The RICH Detector of the NA62 Experiment @ CERN

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on behalf of the NA62 Collaboration

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Moskow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP), Rome I, Rome II, San Luis Potosí, Sofia, TRIUMF, Turin, Vancouver (UBC)

VCI

VIENNA CONFERENCE ON INSTRUMENTATION

FEB 18-22, 2019

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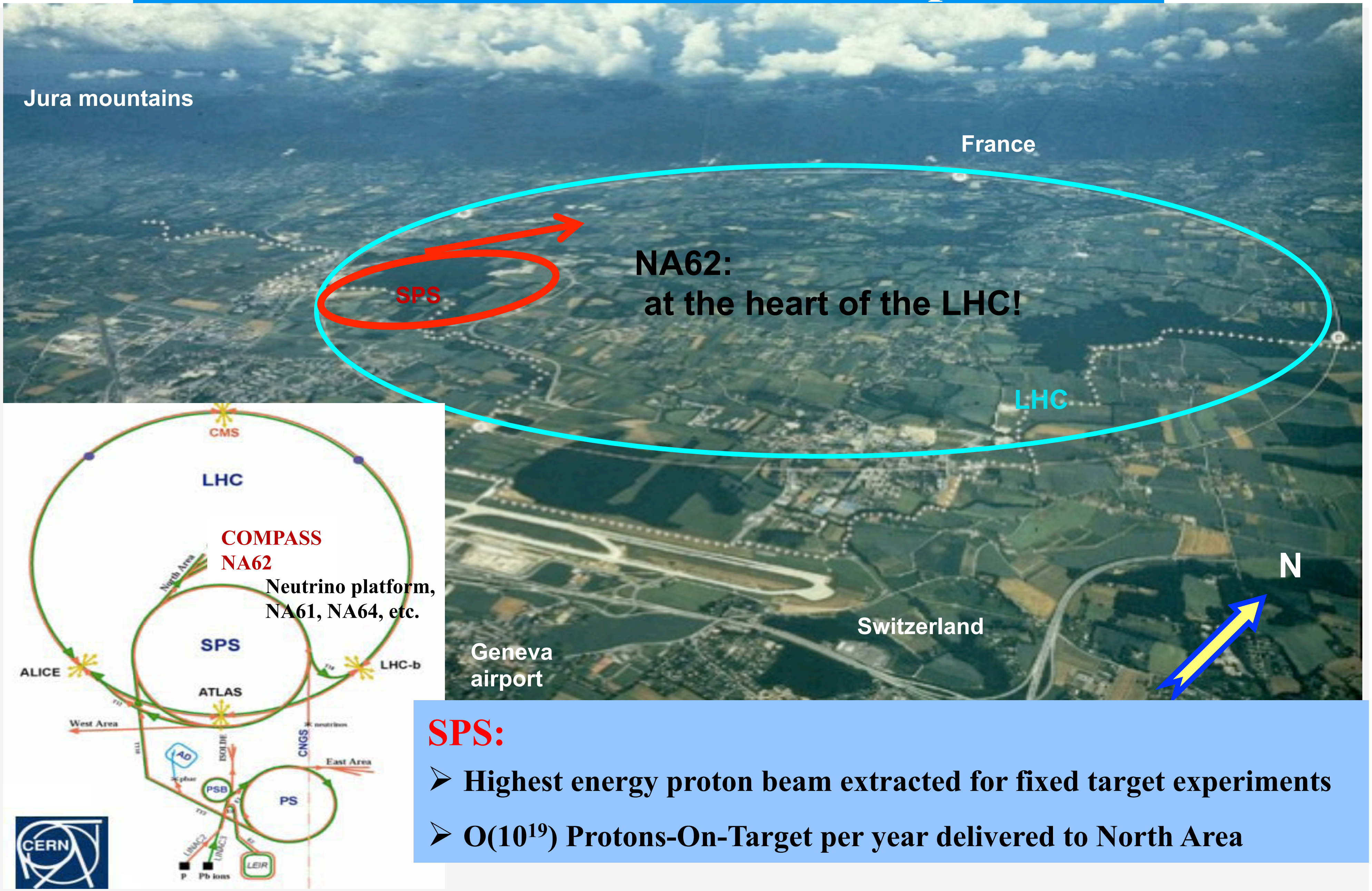
Outline

- The NA62 experiment
- The RICH detector
- Latest RICH performance results
- Conclusions

The CERN Accelerator Complex

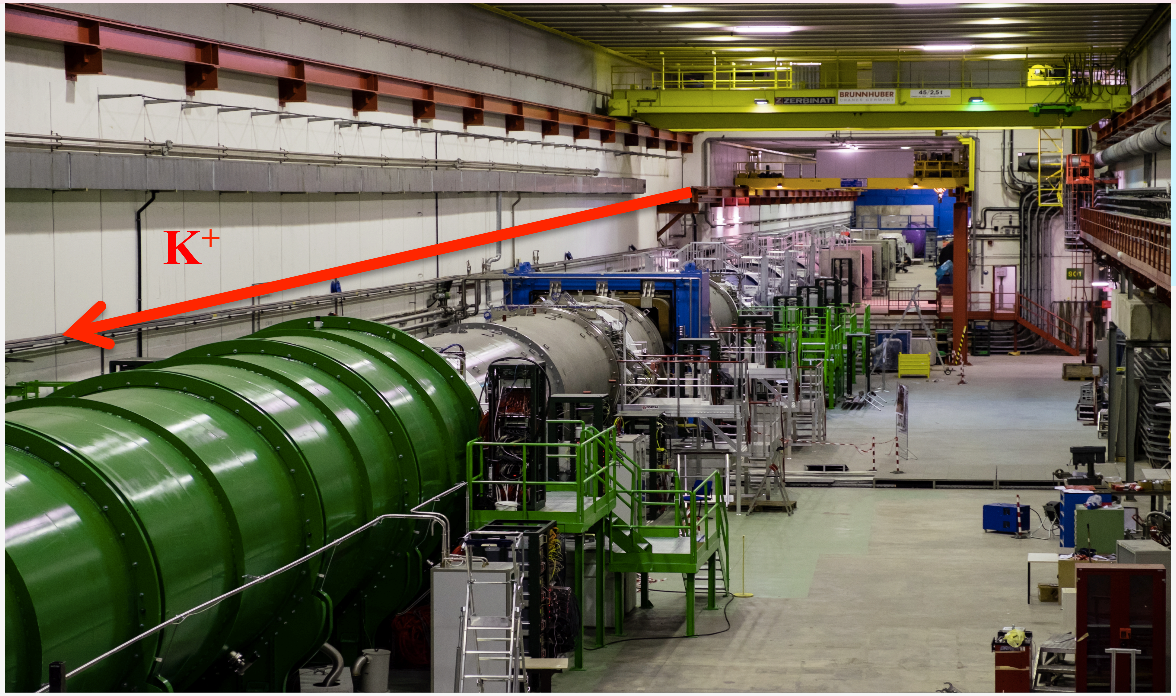


SPS:

- Highest energy proton beam extracted for fixed target experiments
- O(10^{19}) Protons-On-Target per year delivered to North Area

The NA62 Experiment @ CERN

MAIN GOAL: Measurement of BR($K^+ \to \pi^+ \nu \bar{\nu}$) @ 10% accuracy



Broad physics program

- Rare K^+ decays
- LNV-LFV in K^+ decays
- Hidden sector particles

Future plans: Run 3 (2021-2023)

- Complete $\pi^+\nu\nu$ measurement
- Address new physics cases:
  - LFV/LNV measurements, rare decays
  - Dump mode → MeV-GeV mass hidden-sector
    - ⇨ Dark Photons, Heavy Neutral Leptons, Axions/Axion-Like-Particles, etc

2012-2014	2014	2015	2016	2017	2018	2019-2020
Installation	Pilot run	Commissioning	Final Commissioning Physics run (30 days)	Physics run (160 days)	Physics run (217 days)	LS2

2016: 40% of nominal intensity → **5×10^{11}** K^+ decays

2017-18: 60% of nominal intensity → **8×10^{12}** K^+ decays

1 $K^+ \to \pi^+\nu\bar{\nu}$ event observed

Expected Background:

$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$

SES: $(3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \times 10^{-10}$

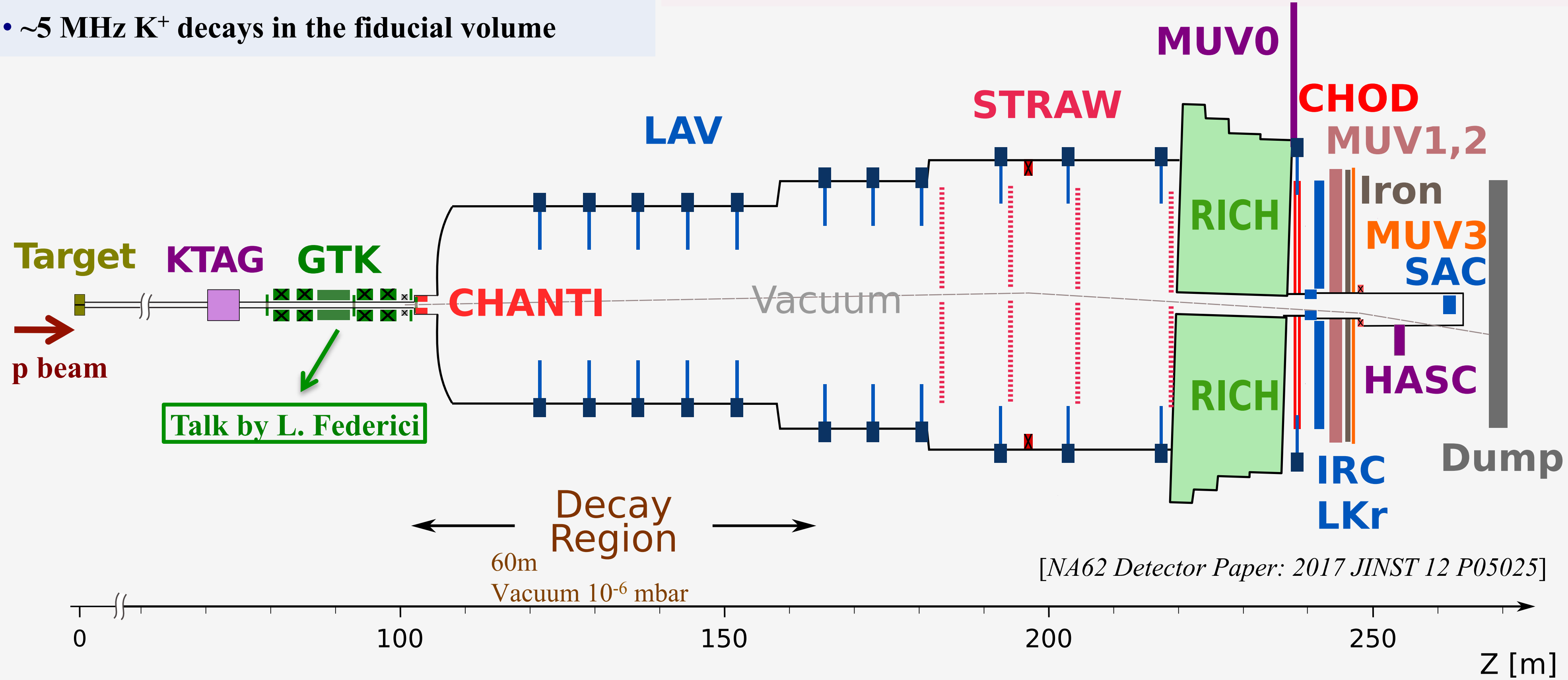
arXiv:1811.08508 (accepted by PLB)

The NA62 Detector

Primary beam: CERN SPS protons
- 400 GeV/c
- 3.3×10^{12} ppp

Secondary beam:
- unseparated positive beam π(70%)/K(6%)/p(23%)
- p_K = 75 GeV/c ($\Delta p/p \sim 1.1\%$)
- Nominal beam rate = 750 MHz@GTK
- K^+ rate ≈ 45 MHz
- ~5 MHz K^+ decays in the fiducial volume

Main Detectors
- **Tracking:** Si-pixel beam tracker **(GTK)** + Straw spectrometer in vacuum **(STRAW)**
- **PID:** Cherenkov for K^+ beam **(KTAG)** and for decay products **(RICH)**
- **Hermetic veto: Photon-veto/calorimeters** + muon veto system
- **CHANTI:** inelastic interactions of beam and collimator/GTK3
- **CHOD:** plastic scintillators for fast charged trigger

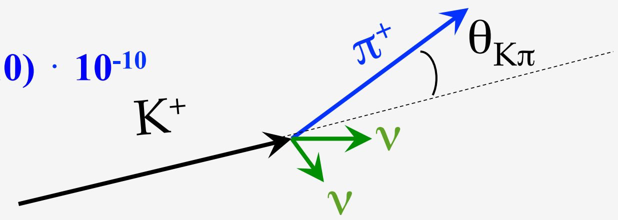


[NA62 Detector Paper: 2017 JINST 12 P05025]

NA62 and RICH requirements

- **Signal**

BR_{SM} =(0.84 ± 0.10) · 10^{-10}



- **Background**

Decay	BR
$\mu^+\nu$ ($K_{\mu 2}$)	63.5%
$\pi^+\pi^0$ ($K_{\pi 2}$)	20.7%
$\pi^+\pi^+\pi^-$	5.6%

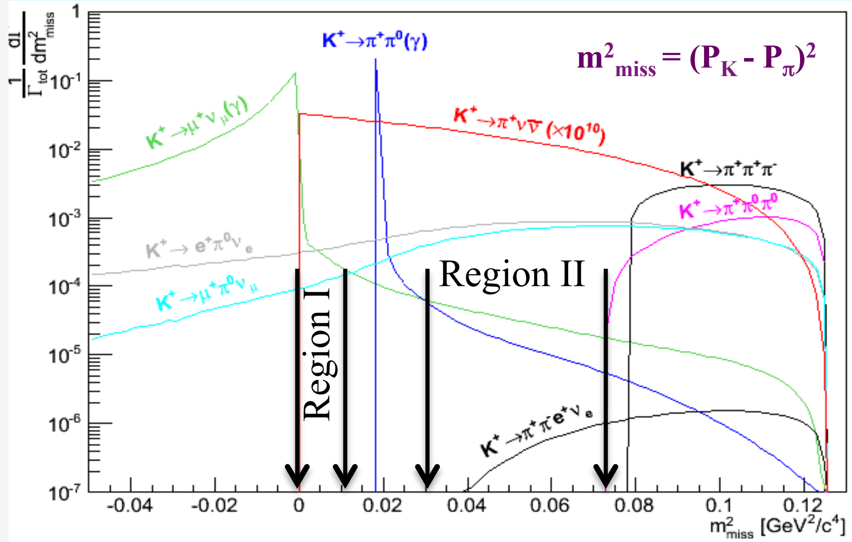
Main Bakground

- **Experimental strategy**
  - Kinematics
  - Particle ID
  - Photon/Muon rejection
  - $15 < P_{\pi+} < 35$ GeV/c

- **Keystones**
  - O(100 ps) timing between subdetectors
  - O(10^4) kinematic rejection
  - $>10^7$ Muon rejection
  - $>10^7$ π^0 suppression

NA62 Requirements

- O(10%) signal acceptance
- 10^{13} Kaon decays in fiducial volume
- O(10^{12}) background rejection

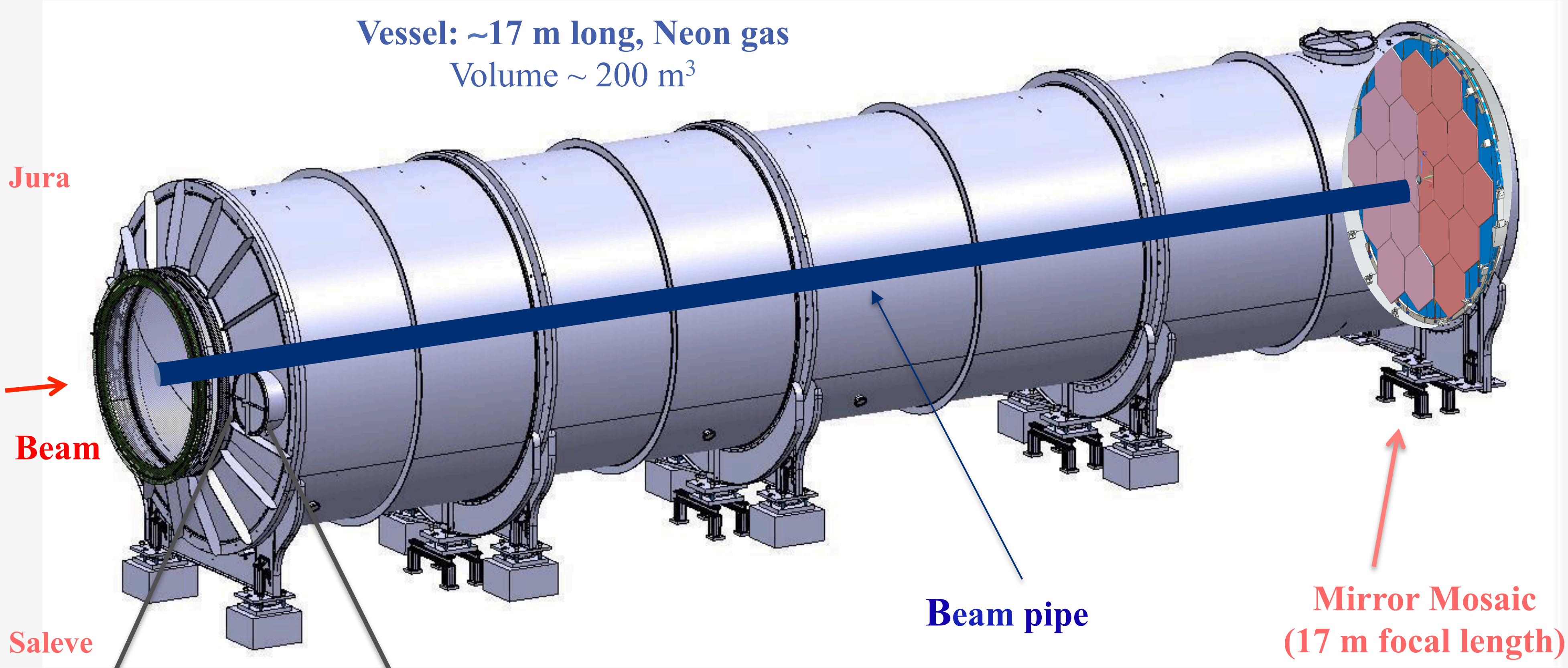


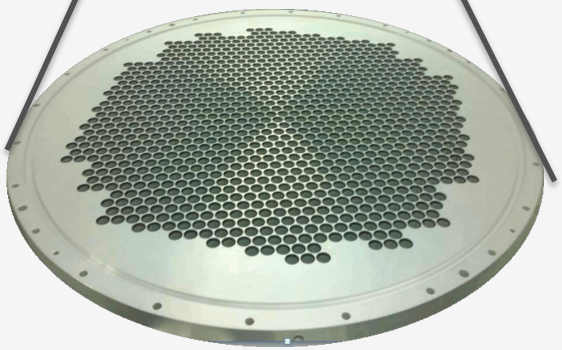
- **Rejection of $K^+ \to \mu^+\nu_\mu$ O(10^{11})**
  - Kinematic cuts: O(10^4)
  - PID in calorimeters: $>10^5$
  - PID in RICH $>10^2$

RICH Requirements

- Muon mis-ID at 10^{-2} level in $15 < P_{\pi+} < 35$ GeV/c
- Measure pion crossing time with a resolution ~100 ps
- Provide a L0 trigger for charged tracks

The NA62 RICH layout



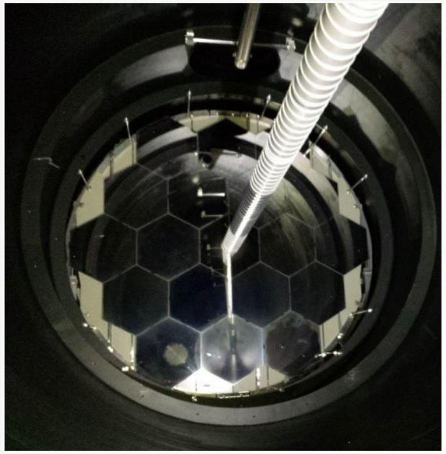


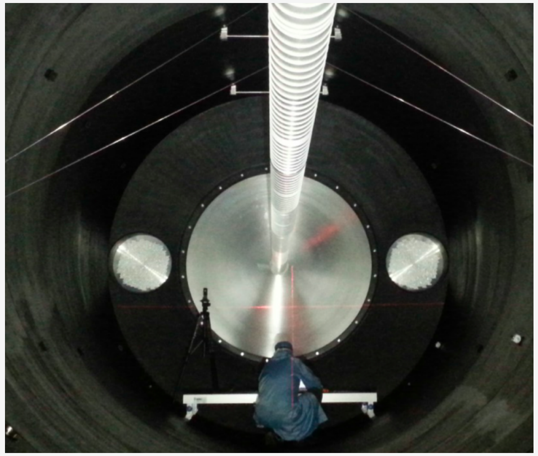
PMT flange (2 flanges x 976 PMTs)
Size: R~300 mm
Winston cones: d=18 mm

RICH vessel and radiator

VESSEL
- Vacuum proof tank
- 17 m long made of structural steel
- 4 longitudinal cylindrical sections:
  decreasing diameter (4→3.4 m) and different lengths
- beam pipe (∅ 168 mm) passing through
- thin Al entrance and exit windows

RADIATOR
- Neon gas slightly above atmospheric pressure
- refractive index (n-1) = 62.8 10^{-6} at λ=300 nm
- low chromatic dispersion
- Cherenkov threshold p = 12.5 GeV/c for π
- low atomic number: θ_{Cmax}= 11.2 mrad
- good light transparency in visible and near-UV



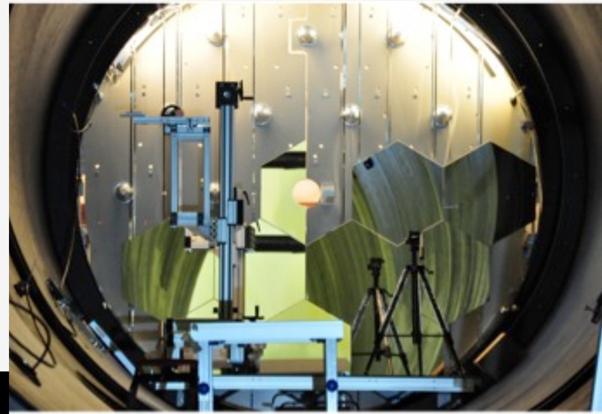


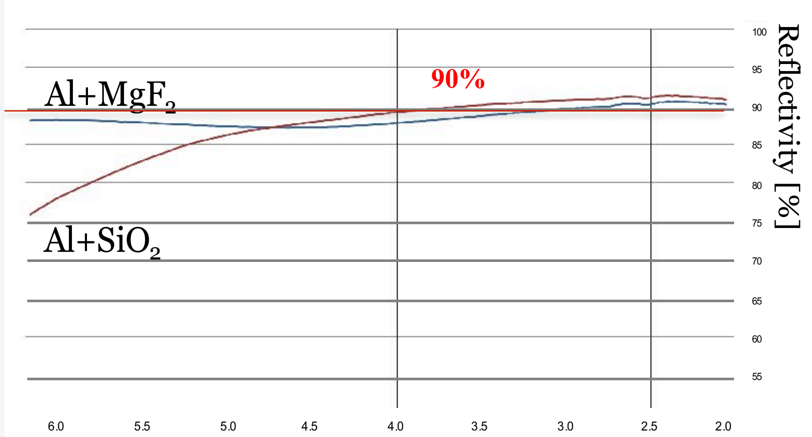
RICH performance rather immune to impurities
- no purification/recirculation system [*IEEE Trans.Nucl.Sci 60 (2013) 1, 265*]
- fresh neon injected after vessel evacuation:
  - first fill in 2014, refill in 2016 after maintenance
  - small top-up refill time by time
  - gas analysis time by time

Gas Analysis	O_2 (ppmV)	H_2O (ppmV)
November 2015	100	~350
June 2017	70-80	~100
December 2017	93	~500
June 2018	73	566

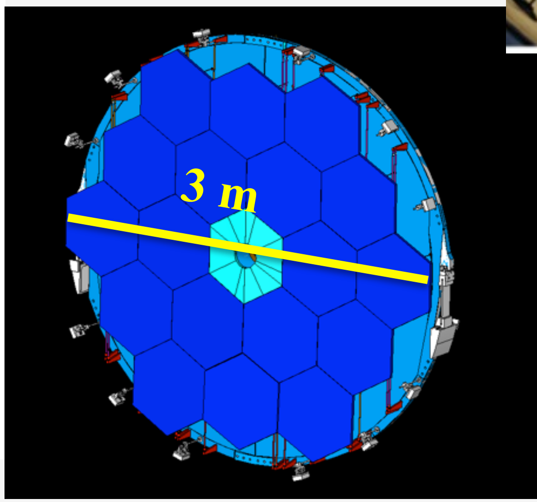
RICH mirror system and mechanics

- Mosaic of 20 spherical mirrors: 18 hexagons + 2 semi-hex
- Two surface orientation (center of curvature at beam pipe sides)
- Radius of curvature (34 ± 0.2) m
- 2.5 cm thick glass, Al coat + thin dielectric film MgF_2
- Average reflectivity ~90% in λ(195-650) nm , $D_0 < 4$ mm

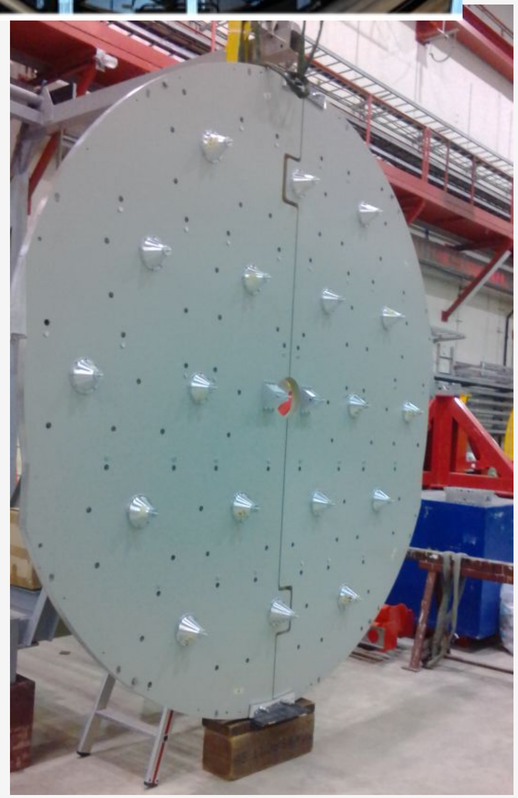




Total reflectivity for two different coating as a function of photon energy.



- Mirrors individually supported by a back dowel connected to the panel
- Two thin Al ribbons keep the mirror in equilibrium allowing its orientation
- A third vertical ribbon is used to avoid mirror rotations
- Remote control of mirror orientation through 38 Piezo motor actuators for alignment



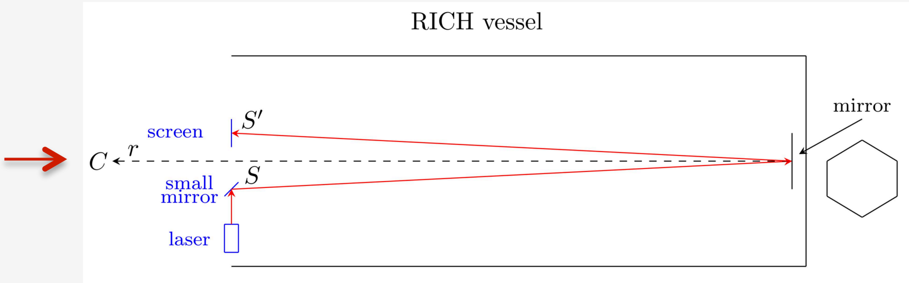
Aluminium honeycomb support structure 5 cm thick, two halves

[*D. Aisa et al., JINST 12 P12017 (2017)*]

Mirror alignment

Preliminary laser alignment

- done before vessel closing
- precision O(500) μrad in terms of mirror orientation

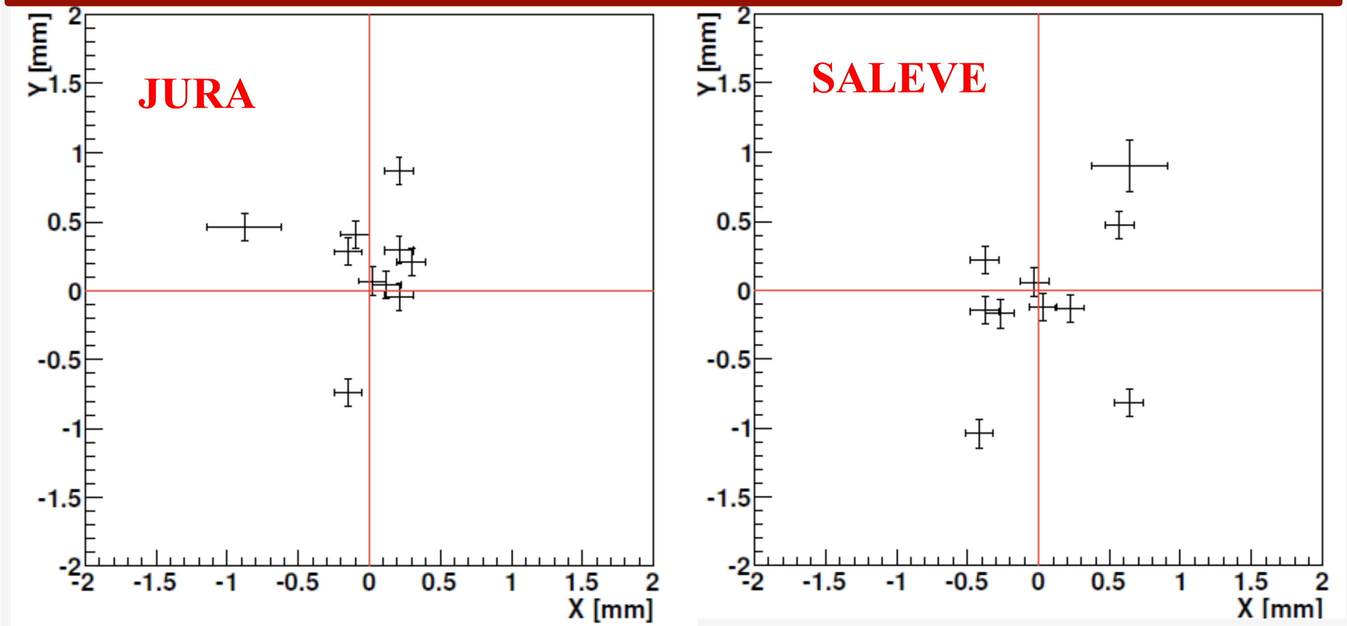


Final alignment with 2016 data

- Single-Track events reconstructed by spectrometer
- Select rings fully contained in a single mirror
- Semi-hexagonal mirrors used as reference
- precision O(30) μrad in terms of mirror orientation
- Iterative procedure
- Compare ring center position on the PMT plane to the position predicted by track extrapolation

→ Align each mirror using piezomotors

RESIDUAL MISALIGMNENT



- All mirrors within ±1mm (one point/mirror)
- Global Offset ~O(20)mm
- Residual misaligment:

→ 1mm (ring center position)

→ 30 μrad (mirror orientation)

- Alignment monthly monitored

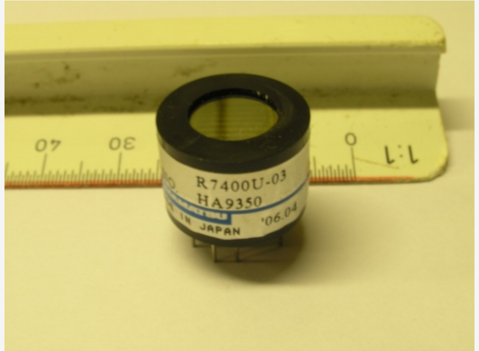
→ Stable along run periods

[G. Anzivino et al., JINST 13 P07012 (2018)]

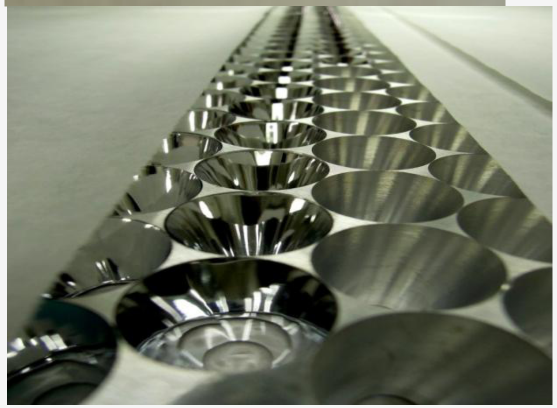
Photodetection system

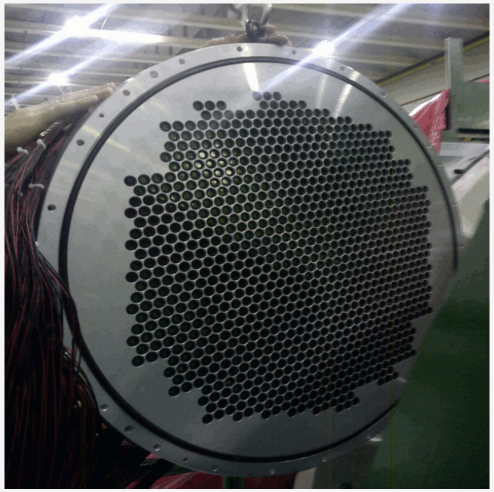
Cherenkov light collected by 1952 PMTs with 18 mm pixel size

- **Hamamatsu R7400U-03**
- **Two aluminium disks placed at the upstream endcap**
- **Winston Cones with aluminized Mylar to optimize light collection**
- **1 mm thick quartz windows to separate Neon from air**
- **Custom made HV divider**
- **No PMT replaced after 2014**



Hamamatsu R7400U-03 Photomultipliers
Sensitivity range 185-650 nm (420 nm peak)
Gain 1.5×10^6 at working point = 900 V
UV glass window, 16 mm Ø (photocatode 8 mm active)
Q.E. ~ 20% at peak
280 ps time jitter (FWHM)



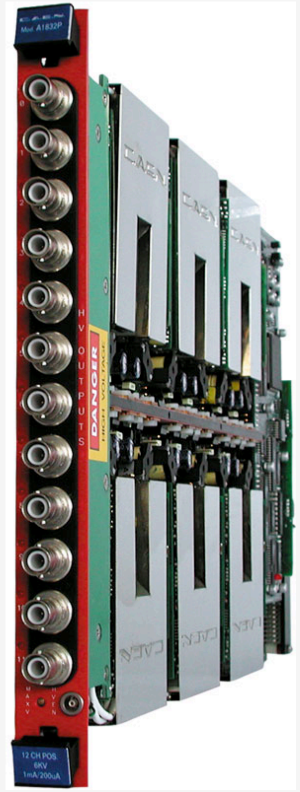


PMTs are assembled in compact hexagonal packing

The RICH HV system

The PMTs require a low-noise 800-1000 V negative voltage supply

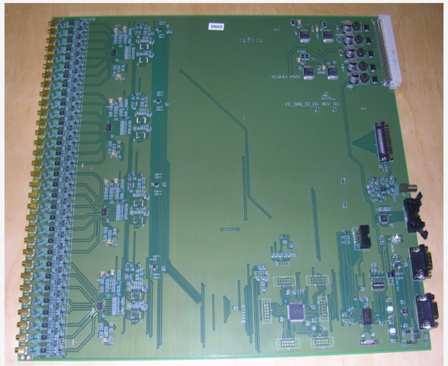
- 4 CAEN Mainframes SY1527 (16 slots)
- A1733N (14 boards,12 ch), A1535SN(15 boards, 24 ch)
- 4 PM feeded by one HV channel
- The last (A1733N) board of each frame has 10 unused (spare) HV channels
- 1 A1733N and 1 A1535SN spare boards
- Some boards replaced and repaired



FRONT-END and TDAQ electronics

RICH Front-End

- Custom made boards (current amplifiers with differential output)
- NINO chips used as fast Time-over-Threshold discriminator
- 64 FE boards of 32 channels each (4 NINO each)
- Signal leading and trailing edge for time slewing corrections



RICH Read-Out

- 128 channels TDC daughter Boards (TDCB), 4 CERN HPTDC each
- NINO → 5 TEL62 mother boards FPGA based, housing 4 TDCB each
  - 4 TEL62 boards for the 1952 PMTs
  - 1 TEL62 board for multiplicity read-out used to produce the L0 trigger
- Trigger primitives are built in parallel with the readout on the same TEL62 board

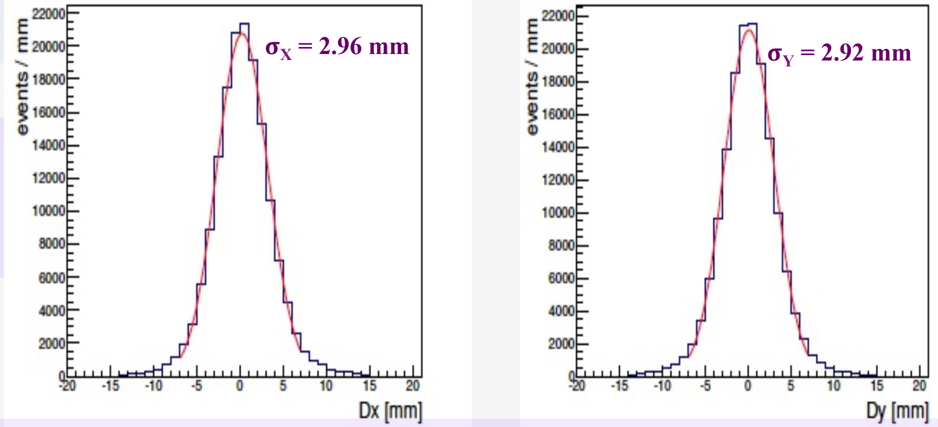
RICH basic performance

Resolution of basic variables → can be compared to other RICH's

- **Clean positrons from $K^+ \to \pi^0 e^+ \nu$ decays**
- **Single rings fully contained in RICH acceptance**
- **Performance after mirror alignment**

2016 DATA

Ring Center resolution



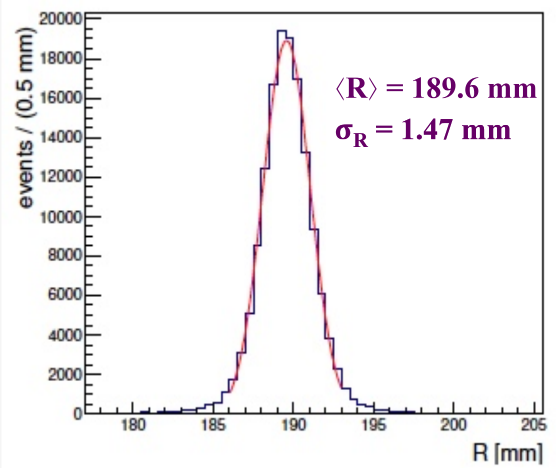
- **Ring center resolution:** gaussian width of difference between measured/expected ring center positions

[*G. Anzivino et al., JINST 13 P07012 (2018)*]

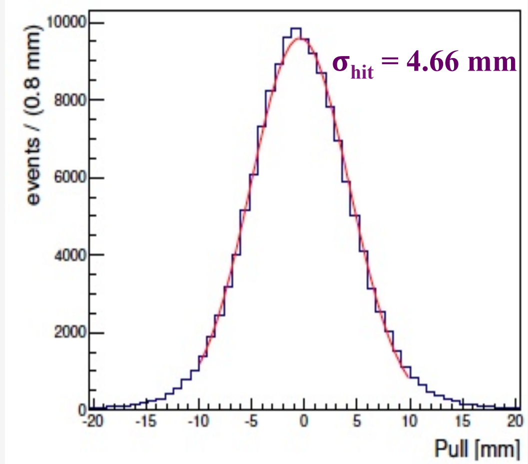
- **Ring radius resolution:** gaussian width

- **Single hit resolution:** gaussian width of the Pull = $(R - R_{exp})\sqrt{(N_{hits} - 3)}$
- **Number of hits/ring:** poissonian fit

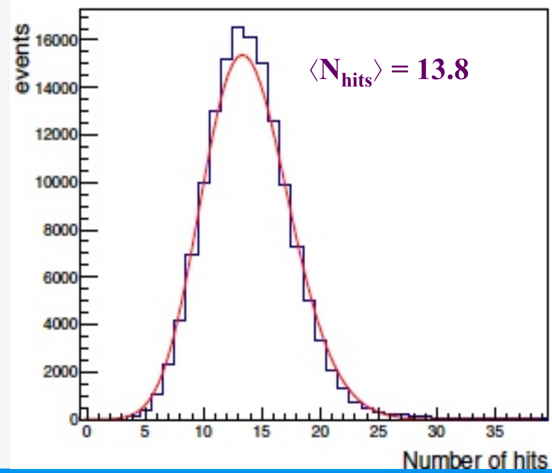
Ring Radius resolution



Single hit resolution



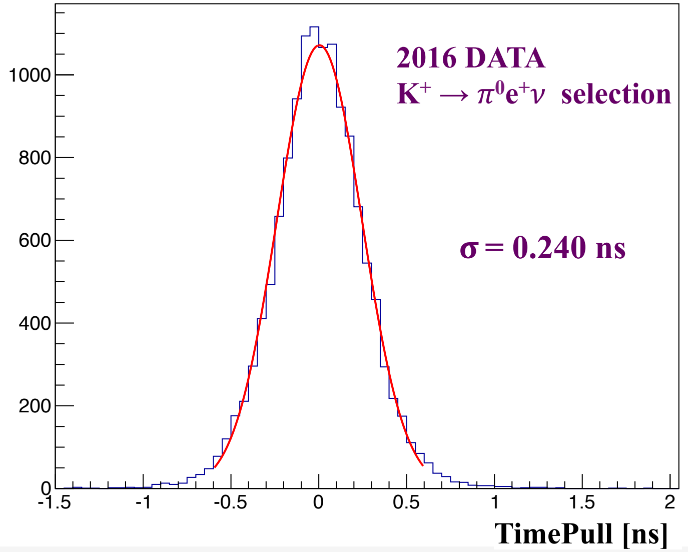
Number of hits per ring



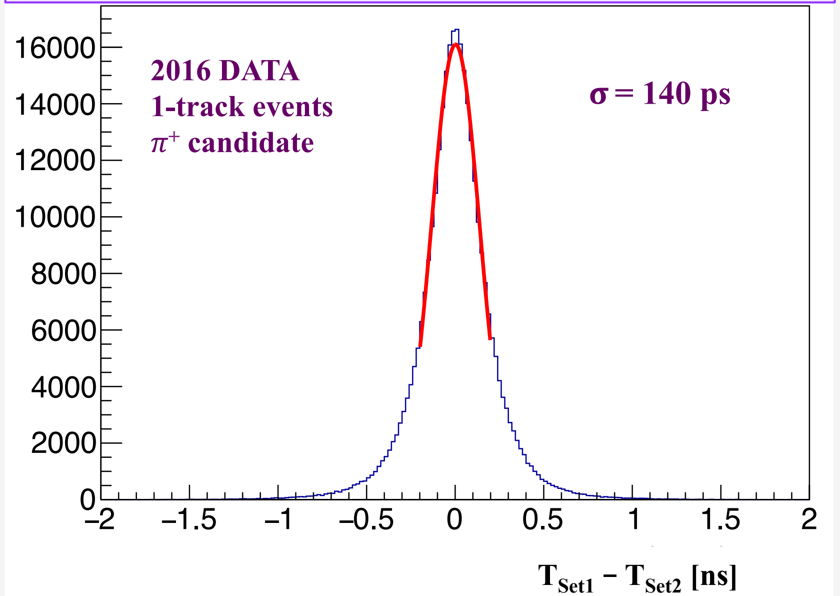
Intrinsic RICH Time resolution:

Hits on Cherenkov ring divided in 2 halves → difference between time average of 2 sets

Single hit time resolution



Event time resolution



2016 DATA

- **Single hit time resolution:**
  gaussian width of TimePull = $0.5 \cdot (T_{Set1} - T_{Set2}) \sqrt{N_{hits}}$

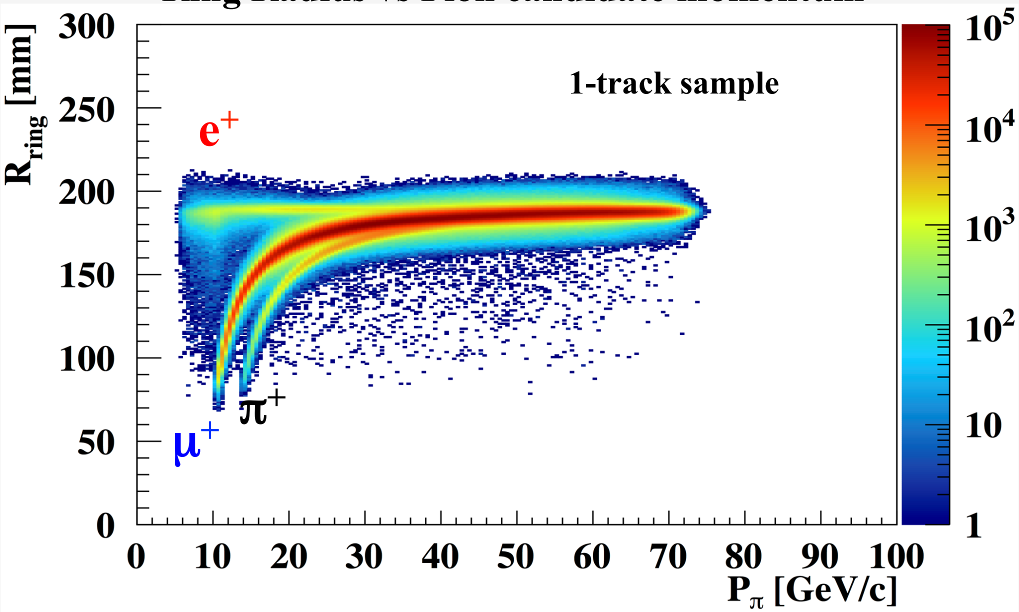
- **Event Time resolution:**
  Time Resolution of the full ring = $0.5 \cdot \sigma$

RICH Time Resolution ~ 70 ps

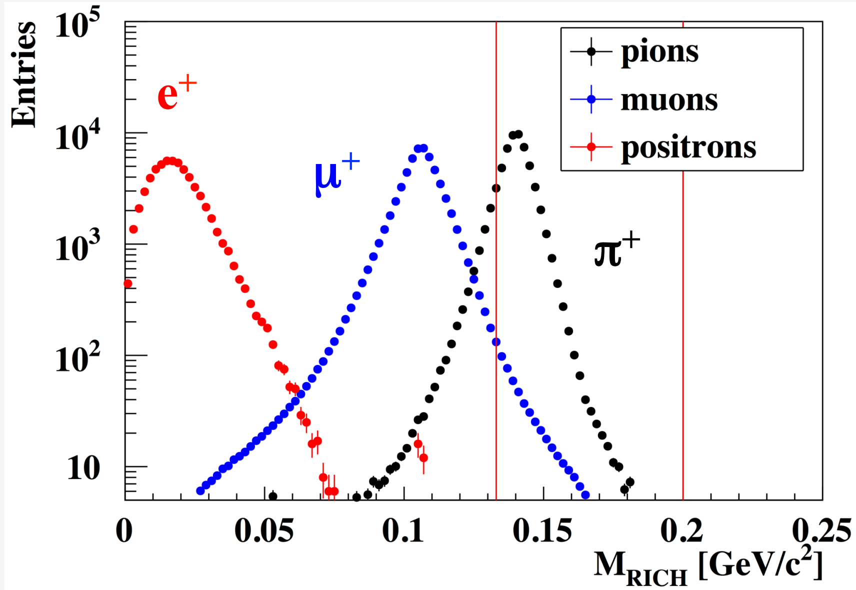
RICH performance: PID

2016 Data $\pi^+\nu\nu$ selection

Ring Radius vs Pion candidate momentum



Particle mass from R (RICH) and P_π (STRAW)

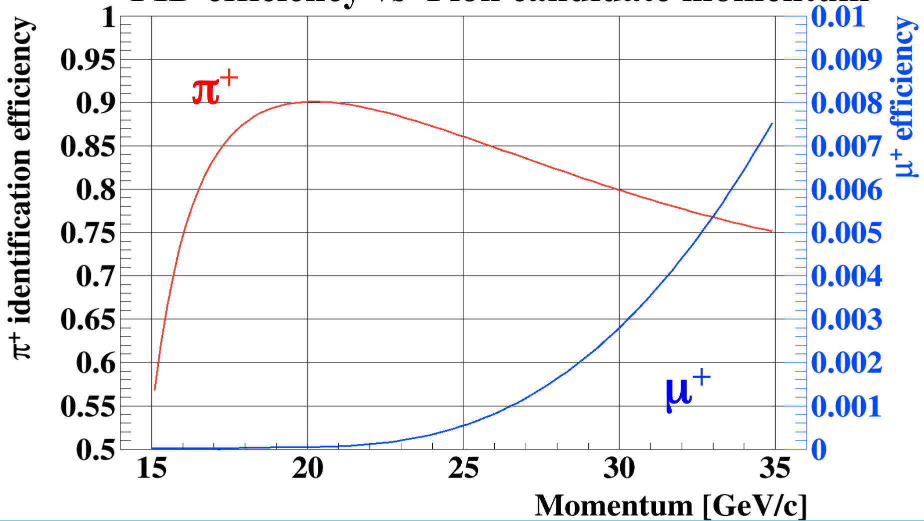


$M_{RICH} = P_\pi \sqrt{(n^2 \cdot \cos^2(\tan^{-1}(R/f)) - 1)}$

P_π: pion momentum, n: refractive index

R: ring radius, f: mirror focal length.

PID efficiency vs Pion candidate momentum

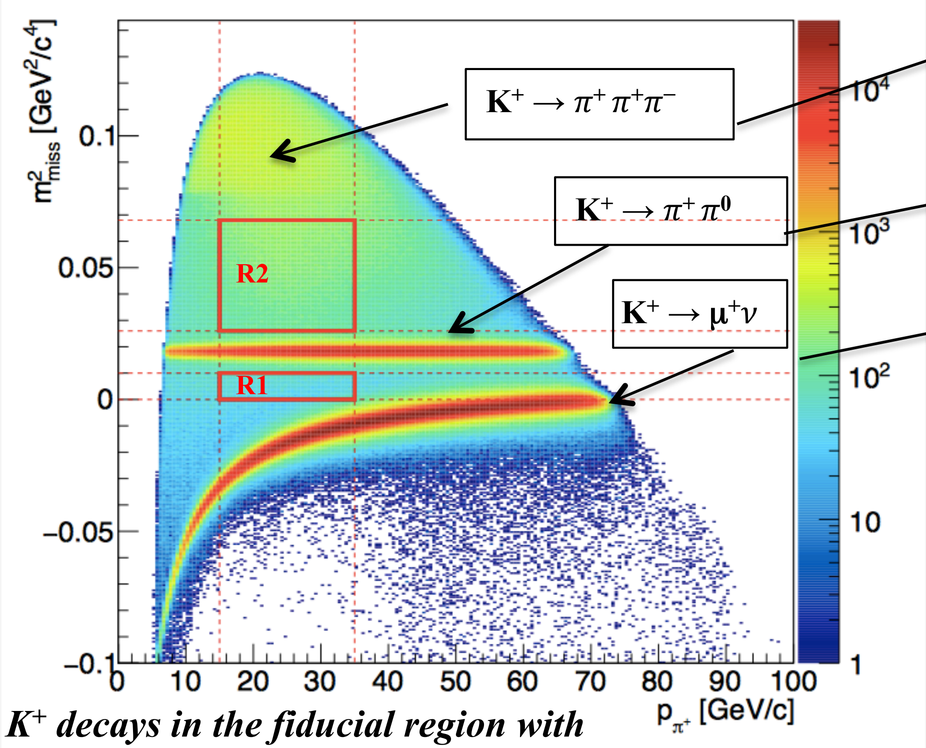


- Track driven Likelihood particle ID discriminant
- Particle mass extracted using track momentum
- Momentum measurement under mass hypothesis
- Average over momentum range (15,35) GeV/c:

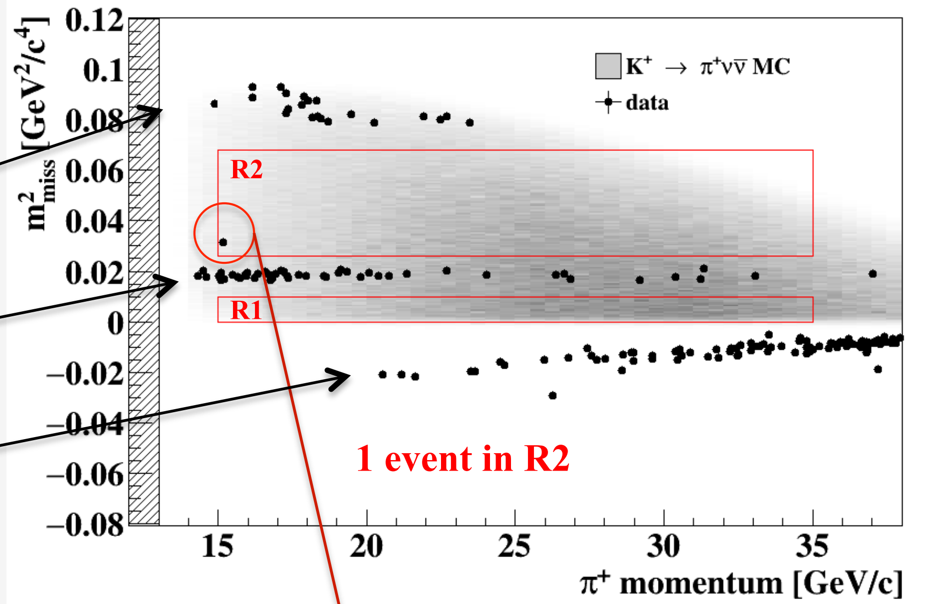
  $2.1 \cdot 10^{-3}$ μ^+ efficiency *vs* 82% π^+ efficiency

$K^+ \to \pi^+\nu\bar{\nu}$ event in the RICH

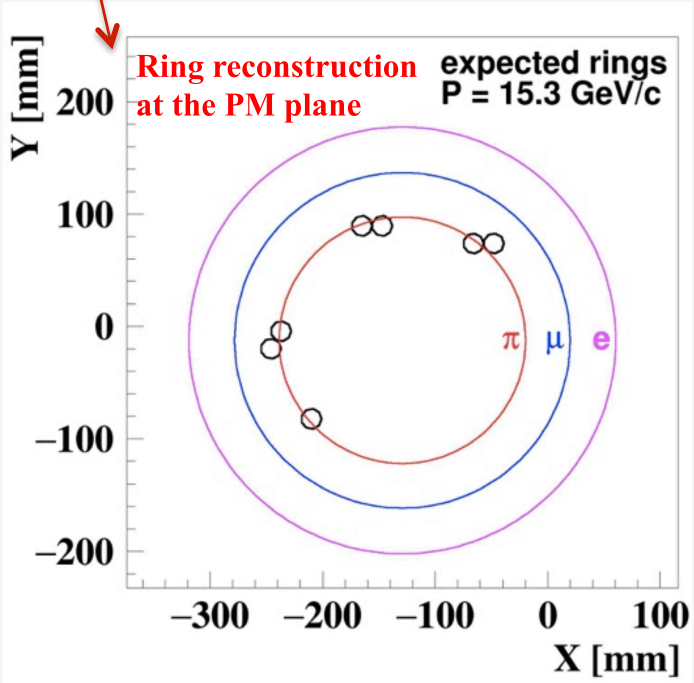
Kinematic selection of signal regions:
$m^2_{miss} = (P_K - P_\pi)^2$ with the m_π hypotesis



K^+ decays in the fiducial region with a single charged particle in final state



2016 DATA



SM prediction: $BR_{SM}(K^+ \to \pi^+\nu\nu) = (0.84 \pm 0.10) \cdot 10^{-10}$

Expected SM signal events: $0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$

Expected background events: $0.15 \pm 0.09_{stat} \pm 0.01_{syst}$

$$BR_{NA62}(K^+ \to \pi^+\nu\nu) < 14 \cdot 10^{-10} \text{ (95\% CL)}$$

NA62 Collaboration arXiv:1811.08508 (accepted by PLB)

Conclusions

- The NA62 RICH detector has been **installed in 2014** and **commissioned in 2014-2015**
- **Refurbished in 2015-2016** winter shutdown, succesfully running since then
- RICH performance very close to expectations
- NA62 was approved up to 2018 with the main goal of measuring BR($K^+ \rightarrow \pi^+ \nu\nu$)
- **Run 3 (2021-2023):** opportunity for NA62 to complete the BR measurement and to address new physics cases
  → **The NA62 RICH will be maintained in working conditions for the next NA62 program**