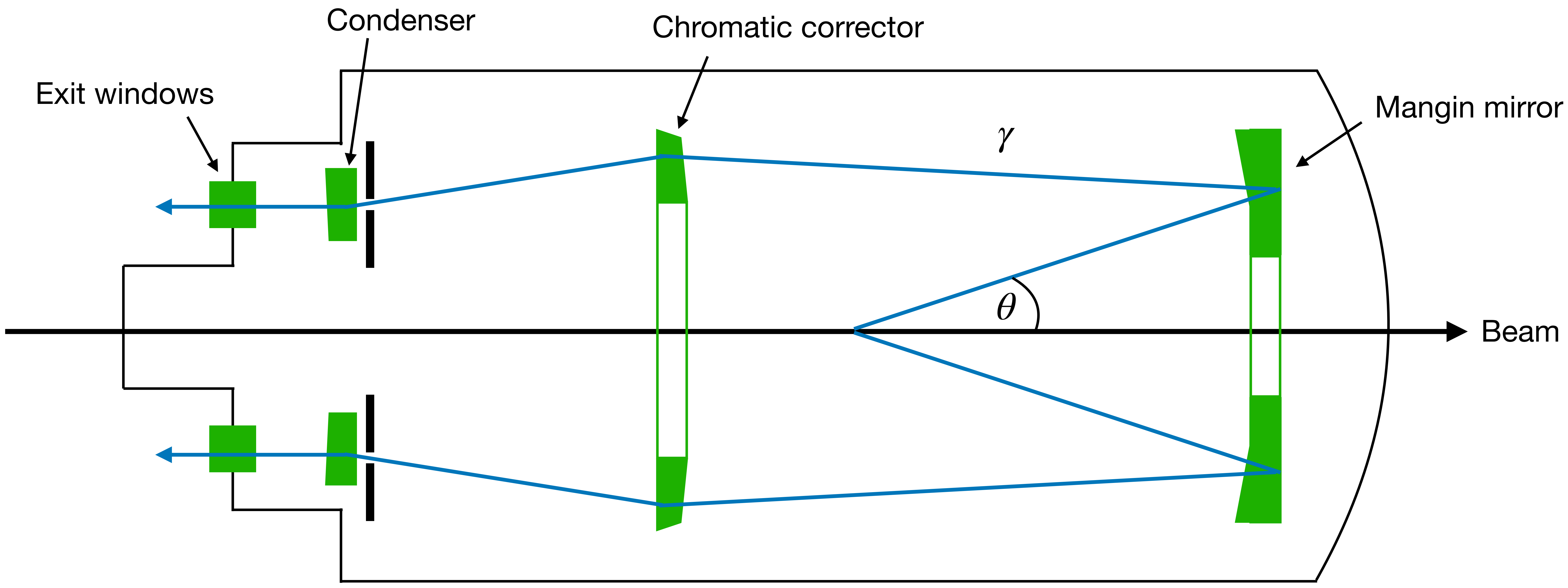
# Kaon Identification

- $K^+$ must be “tagged” within the unseparated secondary hadron beam (~600 MHz).
- Several requirements:
  1. Precise timing - better than 100 ps resolution.
  2. Sustain a $K^+$ rate of 36 MHz.
  3. Tagging efficiency $>$95%.
  4. Misidentification probability between $\pi^+$ and $K^+$ of less than $10^{-4}$.
- This is achieved using a differential Cherenkov counter with achromatic ring focus (CEDAR) coupled to a bespoke photon detection and readout system (KTAG).

# The CEDAR

- $1.1\ \mathrm{m}^3$ gas volume with the pressure tuned to select $K^+$.
- Adjustable aperture between 0-20 mm.
- Internal optical axis precisely aligned with the beam axis.
- Original design used 8 PMTs, one at each exit window, does not work at NA62. PMTs cannot sustain high-rate environment.

$$\cos\theta = \frac{1}{n\beta}$$



# The KTAG

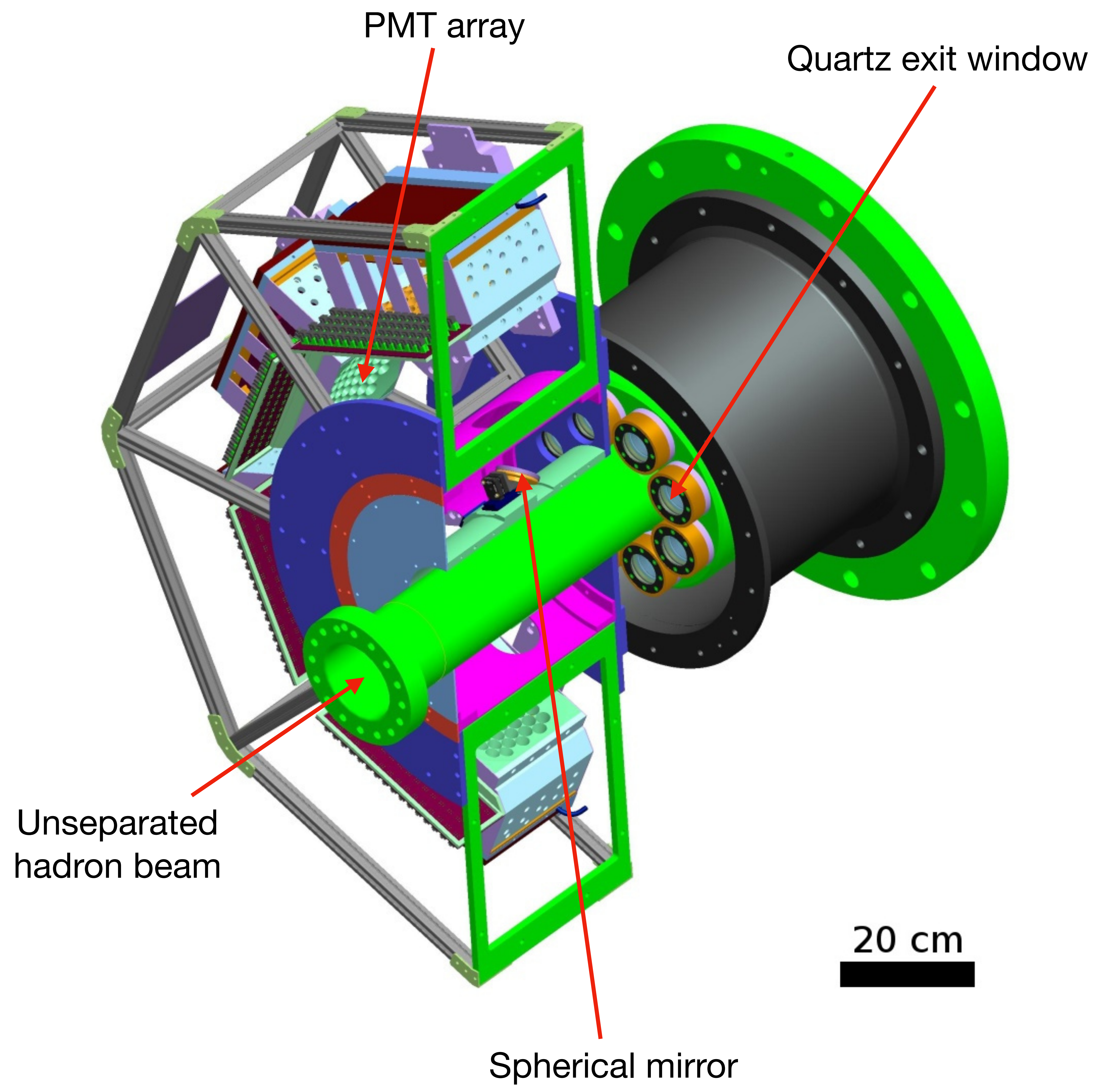



Figure reproduced from
(Nucl. Instrum. Meth. A. 2015; 801: 86-94)

- New photon detector, front-end and read-out systems.

- KTAG consists of octants, each contains:-

1. Focusing lens mounted on quartz exit window focuses light onto a spherical mirror.

2. Spherical mirror reflects light radially onto an array of 48 PMTs (Hamamatsu, 32 R9880-110 + 16 R7400).

- Using $N_2$ the KTAG achieved a time resolution of 70 ps with an average of 19 photons per $K^+$.

- $K^+$ tagged by requiring coincident light in at least 5 sectors.

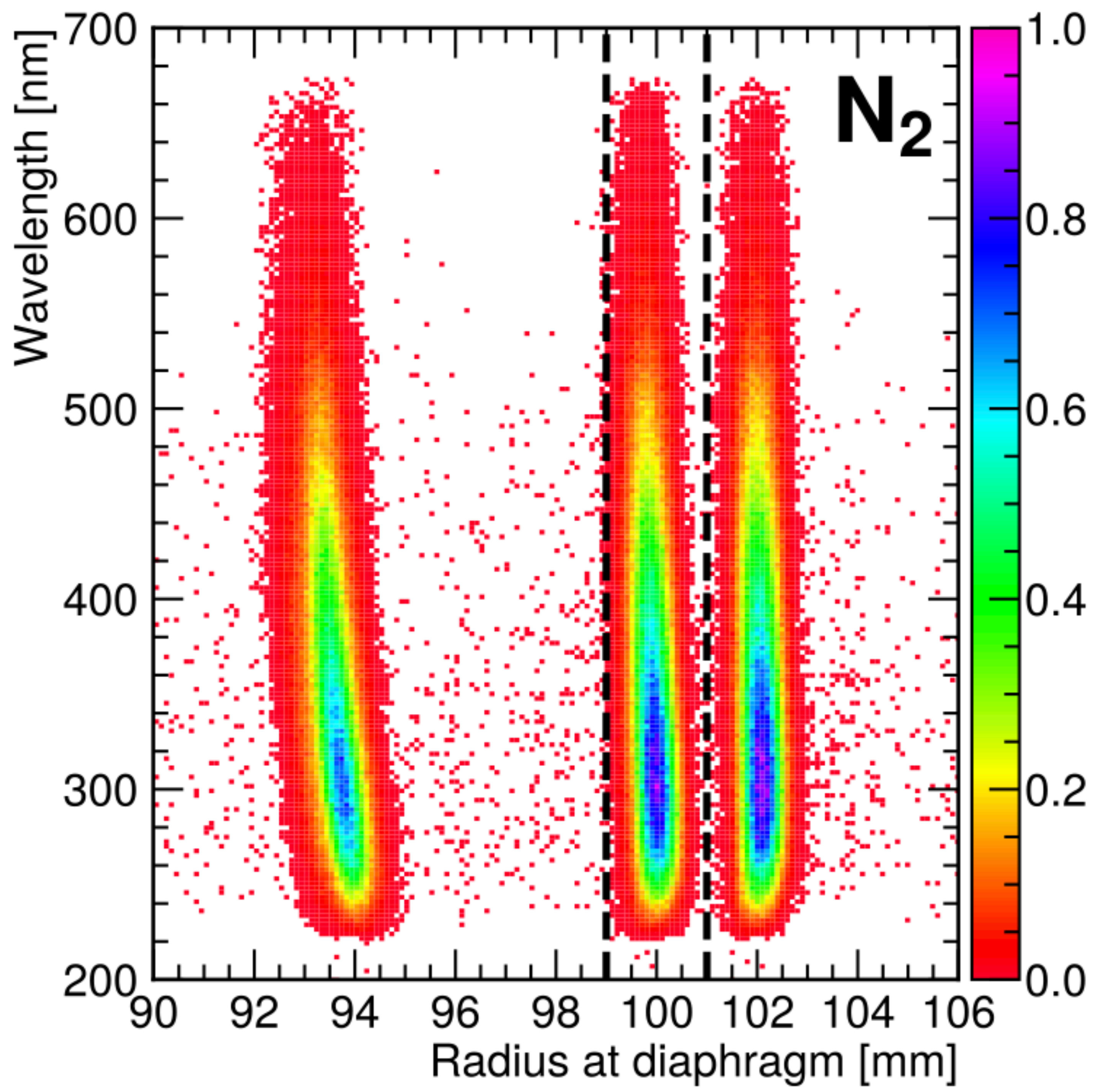
# Motivation for CEDAR-H

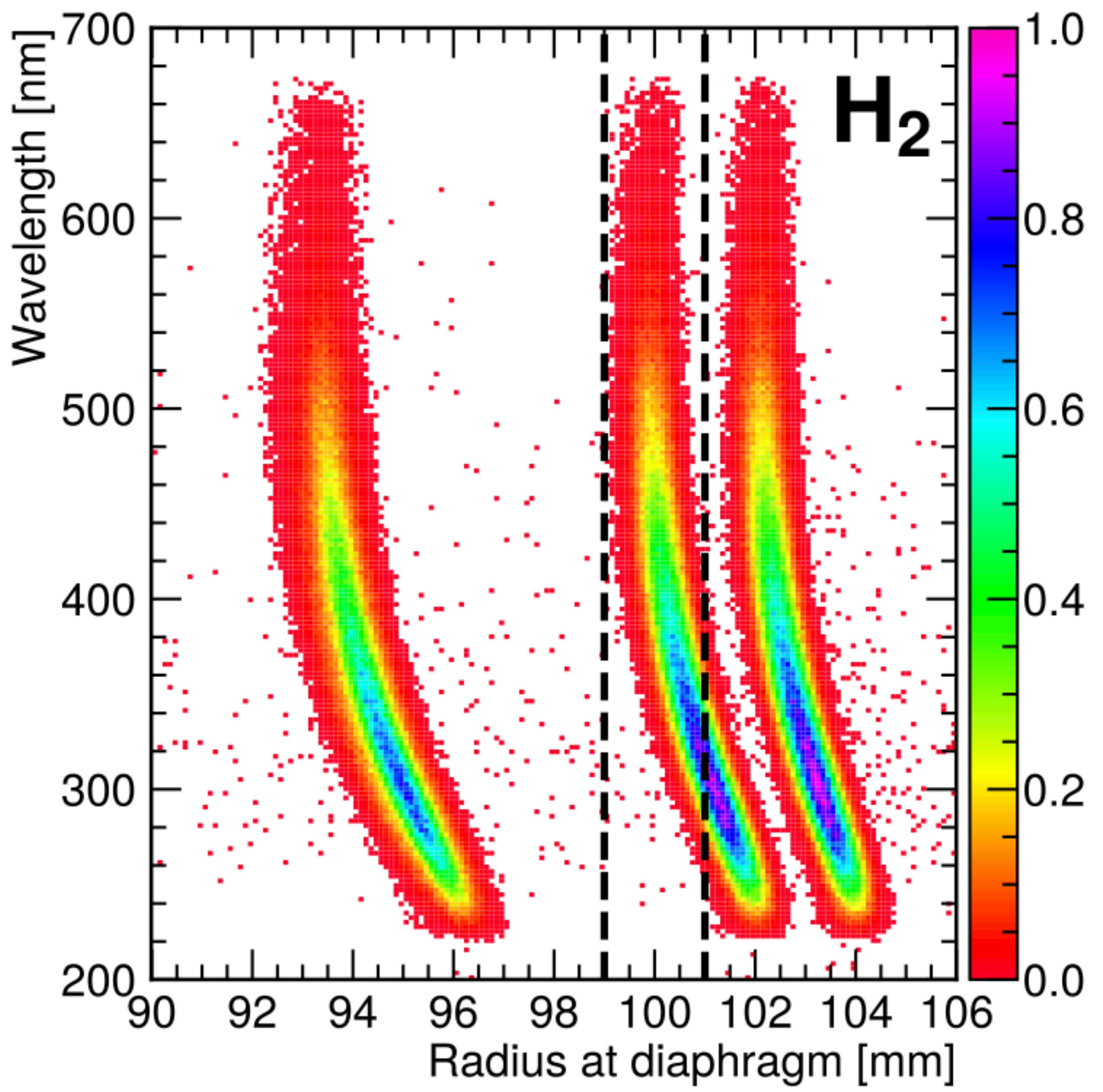
- CEDAR-W filled with $N_2$ at 1.7 bar is the biggest contributor to material in the beam line. Total of $39 \times 10^{-3} X_0$ with $35 \times 10^{-3} X_0$ from the gas.

- CEDAR-H uses $H_2$ radiator. At 3.8 bar, the material contribution from CEDAR-H is $7.3 \times 10^{-3} X_0$. Reduces inelastic scattering.

- New optics required to account for different optical properties of $H_2$.

- Distributions of photons using different radiators but with CEDAR-W optics.



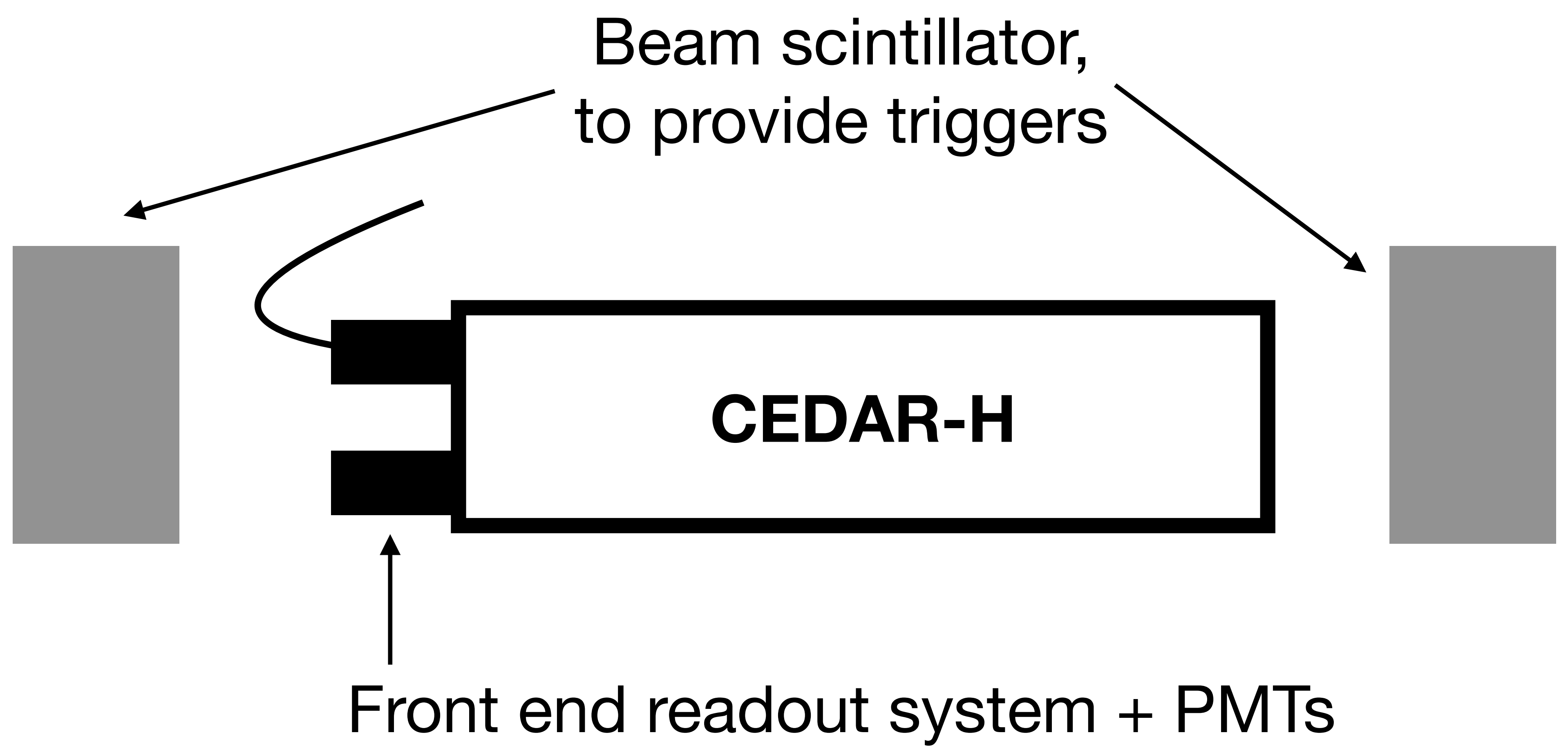
# CEDAR-H Development

- Extensive simulations at University of Birmingham using GEANT4 to analytically find initial optical parameters.
- Optical properties of $H_2$ vary with gas pressure.
- Simulations performed at different pressures to maximise photon yield.
- Pressure of 3.8 bar considered the working point.
- Left: Description of the optical parameters in CEDAR-W and CEDAR-H.

| **CEDAR type** | | **CEDAR-W** | **CEDAR-H** |
|---|---|---|---|
| Nominal gas type | | $N_2$ | $H_2$ |
| Nominal pressure [bar] | | 1.71 | 3.80 |
| Gas vessel cylinder | Length | 4500 | 4500 |
| | Inner radius | 267 | 267 |
| Gas vessel cap | Length | 339 | 280 |
| | Inner radius | 139 | 139 |
| Chromatic corrector | Position along the beam axis | 1855 | 1902 |
| | Radius of curvature | 1385 | 1307 |
| | Central thickness | 20 | 20 |
| | Inner radius | 75 | 75 |
| | Outer radius | 160 | 160 |
| Mangin mirror | Position along the beam axis | 5353 | 5362 |
| | Radius of curvature: | | |
| | - refracting surface | 6615 | 8994 |
| | - reflecting surface | 8610 | 9770 |
| | Central thickness | 40 | 40 |
| | Inner radius | 50 | 40 |
| | Outer radius | 150 | 150 |
| Diaphragm | Position along the beam axis | 872 | 911 |
| | Aperture central radius | 100 | 100 |
| Condensers | Position along the beam axis | 832 | 871 |
| | Maximum thickness | 10 | 10 |
| | Radius of curvature | 300 | 300 |
| Quartz windows | Position along the beam axis | 472 | 531 |
| | Thickness | 10 | 10 |
| | Radius | 22.5 | 22.5 |
| | Radial distance to window centre | 103 | 103 |
| Optical caps | Position along the beam axis | 450 | 450 |
| | Maximum thickness | 4.24 | 4.24 |
| | Radius of curvature | 114.62 | 114.62 |
| Spherical mirrors | Position along the beam axis | 322 | 322 |
| | Radius of curvature | 51.68 | 77.52 |
| | Diameter | 50 | 50 |
| | Radial distance to mirror centre | 106 | 106 |

# CEDAR-H Test Beam

- CEDAR-H performance measured at test beam at CERN on H6 beam line in Oct. 2022.
- No KTAG, instead 8 ET 9820QB PMTs, one at each CEDAR exit window.
- CEDAR-H was 440 m downstream of target at test beam, 70 m at NA62.
- 400 GeV/c primary proton beam from SPS on a beryllium target.
- 75 GeV/c H6 beam composition estimated to be: 4% kaons, 25% protons, 71% pions.
- Validated performance of optics and their alignment. Measured $K^+$ identification efficiency and $K-\pi$ separation.

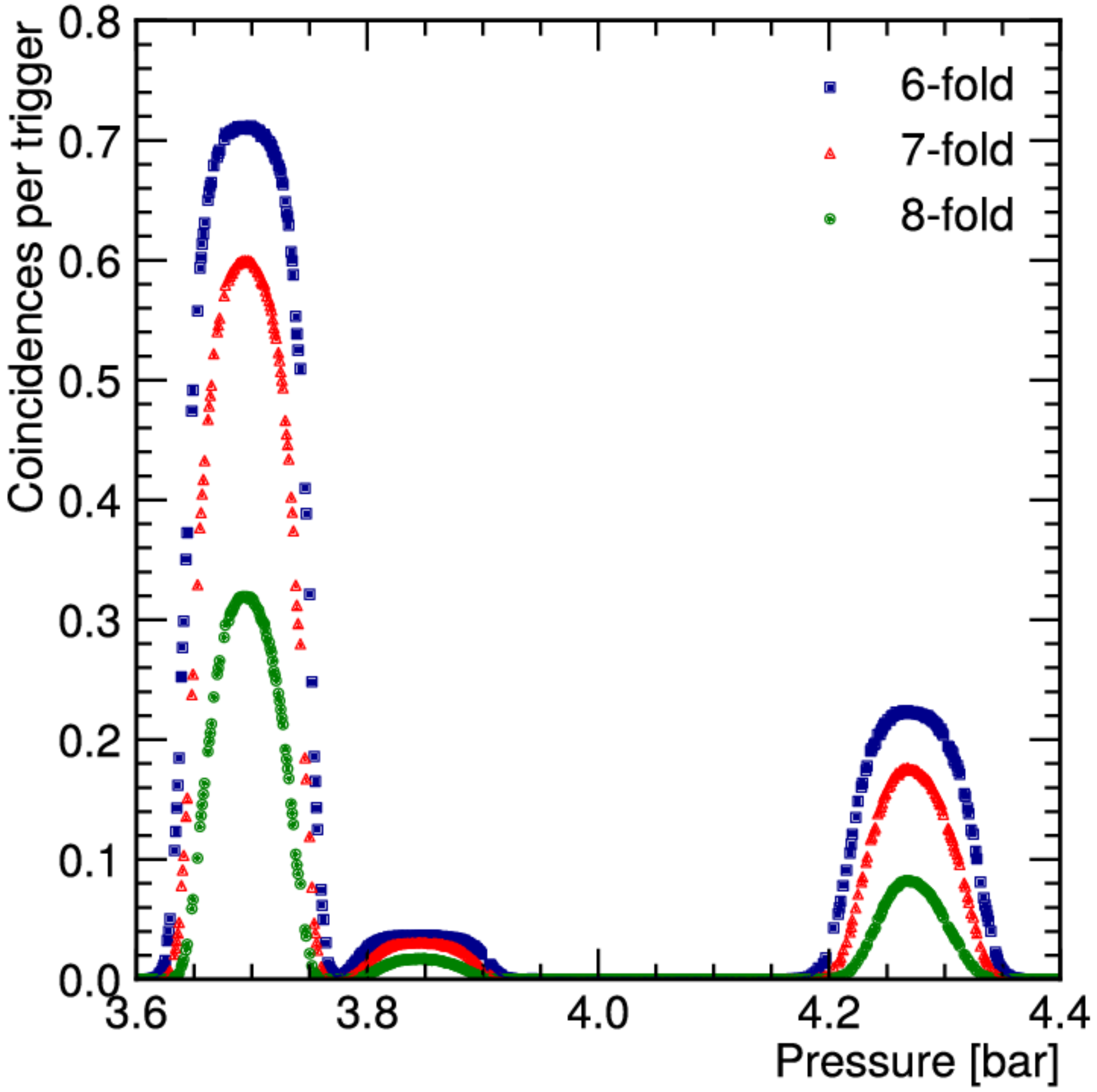


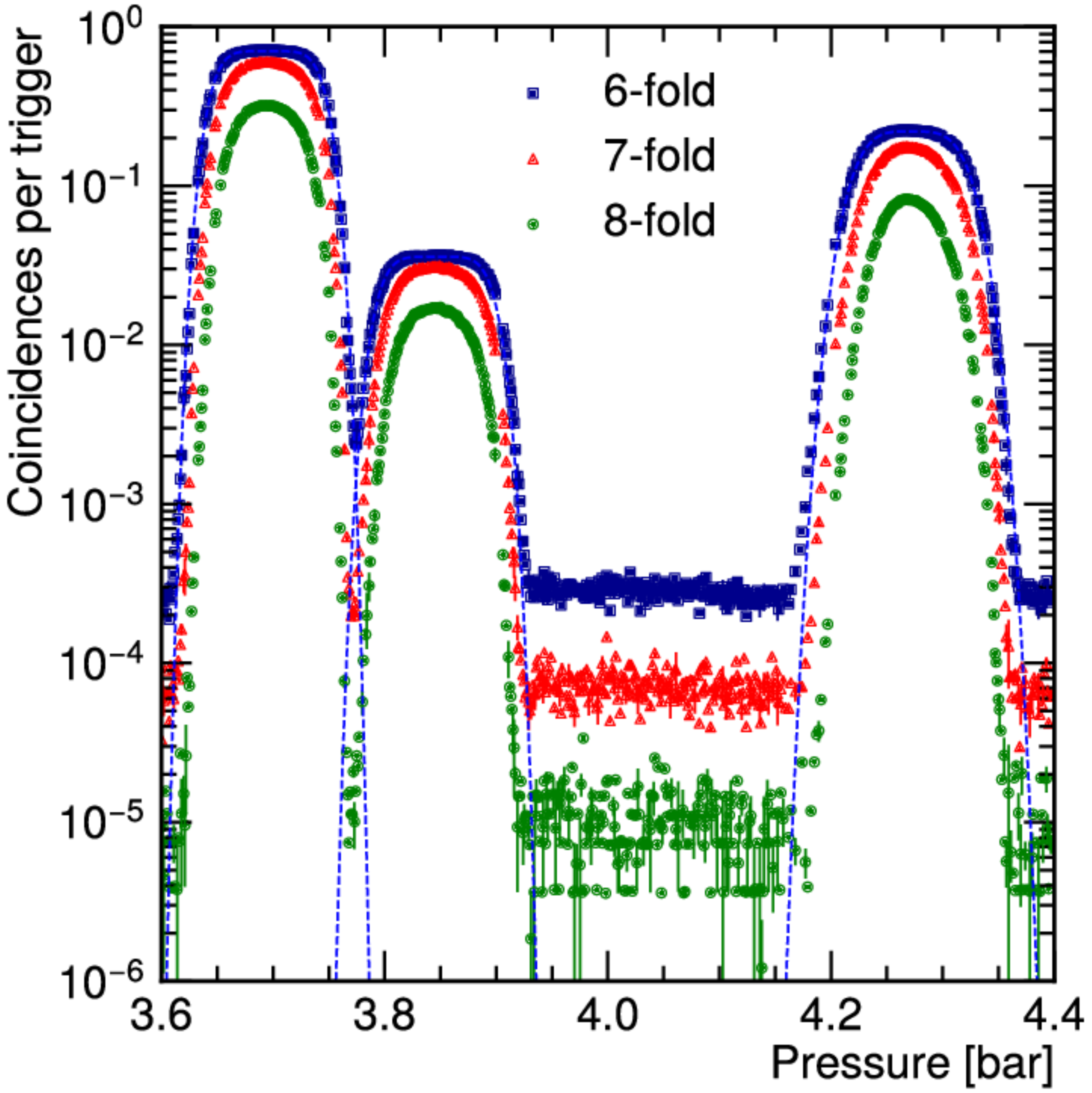


CEDAR-H at the H6 test beam.

# Test Beam Results

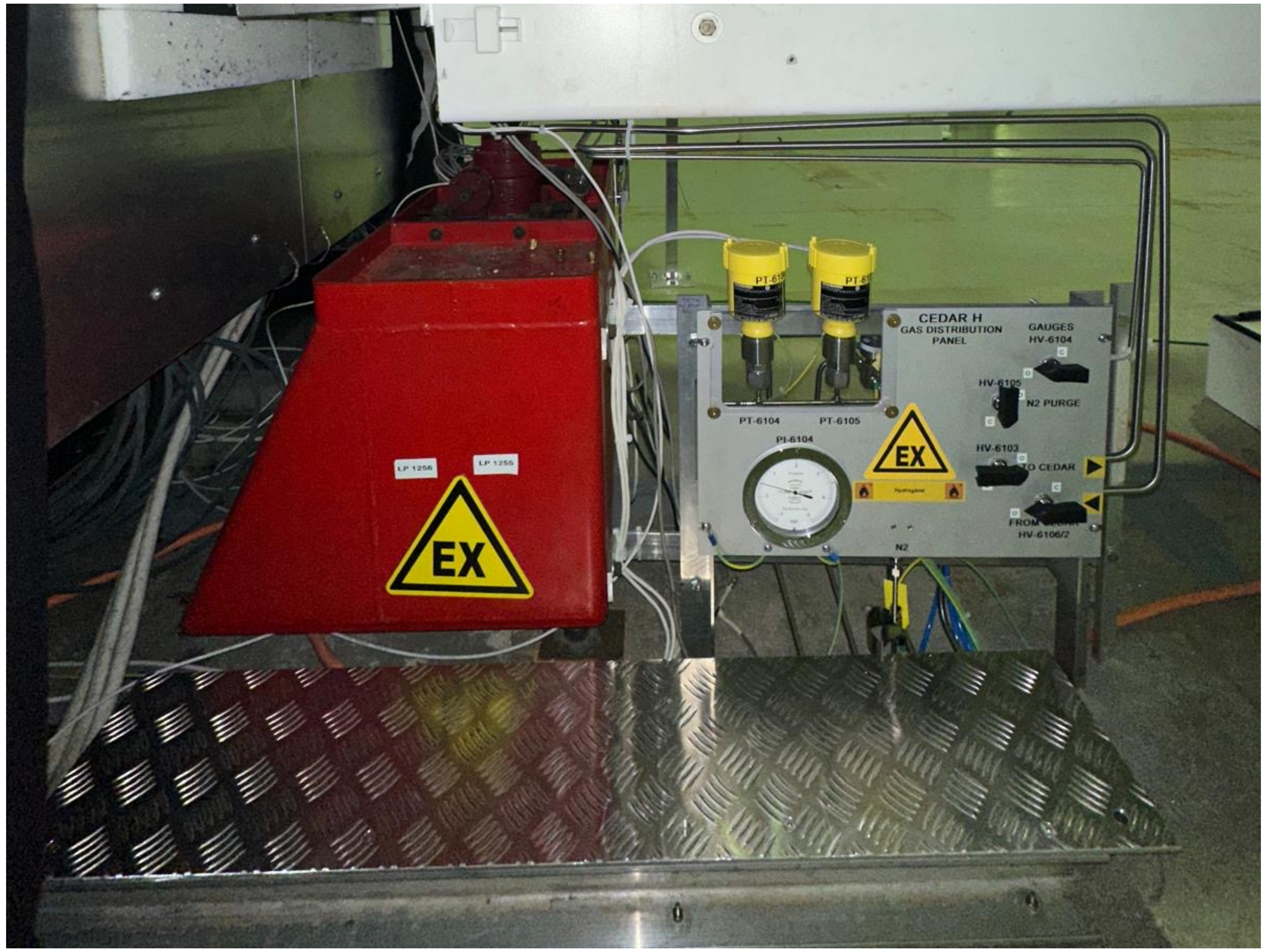
- At **3.85 bar** the light yield was **19.1 photons** per kaon.
- Probability of misidentification ($10^{-4}$) from fitting trailing edge of pion peak.
- Diaphragm width chosen maximise photon yield and maintain required mis-id rate.



# Installation at NA62

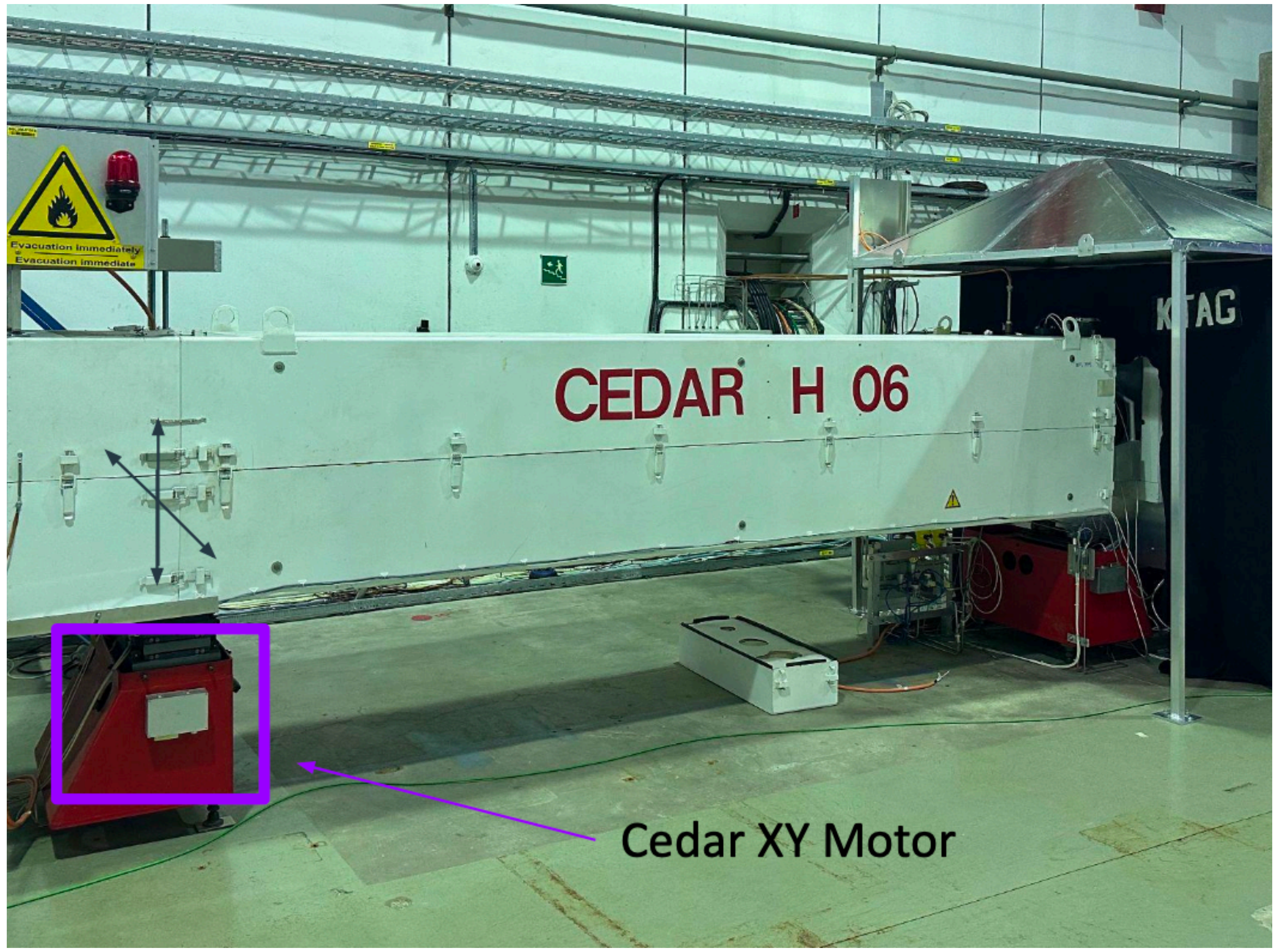
- Installed for the start of 2023 data taking.
- Extensive safety systems to alert in the case of hydrogen leakage.
- Atmospheric explosive zone (ATEX) ~ 1 m around the CEDAR-H.



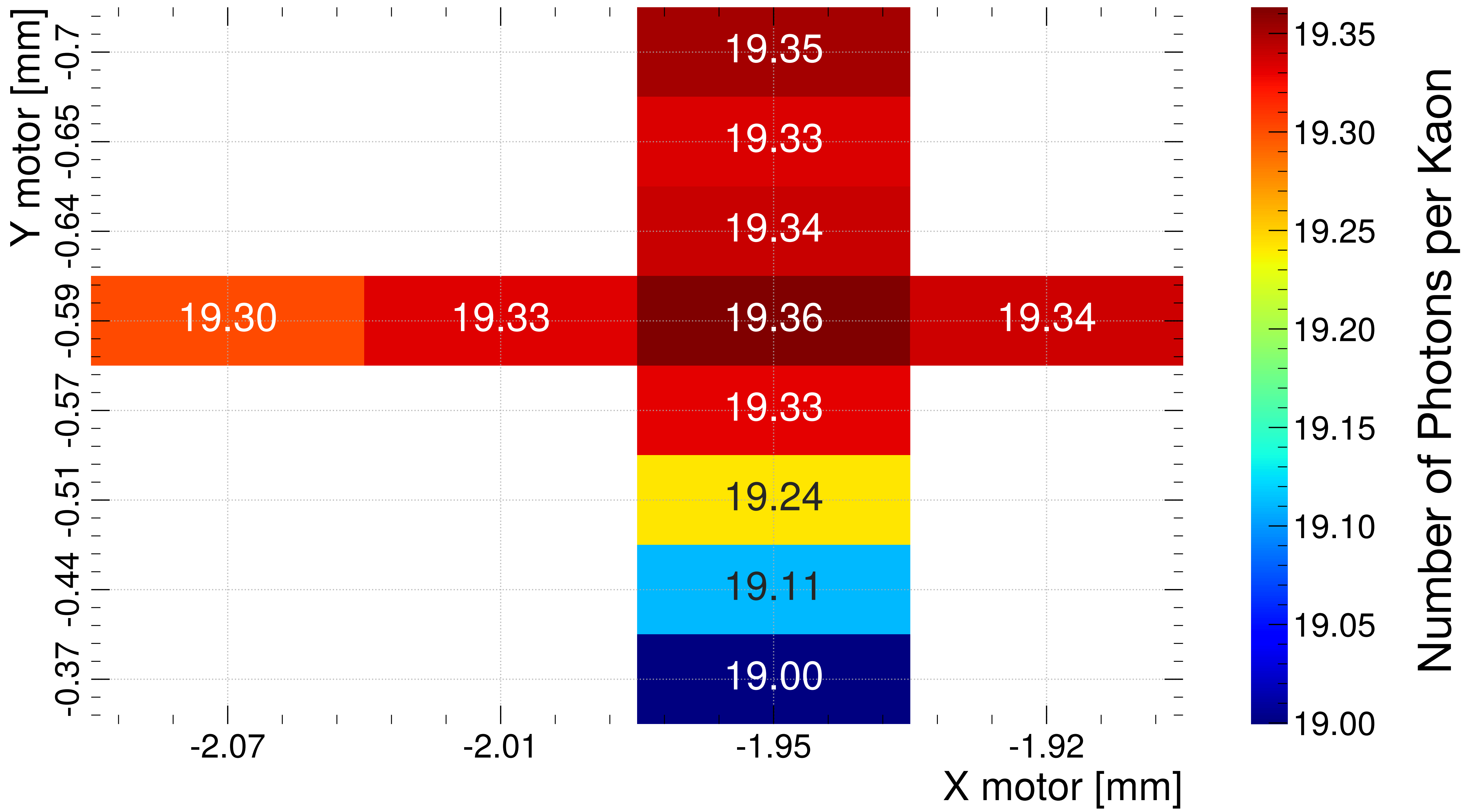

# Commissioning: Alignment

- CEDAR aligned to the beam by moving the XY motors. Must be done with a thin diaphragm width.

- Considered aligned when $N_\gamma$ per kaon is maximised for a fixed diaphragm width at the pion peak pressure.

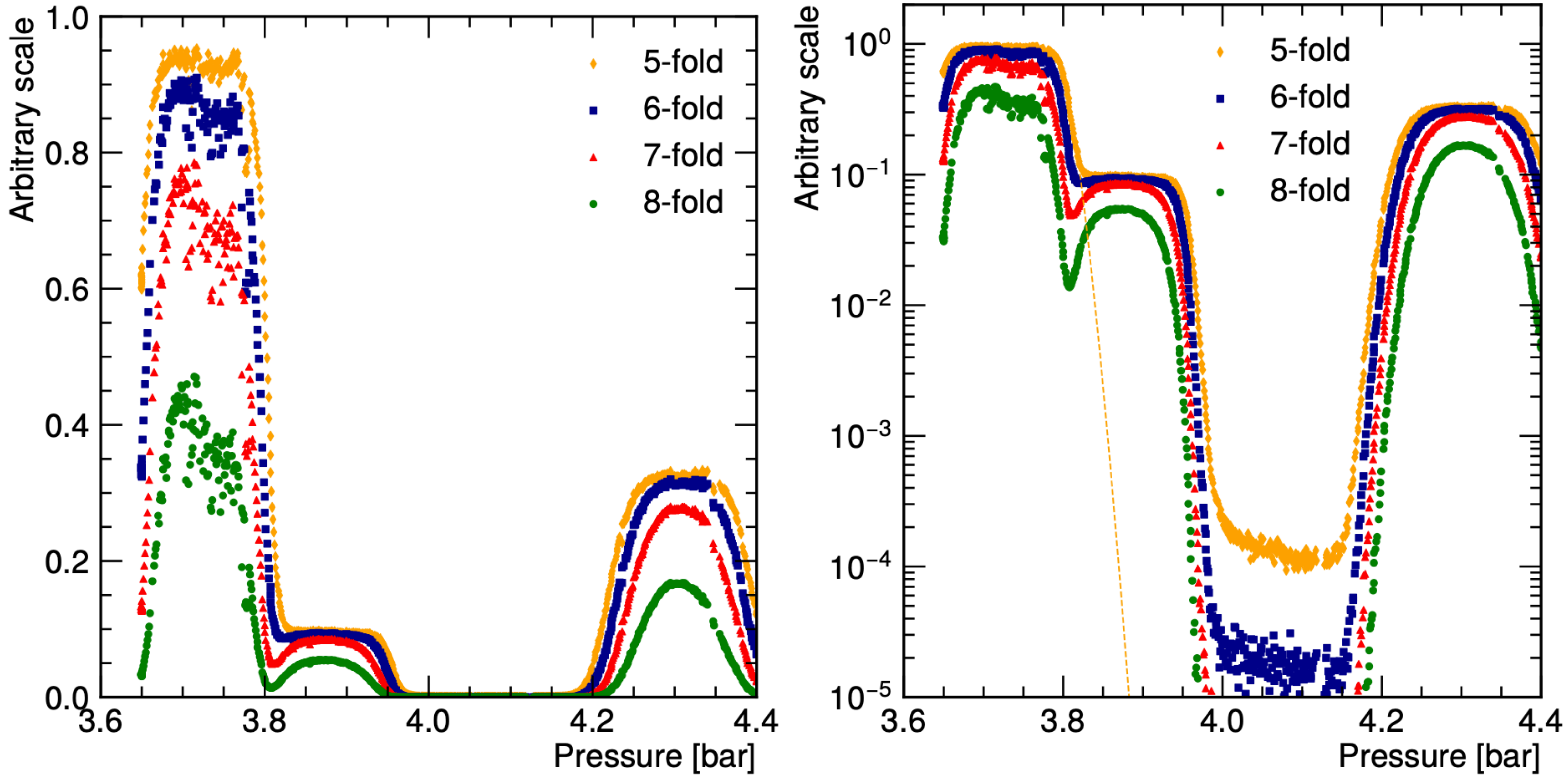



Alignment of CEDAR-H in 2024

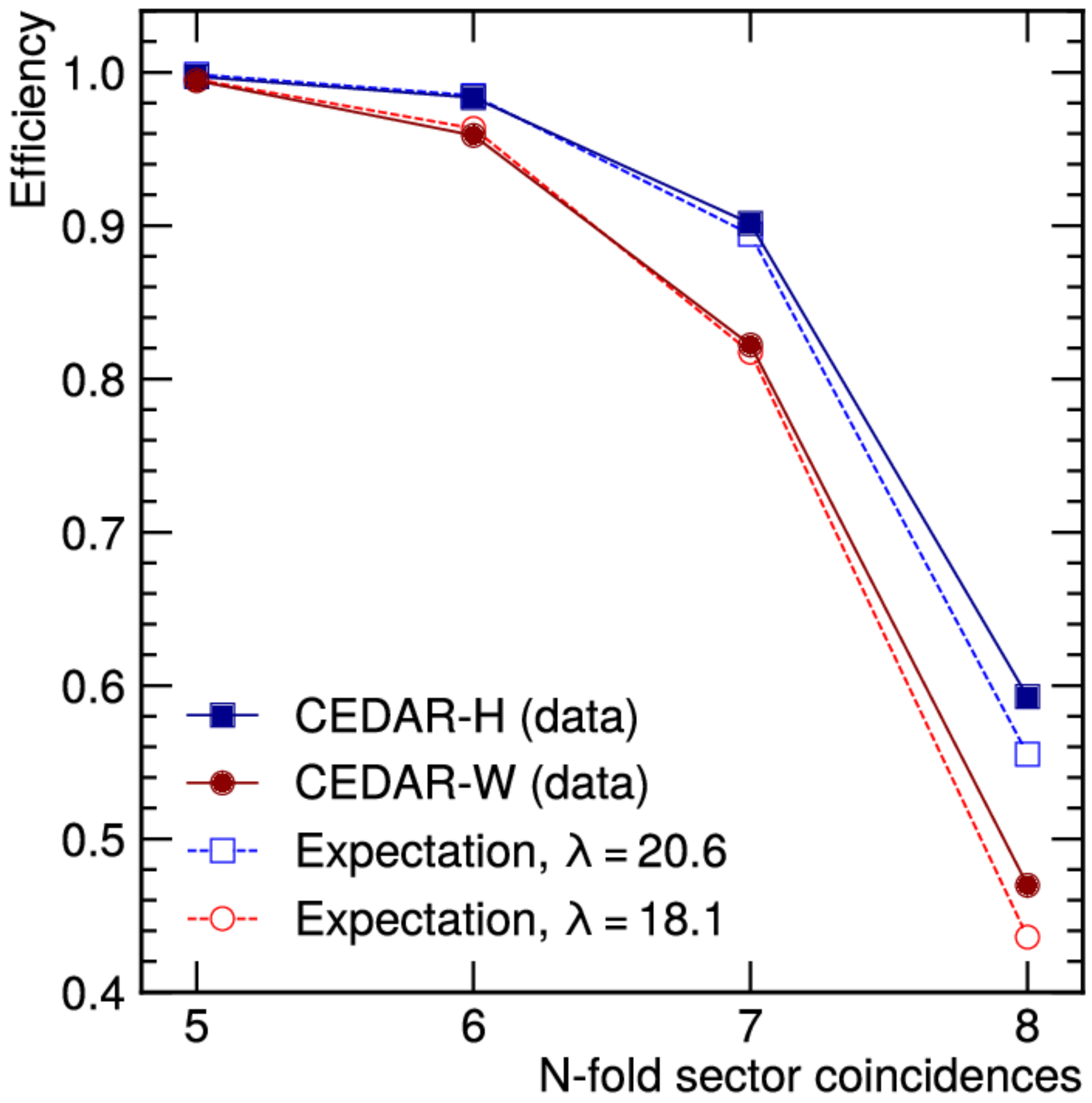


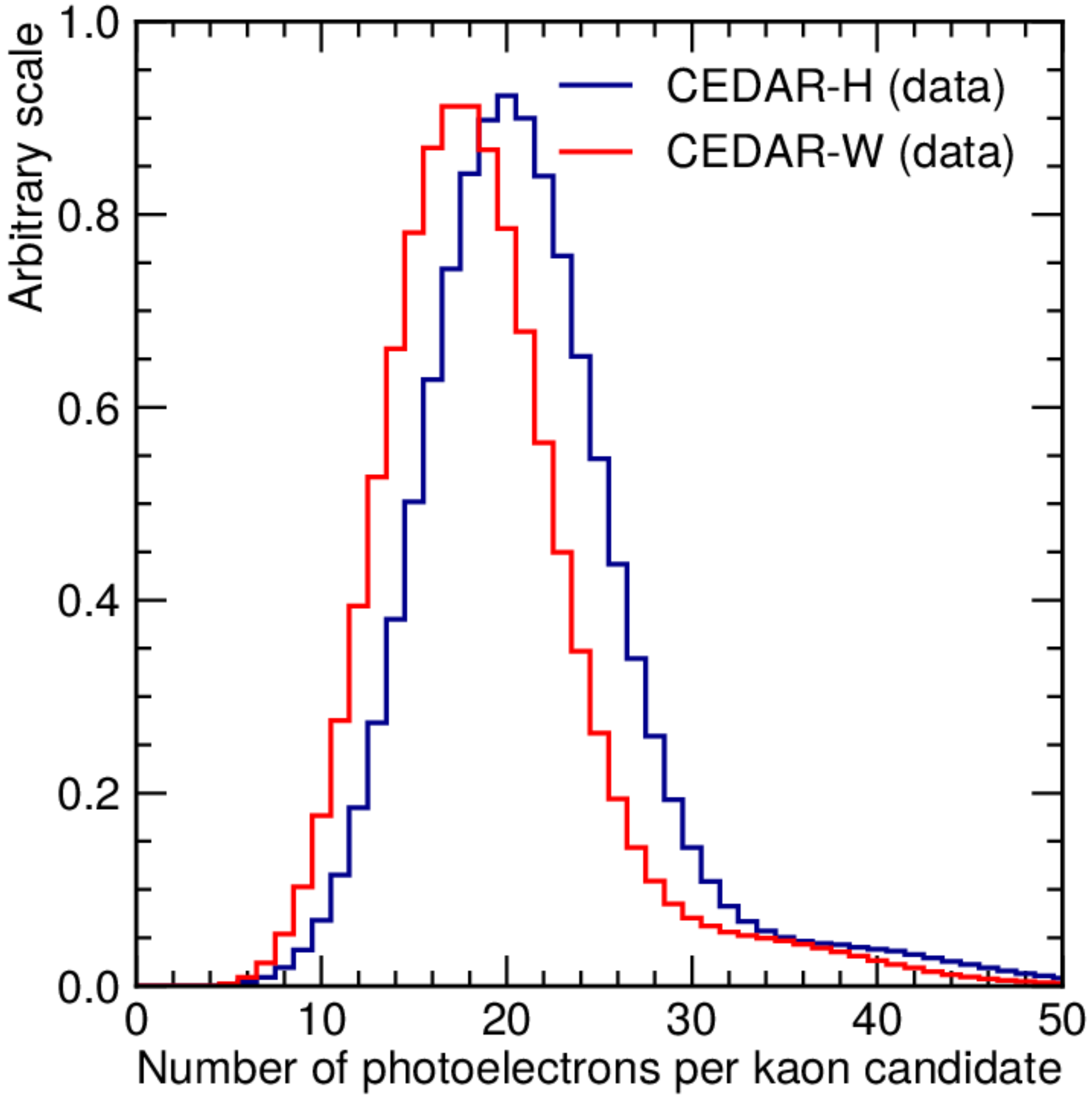
# Commissioning: Pressure Scans

- Similar to test beam, multiple pressure scans performed at varying diaphragm apertures.
- Light yield of ~21 photons per kaon. Improved with respect to the test beam due to using KTAG.
- Relative height of peaks is determined by the beam composition (6% kaons, 23% protons and 70% pions).



# CEDAR-H Performance at NA62




>99.5% efficiency for a 5-fold coincidence in 2024 data. Measured using $K^+ \to \pi^+\pi^+\pi^-$ events.

~10% increase in the number of photons per kaon compared to CEDAR-W

30% reduction of elastically scattered beam particles originating upstream of GTK3.

# Summary

- CEDAR-H was proposed to reduce the material in the beam path at NA62. Achieved by switching radiator medium from nitrogen to hydrogen.

- Test beam at CERN in 2022 ratified performance of CEDAR-H.

- Successfully installed at NA62 for start of run 2023 and currently operating (2024) with approximately:

  ❖ ~21 photons per kaon giving a time resolution of ~65 ps.

  ❖ Kaon tagging efficiency >99.5 % using 5-sector coincidence.

  ❖ Pion misidentification probability $\leq 10^{-4}$

- Improvement in performance on the previous CEDAR-W.