The RICH detector of the NA62 experiment at CERN

technical design, operational characteristics and basic performance

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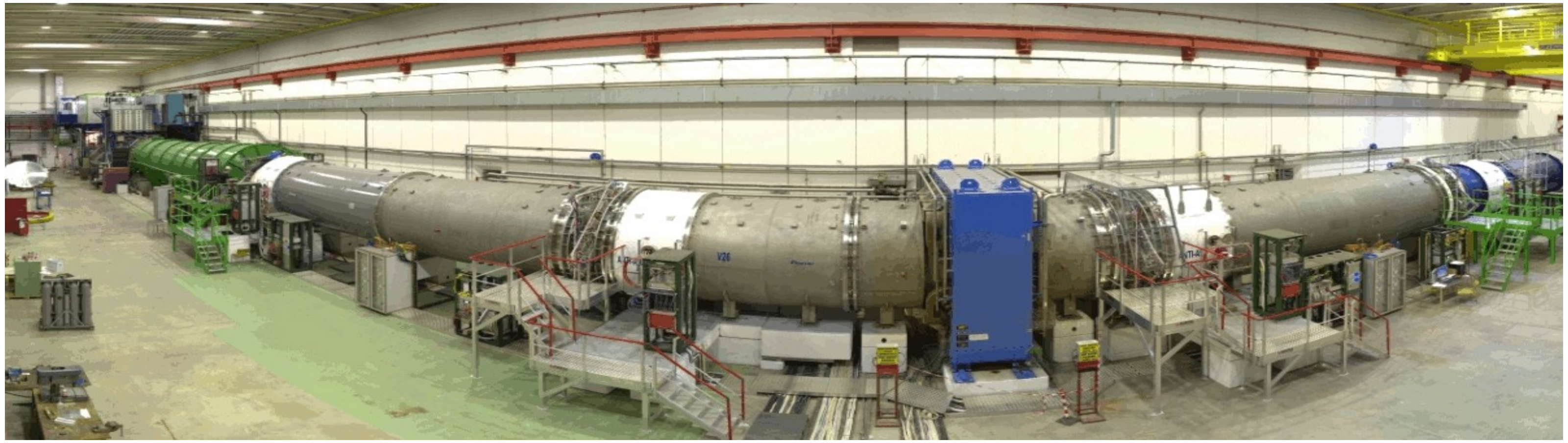
on behalf of the NA62 RICH working group

The NA62 Experiment



- Fixed target experiment installed in the North Area of the CERN SPS
- Main goal: measure ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay with 10% precision

$$BR_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$$

Buras et al., [arXiv:2109.11032]

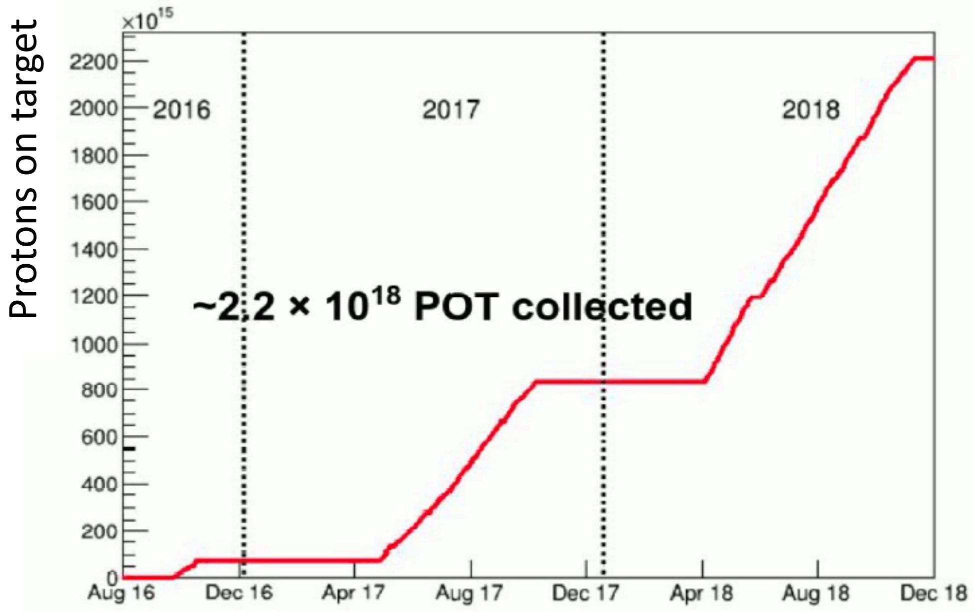
$$BR_{NA62}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(10.6^{+4.0}_{-3.4}{}_{stat} \pm 0.9_{syst}\right) \times 10^{-11}$$

NA62 Collaboration [JHEP 06 (2021) 093]

- Yet NA62 covers a broad kaon and beam-dump physics programme

NA62 Timeline

400 GeV/c protons from SPS hitting a beryllium target



- NA62 Approval: 2008
- Detector R&D and installation: 2009 $\rightarrow$ 2015
- Commissioning: 2015
- Run1: 2016, 2017 and 2018
- Run2: 2021, 2022 in progress, approved till LS3

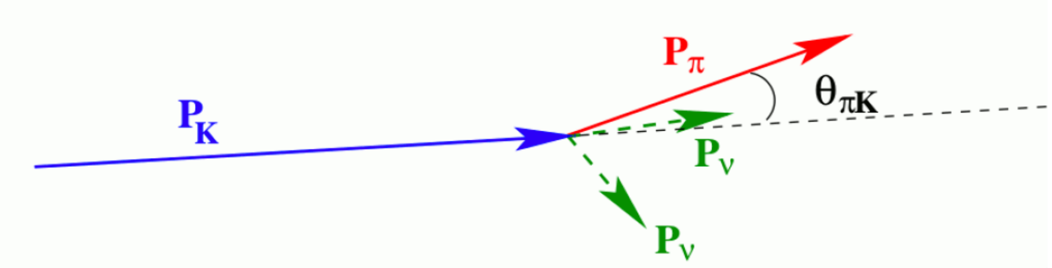
	2016	2017	2018
% of nominal intensity	40	60	60-70
K^+ decays in FV*	$\sim 2 \times 10^{11}$	$\sim 2 \times 10^{12}$	$\sim 4 \times 10^{12}$

* FV = Fiducial Volume

NA62 and RICH Requirements

K^+ beam with 75 GeV/c momentum $\rightarrow K^+$ decays in flight

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ experimental signature



K^+ main (background) decays

Decay channel	Branching ratio
$K^+ \rightarrow \mu^+ \nu$ ($K_{\mu 2}$)	$(63.56 \pm 0.11) \cdot 10^{-2}$
$K^+ \rightarrow \pi^+ \pi^0$ ($K_{2\pi}$)	$(20.67 \pm 0.08) \cdot 10^{-2}$
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$ ($K_{3\pi}$)	$(5.583 \pm 0.024) \cdot 10^{-2}$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ (K_{e4})	$(4.247 \pm 0.024) \cdot 10^{-5}$

To measure $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ @ 10%

- $O(10\%)$ signal acceptance
- $O(10^{13})$ K^+ decays in the fiducial volume
- $O(10^{12})$ background rejection →

NA62 requirements

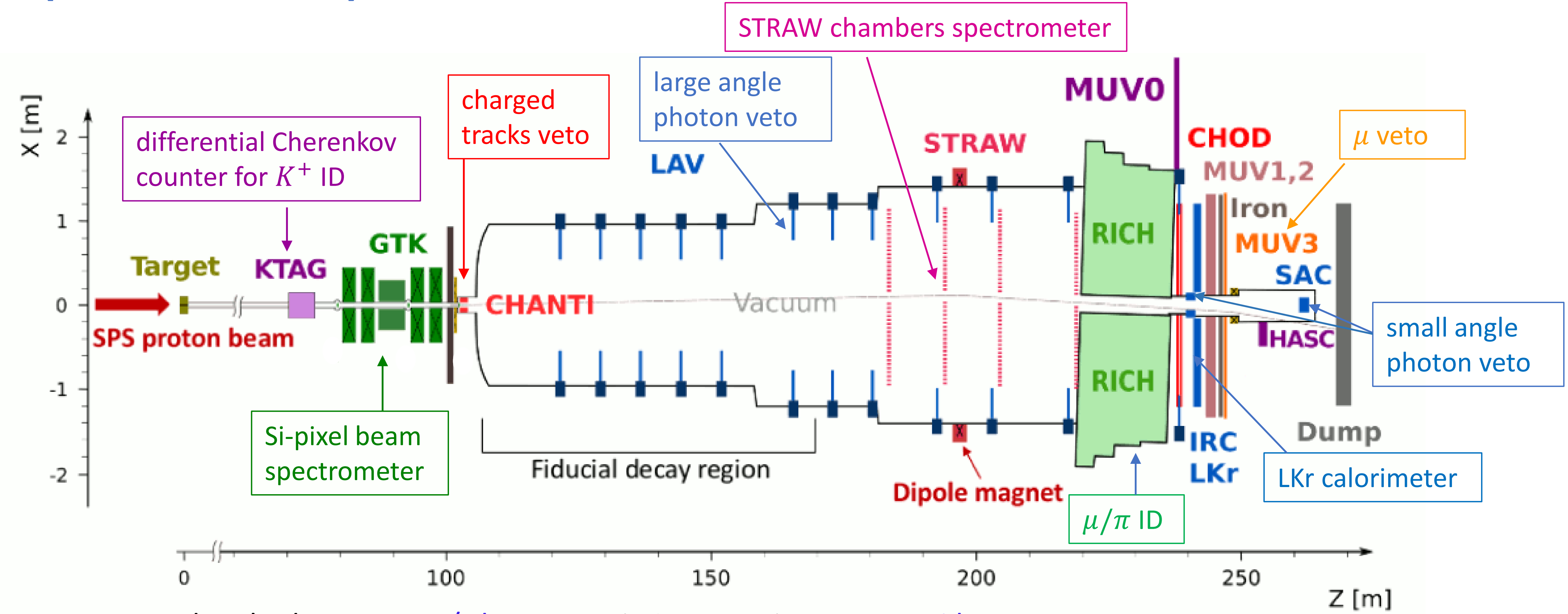
- Time coincidence: $O(100\ ps)$
- Kinematic rejection: $O(10^4)$
- Muon rejection: > $O(10^7)$
- π^0 rejection: >10^7

RICH requirements

- Time resolution: $O(100\ \text{ps})$
- μ^+mis-ID <1% (15 < p_{track} < 35 GeV/c)
- Provide L0 trigger for charged tracks

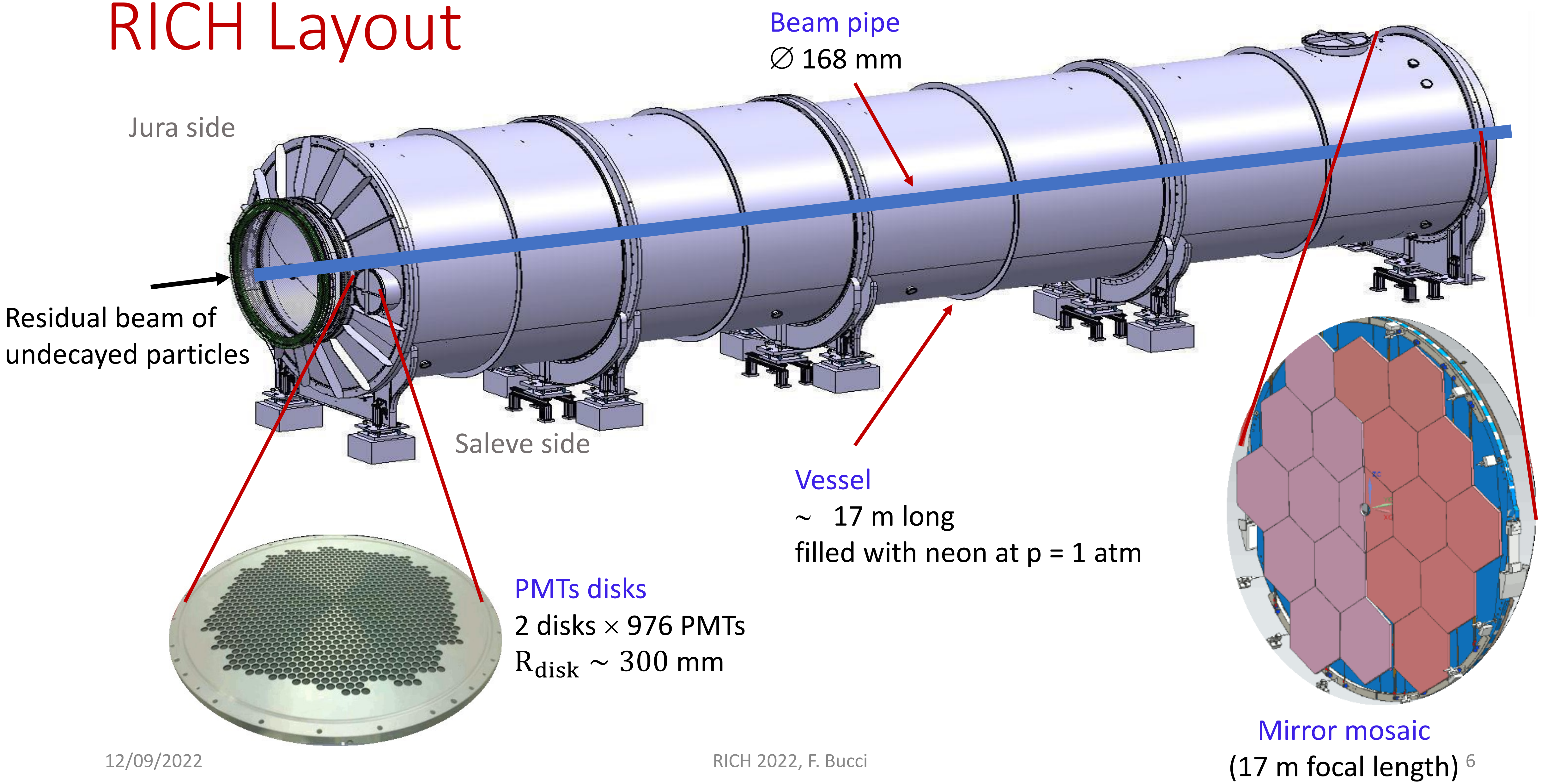
NA62 Detector Layout

[2017 JINST 12 P05025]

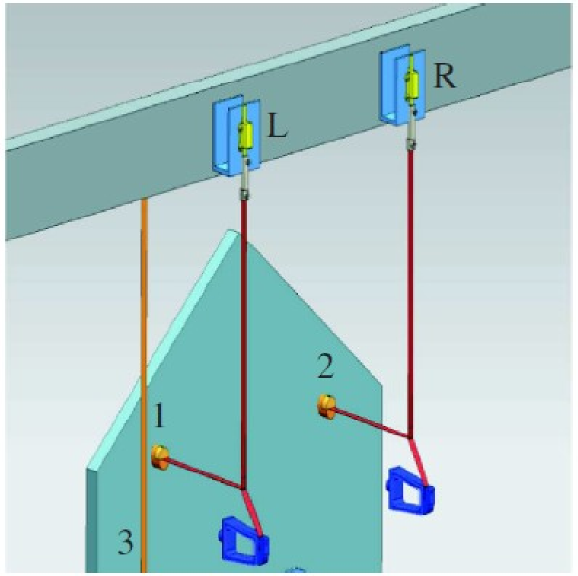


- Secondary hadron 75 GeV/c beam: 70% pions, 24% protons, 6% kaons
- 60 m long fiducial region, ~ 5 MHz K$^+$ decay rate, vacuum ~ O(10^{-6}) mbar

RICH Layout


Beam pipe
∅ 168 mm
Jura side
Residual beam of
undecayed particles
Saleve side
Vessel
~ 17 m long
filled with neon at p = 1 atm
PMTs disks
2 disks × 976 PMTs
$R_{disk} \sim 300$ mm
Mirror mosaic
(17 m focal length)

RICH Mirrors System



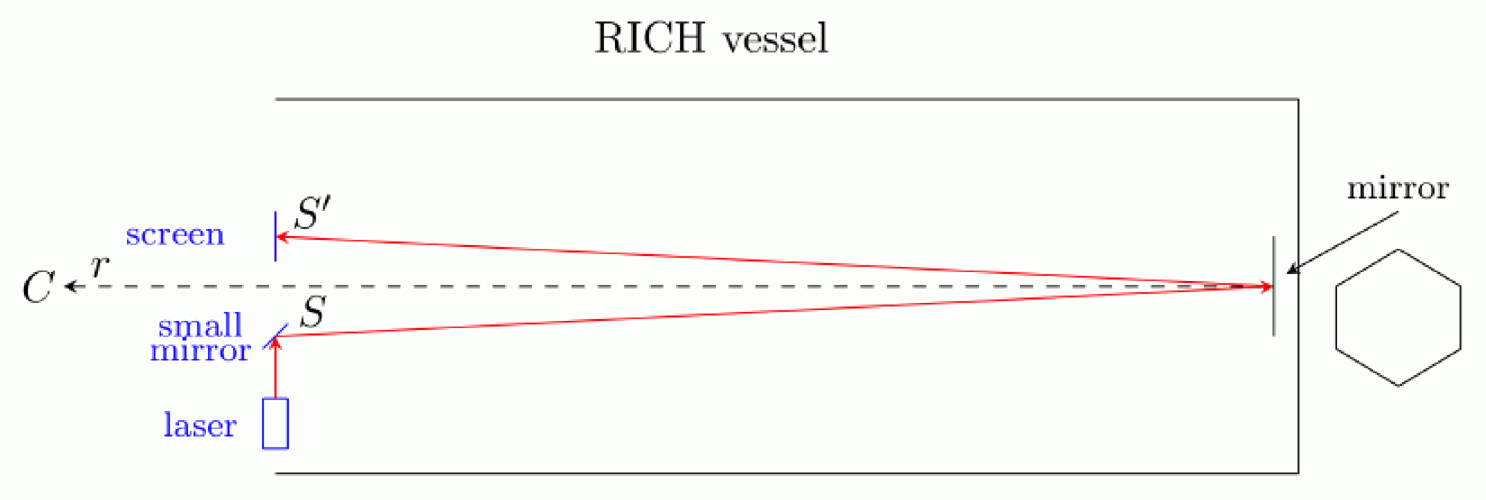
Mosaic of spherical mirrors

- 18 hexagonal mirrors (35 cm side dimension) and 2 semi-hexagonal with beam pipe hole
- 2.5 cm thick glass (~ 20% X_0)
- Al coat + thin MgF_2 dielectric film
- Spherical mirrors f = 17.0 $\pm$ 0.1 m
- Average reflectivity > 90% (195-650 nm)

Support system

- 2 halves of Al honeycomb panel 5 cm thick
- Mirrors supported by a dowel inserted in the back
- 2 actuating Al ribbons at $\pm$ 45° with respect to the vertical for mirror orientation
- A third vertical ribbon to avoid mirror rotation
- Piezo motors, out of acceptance to pull the actuating ribbons

RICH Mirrors Alignment



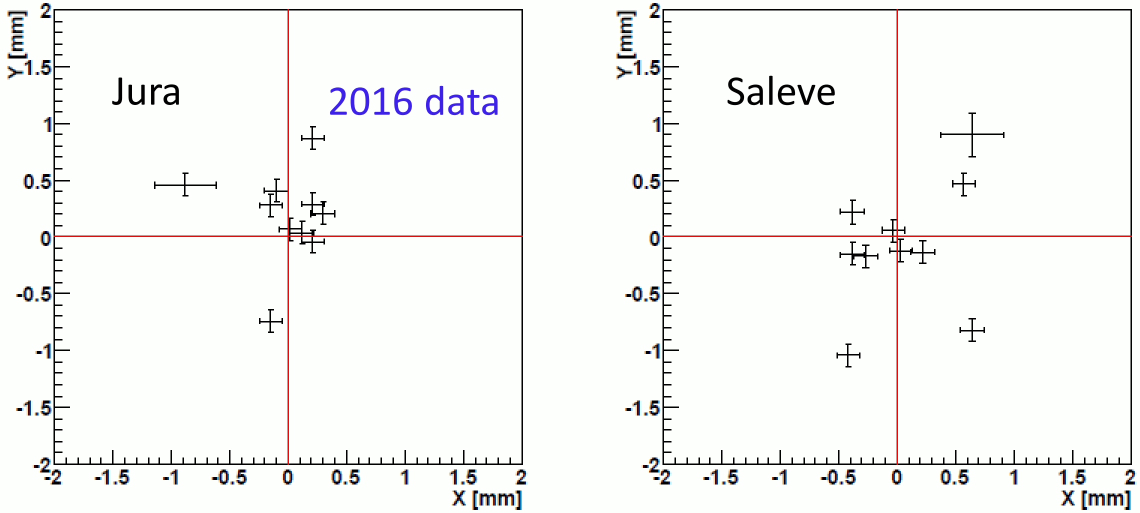
[Anzivino et al. 2018_JINST13 P07012]

Preliminary laser alignment

- Measured before closing the vessel
- Setup with ~ 10 m lever arm
- Precision O(500 μrad) in terms of mirror orientation

Precise alignment with data

- Measured regularly during data taking
- Use reconstructed tracks
- Iterative procedure
- Precision O(30 μrad) in terms of mirror orientation
- Stable along run periods



All mirrors within ± 1 mm

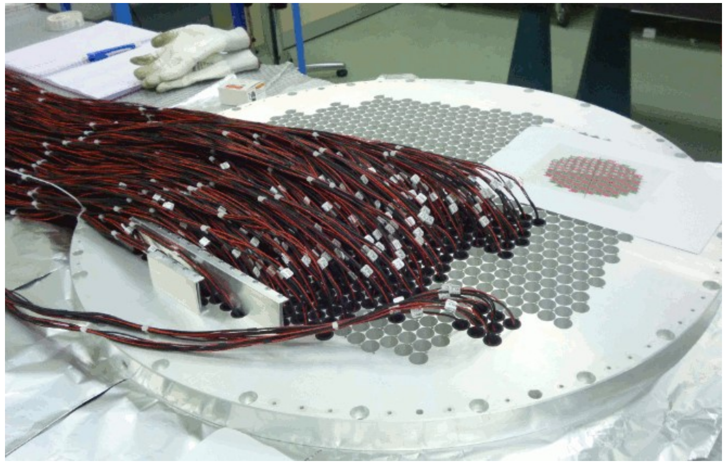
RICH Photodetection System

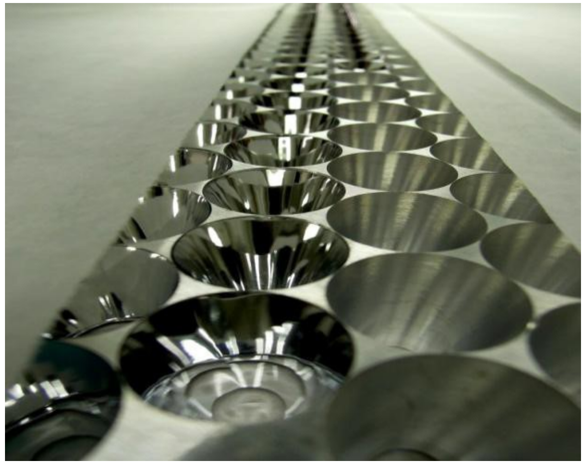
2 Al disks placed on mirror focal plane, each instrumented with 976 PMTs

- Hamamatsu R7400U-03 PMTs
- Compact hexagonal packing, 18 mm pixel size
- Light collected by means of Winston cones with Al mylar
- 1 mm thick quartz window to separate neon from air
- Custom made HV dividers to reach best compromise between signal quality (time resolution) and resistance values (heat dissipation)

No need to replace any PMT since 2014

Hamamatsu R7400-03 PMTs
Sensitivity range 185-650 nm (420 nm peak)
Gain 1.5×10^6 at 900 V
UV glass window, 16 mm ∅ (8 mm active ∅)
Q.E. ~ 20% at peak
280 ps time jitter (FWHM)





RICH Basic Performance

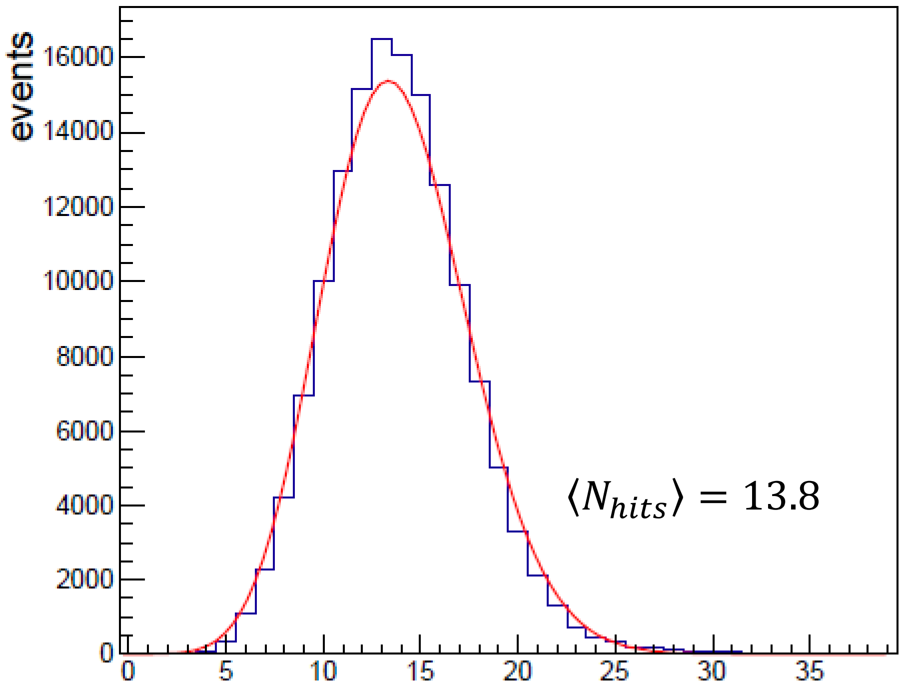
- RICH basic performance measured with a clean sample of e^+ from $K^+ \to \pi^0 e^+ \nu_e$
- Unbiased sample: ring radius and number of hits do not depend on the momentum
- Require positron rings fully contained within RICH acceptance

Basic performance

- Average number of hits: $\langle N_{hits} \rangle$
- Average electron ring radius and ring radius resolution: $\langle R_e \rangle$, σ_{R_e}
- Single hit space resolution
- Single hit time resolution

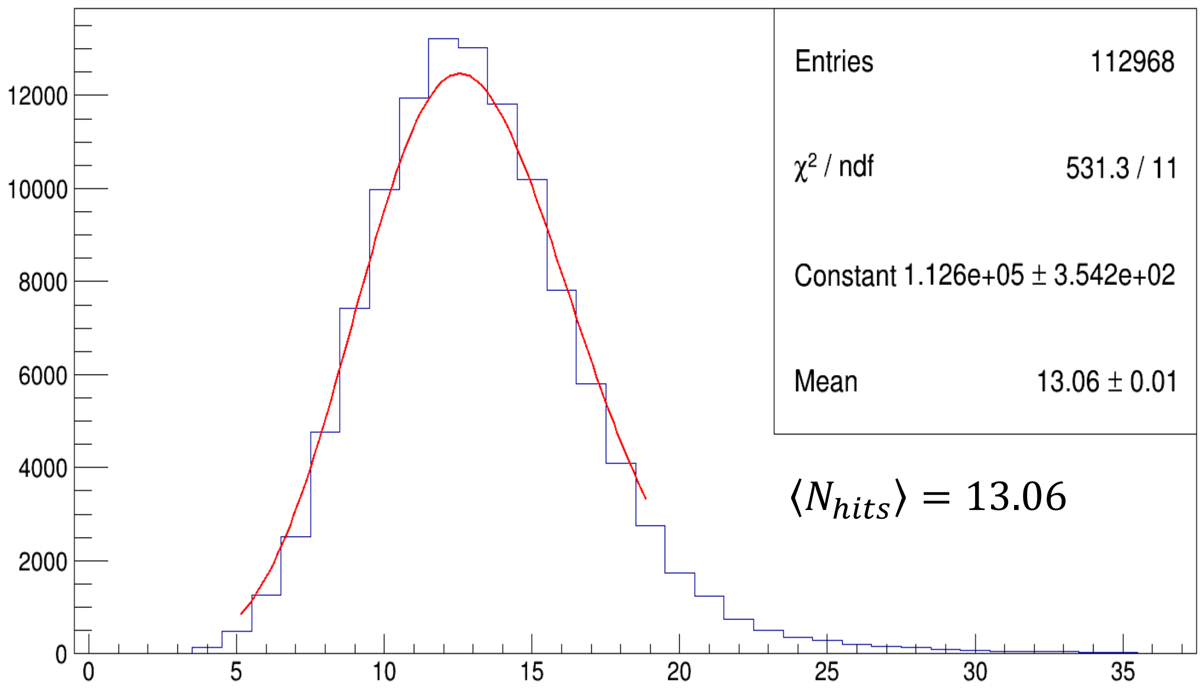
Number of Hits

2016 Data – positron selection



Anzivino et al, 2017_JINST_12_P12017

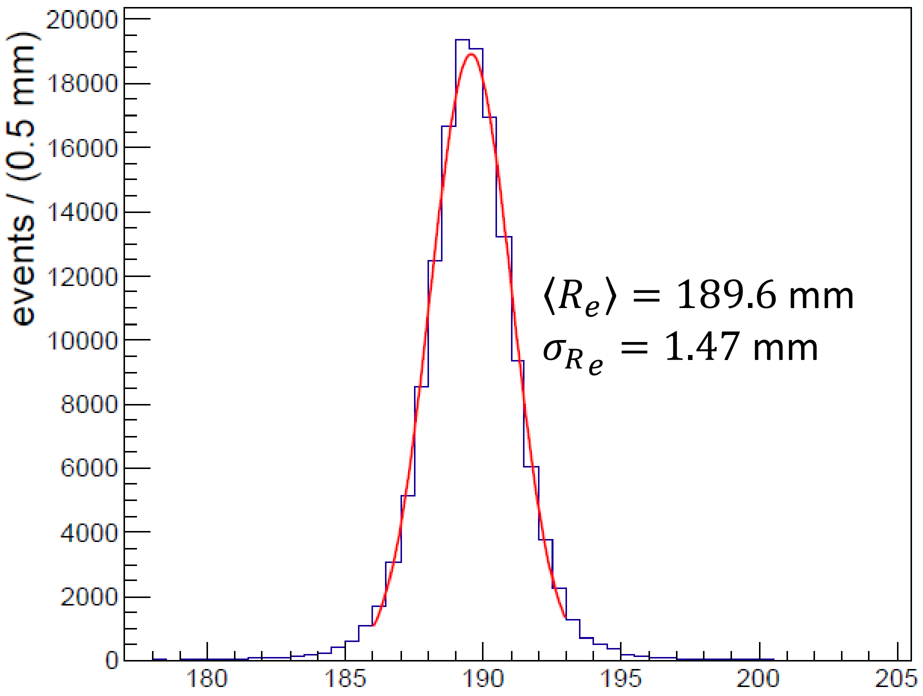
2022 Data – positron selection



Only 0.8 hits lost in 6 years ($\sim$ 0.12 per year)

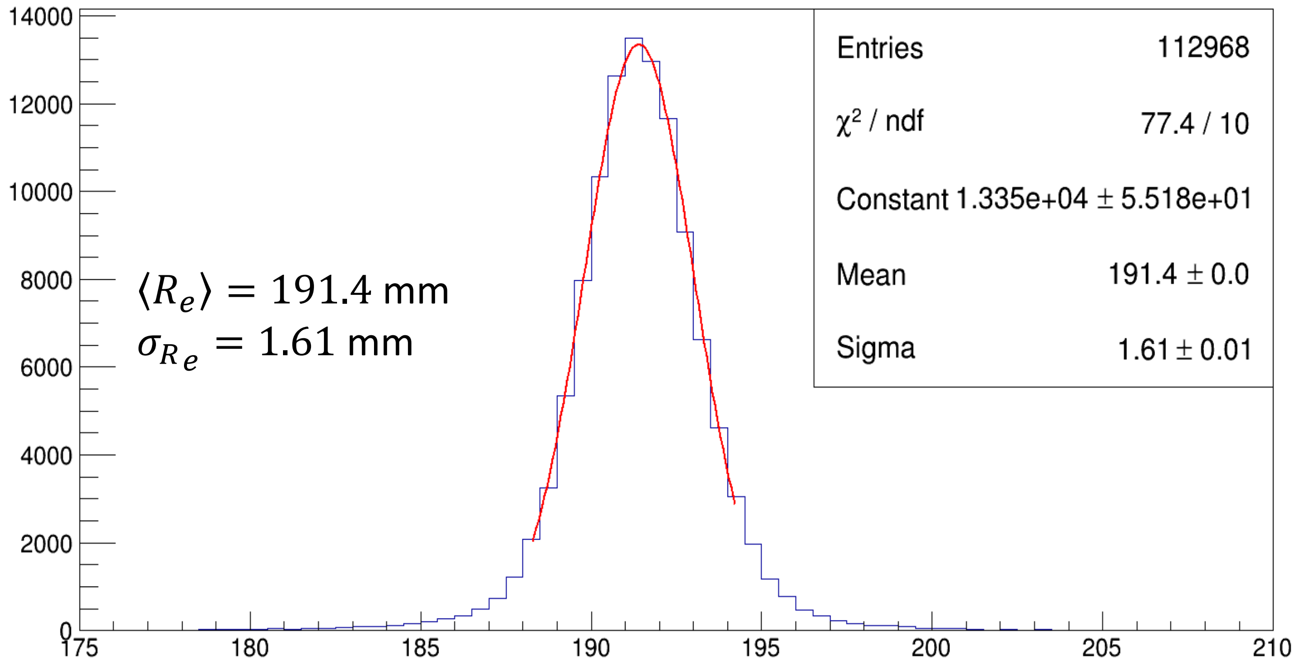
Electron Radius

2016 Data – positron selection



Anzivino et al, 2017_JINST_12_P12017 R [mm]

2022 Data – positron selection



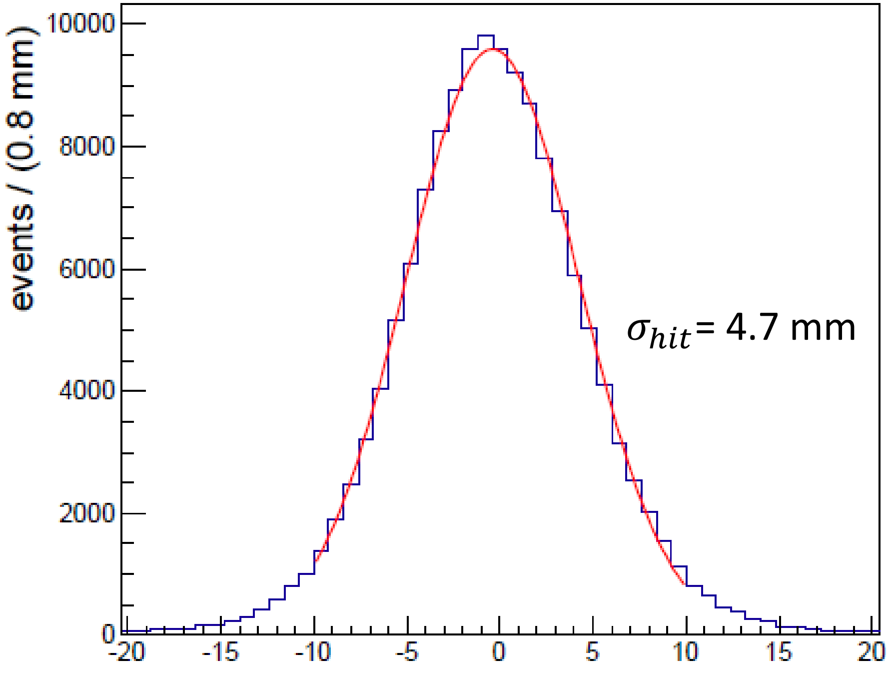
R [mm]

- Ring radius increase in Run1 with respect to Run2 due to different p/T conditions
- No significant increase of the ring radius is observed in 2022 with respect to 2021 ($< 10^{-4}$ relative)

Single Hit Space Resolution

- Compute the Space Pull = $(\mathrm{R}-\mathrm{R}_{exp})\sqrt{\mathrm{N}_{hits}-3}$, where R is the ring radius as obtained by the fit and R_{exp} the radius calculated from the momentum assuming the electron mass
- The single hit spatial resolution $\sigma_{hit} = \sigma_{Space\ Pull}$

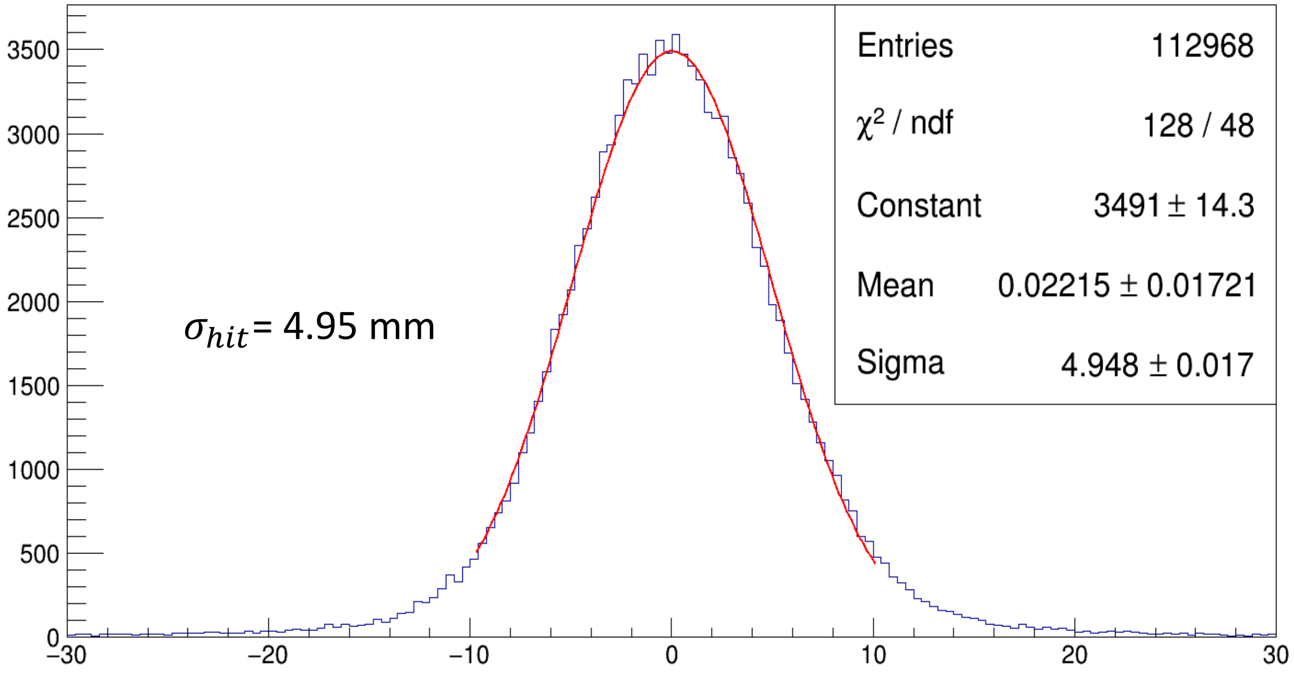
2016 Data – positron selection



Anzivino et al, 2017_JINST_12_P12017

Space Pull [mm]

2022 Data – positron selection

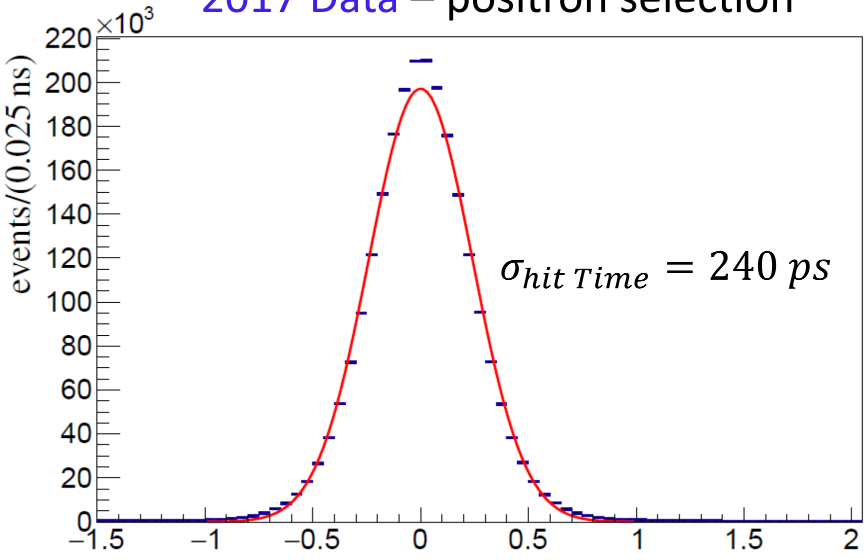


Space Pull [mm]

Single Hit Time Resolution

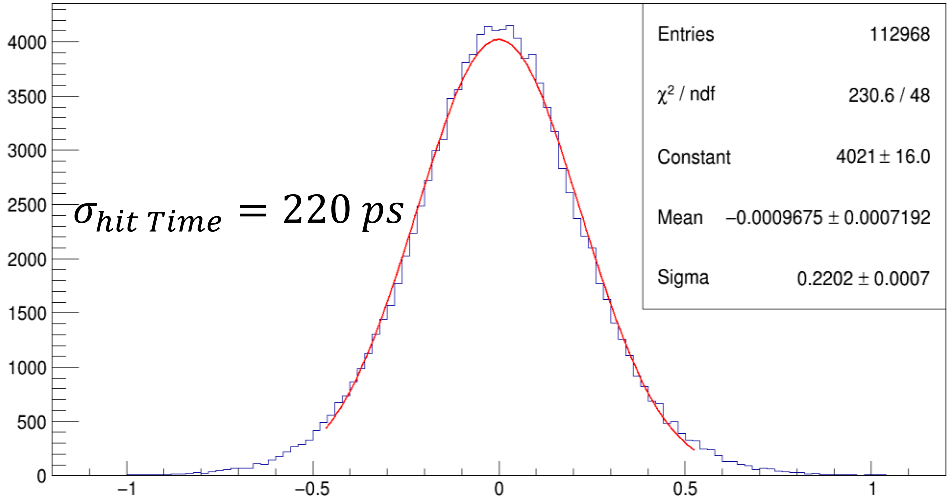
- For each event the RICH hits are randomly split into 2 groups
- The average time of each group, T_1 and T_2 is computed
- Compute the Time Pull = $\frac{(T_1 - T_2)}{2}\sqrt{N_{hits}}$
- The single hit time resolution $\sigma_{hit\ Time} \simeq \sigma_{TimePull}$

2017 Data – positron selection



Anzivino et al, 2020_JINST_15_P10025 Time Pull [ns]

2022 Data – positron selection



Time Pull [ns]

Ring time resolution: $\sigma_t = \frac{TimePull}{\sqrt{N_{hits}}} \sim 70$ ps

Possible Future RICH Upgrades

The NA62 Collaboration is preparing a Letter of Intent (LoI) for a high-intensity kaon experiment (HIKE)

First step of the project that regards charged and neutral kaons is:

- an experiment to measure $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$ to within $\sim 5\%$
- and also lepton universality/number/flavour violation, chiral parameters and precisions measurements

Requires 4× increase in intensity $\rightarrow$ matches present limit with charged secondary beam (after major upgrades)

In this perspective, the main request to a RICH for HIKE is a ring time resolution at the level of 20-30 ps to reduce the coincidence window with GTK and CEDAR

Other desiderata:

- Increase sensors granularity
- Increase acceptance on negative tracks

New Sensors

Best candidates: Silicon photomultipliers

- Already on the market SiPMs with single photon time resolution $\sim$ 100 ps FWHM and QE $\sim$ 40%
- An extra 10% enhancement in the number of detected photons can be assumed due to a smaller passive area on the PMTs disk (no Winston cones needed)

Extrapolation from current status (multiplying the number of detected photons by 2.2)

NA62 RICH

$\sigma_t(\text{single photon}) = 240\ \text{ps}$

QE: ~ 20%

N_γ for π^+ at 15 GeV/c: $\sim\ 7 \rightarrow \sigma_t(\text{ring}) \simeq 90\ \text{ps}$

N_γ for π^+ at 45 GeV/c: $\sim 12 \rightarrow \sigma_t(\text{ring}) \simeq 70\ \text{ps}$

HIKE RICH

$\sigma_t(\text{single photon}) = 100\ \text{ps}$

QE: ~ 40%

N_γ for π^+ at 15 GeV/c: $\sim 15 \rightarrow \sigma_t(\text{ring}) \simeq 25\ \text{ps}$

N_γ for π^+ at 45 GeV/c: $\sim 26 \rightarrow \sigma_t(\text{ring}) \simeq 20\ \text{ps}$

Need to re-design the front end electronics

New Sensors

Problems related to SiPMs

Dark counts

- A 100kHz dark counts rate per mm^2
- with a coincidence window of 800 ps (±400 ps)
- and an annulus area of $\sim 50 \cdot 10^3\ \mathrm{mm}^2$

$\sim$ 4 spurious hits per the ring

To lower such contamination at few % level need to cool the SiPMs (-20/-30° C)

QE:

- SiPMs are usually more efficient at higher λ with respect to PMTs

Cross talk:

- Strongly dependent from the SiPM type
- Add an extra contribution to hit space resolution

Aging:

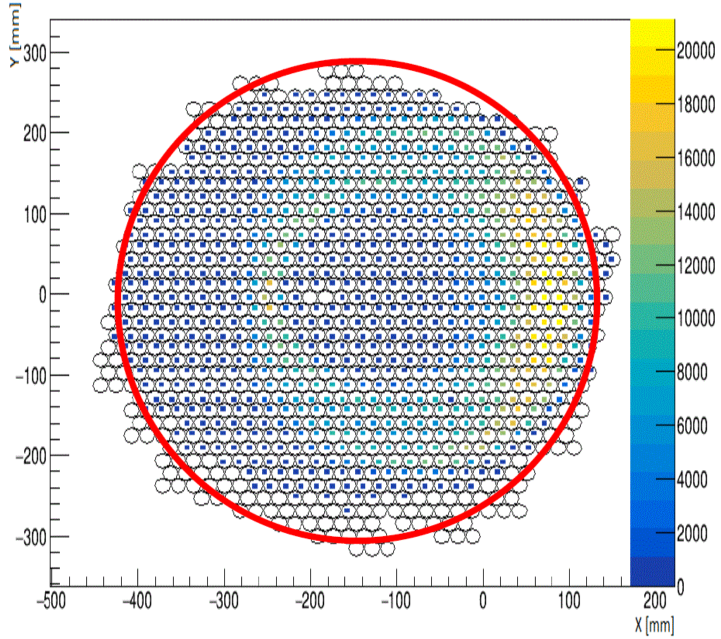
- Instrumented disks are far away from the beam pipe, nevertheless radiation level in HIKE environment must be studied

Negative Tracks Acceptance

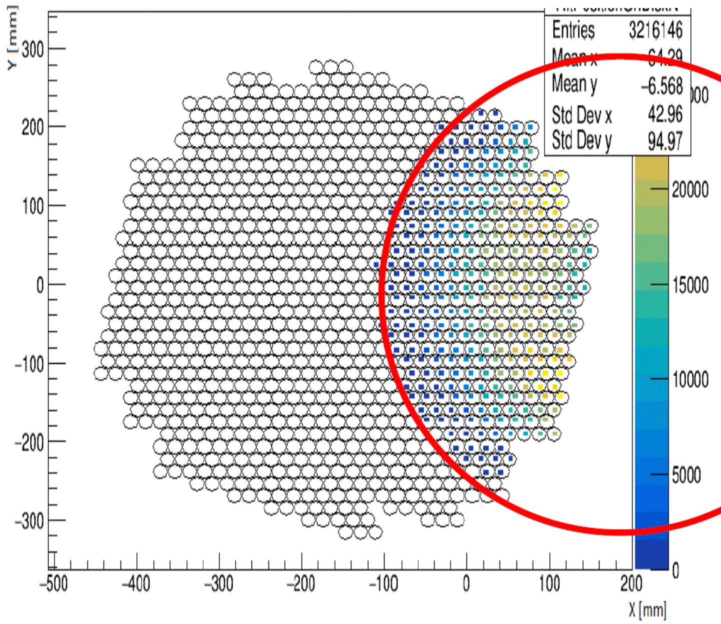
NA62 RICH was designed to measure $\mathrm{BR}(K^+ \rightarrow \pi^+\nu\bar{\nu})$, thus optimizing positive charged tracks identification

- Most of the positive tracks within the NA62 experiment go toward the Saleve side
- Select $\mathrm{K}^+ \rightarrow \pi^+\pi^-\pi^+$ decay and look at the illumination of the PMTs disk on the Jura side

Hits distribution due to π^+



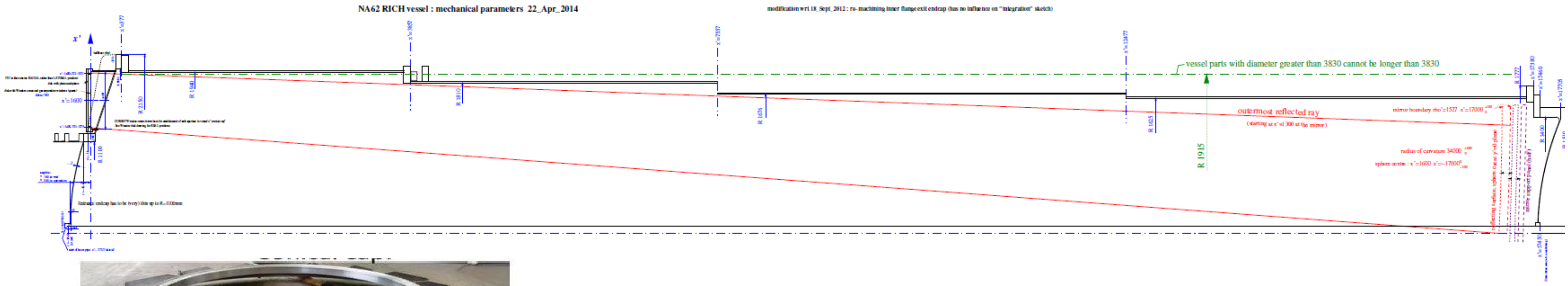
Hits distribution due to π^-

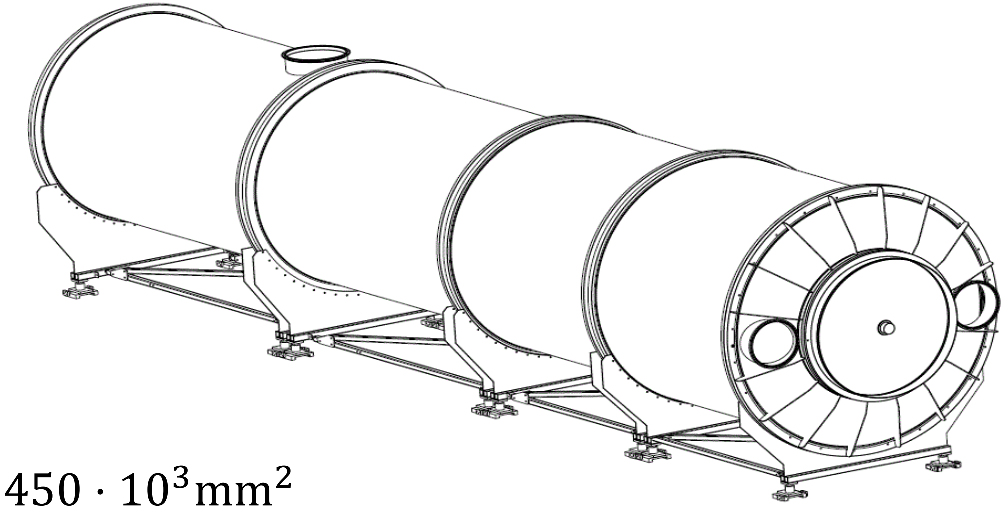


Moving the center of curvature of Jura mirrors to increase the acceptance of negative tracks, if feasible, makes the acceptance for positive tracks decrease

Negative Tracks Acceptance

Can we increase the size of the Jura disk without touching the vessel but only the conical entrance window?





- Neither easy nor costless
- Instrumented surface from $280 \cdot 10^3 \mathrm{mm}^2$ to $450 \cdot 10^3 \mathrm{mm}^2$

Conclusions

Highly demanding detector that, still after 6 years and without any intervention, fulfils all the design requirements and plays a fundamental role in the measurement of $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$:

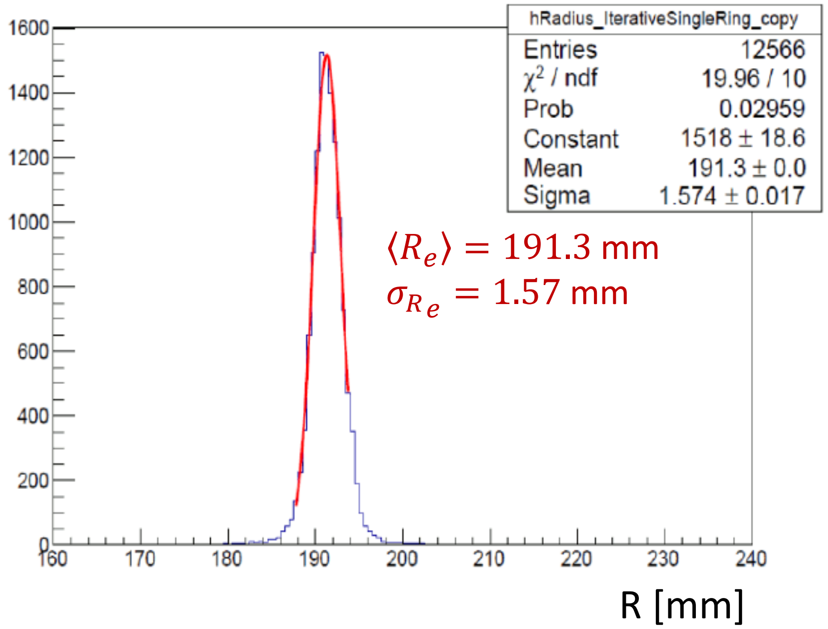
- the optimal RICH time resolution, $\sigma_t \sim 70\ \mathrm{ps}$, is essential for the L0 trigger and to suppress accidental background
- while the RICH PID performance is crucial to reduce background from kaon decays (see talk by V. Duk on Tuesday)

An upgrade of the sensors to reach an even better time resolution, $\sigma_t \sim$ 20-30 ps, for a possible future high intensity kaon experiment is under study

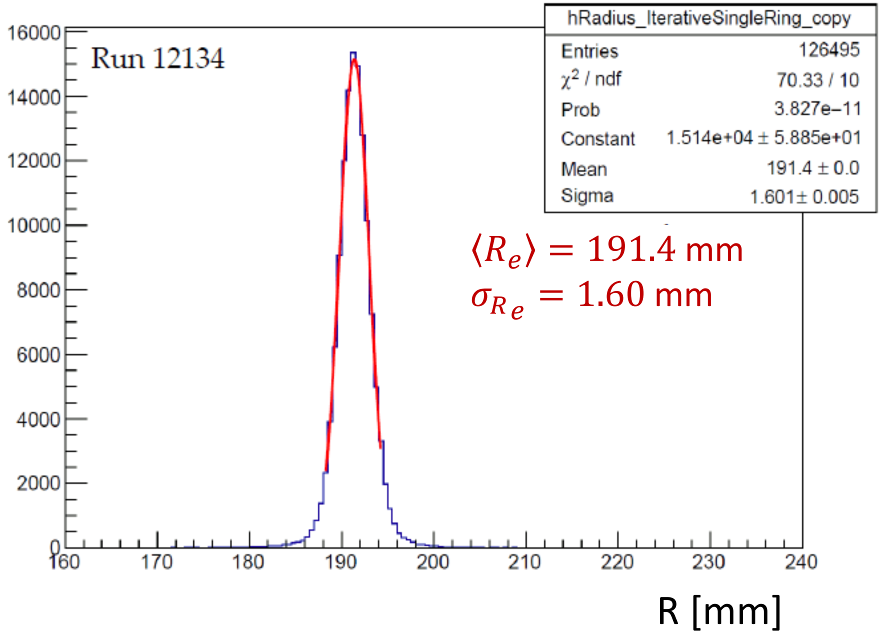
Spares

Electron Radius

2021 Data – positron selection



2022 Data – positron selection

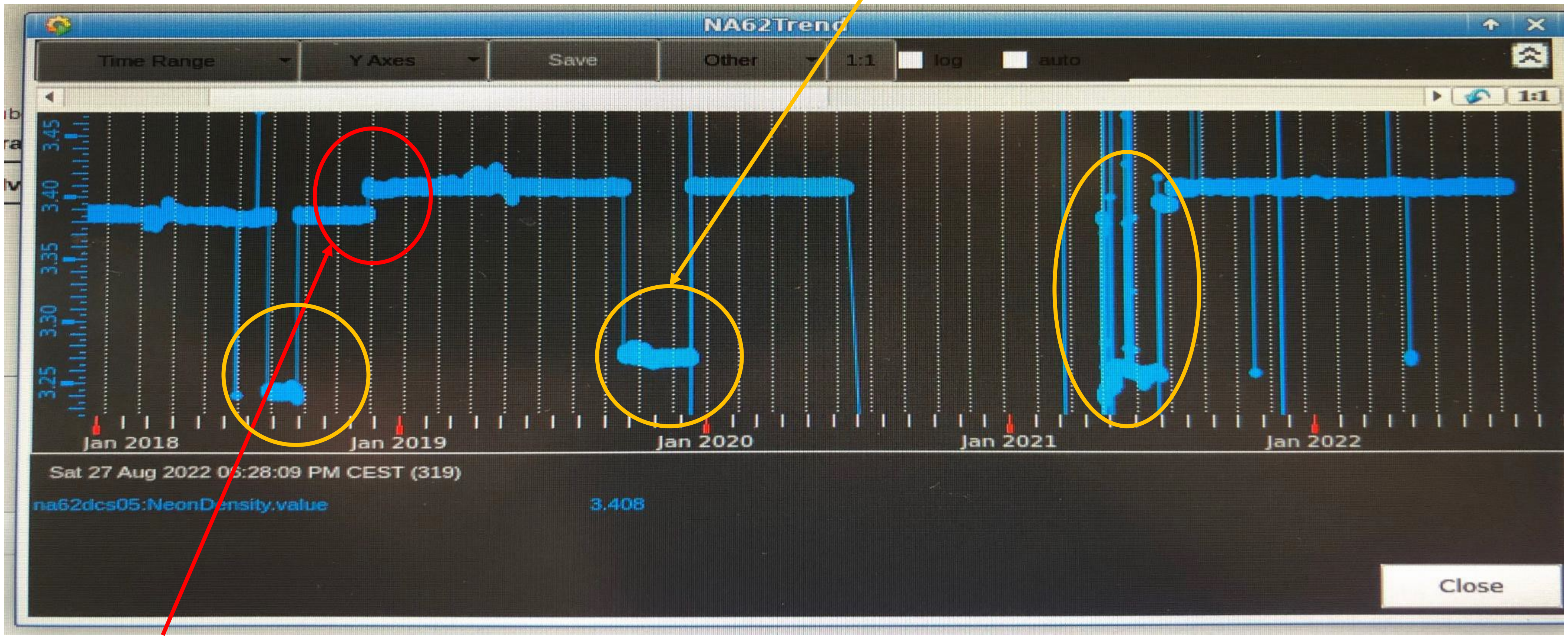


No significant increase of the ring radius is observed in 2022 w.r.t. 2021 ($< 10^{-4}$ relative)

p/T Trend

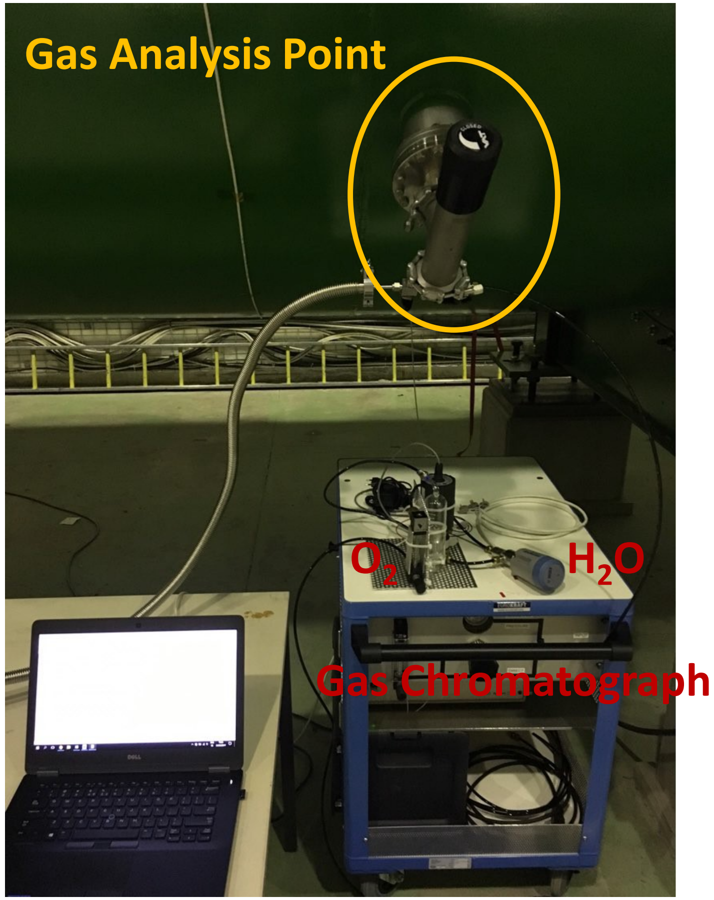
Stable during data taking

Temperature sensors problems



Neon refill on the 21th of November 2018 ($\Delta p/p \sim + 0.55$)

Gas Measurements



Date	O_2 (ppm)	H_20 (C°)	H_2O (ppm)
November 2015	100	-31°C	~350
December 8th, 2017	93.0	-26°C	~500
June 12th, 2018	73.0	-25.35°C	607
October 25th, 2018	72.5	-24.6°C	654
December 6th, 2018	74.3	-25°C	629
??	77	-20°C	1020
??	74	-19.9°C	1020
August 28th, 2022	?	-17°C	1490