The RICH Detector of the NA62 Experiment at CERN

PATRIZIA CENCI
Sezione INFN di Perugia

on behalf of the
NA62 RICH Working Group

RICH 2018 - 10th International Workshop on Ring Imaging Cherenkov Detectors
Russian Academy of Sciences, Moscow, July 29 – August 4, 2018.
OUTLINE

- The NA62 Experiment
- The NA62 RICH
- Latest measurements of the RICH Performances
- Conclusions
The NA62 Experiment at CERN

- Fixed target experiment at CERN SPS, proposed in 2005
- Main goal: measure $\text{BR}(K^+ \rightarrow \pi^+\bar{\nu})$ with 10% precision
- Taking data, approved until 2018 (Run 2)

Requirements
- $10^{13}$ Kaon decays
- $O(10^{12})$ background rejection
- $O(10\%)$ signal acceptance

Broad physics program
- Rare $K^+$ decays
- LFV-LNV in $K^+$ decays
- Hidden sector particles

The NA62 Collaboration:
Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Merced, Moskow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP), Rome I, Rome II, San Luis Potosí, SLAC, Sofia, Turin, Vancouver (UBC)
Fixed target experiments in the North Area

SPS: highest energy proton beam extracted for fixed target experiments
The CERN Accelerator Complex

SPS: $O(10^{19})$ Protons-On-Target per year delivered to North Area

Compass, NA62, Neutrino platform, NA61, NA64, etc.
NA62 data taking and first $\pi^+\nu\nu$ results

- **2007-2008**: $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$ measurement
- **2014**: pilot run
- **2015**: commissioning run
- **2016**: commissioning + physics run (30 days)
  - 13 x $10^{11}$ ppp on target (40% nominal intensity)
  - ~ $10^{11}$ $K^+$ decays useful for $\pi^+\nu\nu$
    \[ \Rightarrow K^+ \rightarrow \pi^+\nu\nu \text{ preliminary results} \]
- **2017**: physics run (160 days)
- **2018**: 217 days physics run, ongoing
  \[ \Rightarrow \text{ expect } \sim 20 \pi^+\nu\nu \text{ SM events} \]

**Future plans: Run 3 (2021-2023)**
- Complete $\pi^+\nu\nu$ measurement
- Address new physics cases:
  - LFV/LNV measurements, rare decays
  - Dump mode to search for MeV-GeV mass **hidden-sector** candidates
    \[ \Rightarrow \text{ Dark Photons, Heavy Neutral Leptons, Axions/Axion-Like-Particles, etc} \]

**2016 integrated statistics for $\pi^+\nu\nu$**

\[ \sim 10^{11} \text{ $K^+$ decays good for } \pi^+\nu\nu \]

**1 $K^+ \rightarrow \pi^+\nu\nu$ event observed**

Expected Background:

\[ 0.15 \pm 0.09_{\text{stat}} \pm 0.01_{\text{syst}} \]

**SES:** \[ (3.15 \pm 0.01_{\text{stat}} \pm 0.24_{\text{syst}}) \times 10^{-10} \]
The NA62 Detector

Primary SPS proton beam
- \( p = 400 \text{ GeV/c}, 10^{12} \text{ p/s} \)
- 3.4 s effective spill
The NA62 Detector

Primary SPS proton beam
- $p = 400 \text{ GeV/c}, 10^{12} \text{ p/s}$
- 3.4 s effective spill

Secondary positive beam
- $p_K = 75 \text{ GeV/c}$ ($\Delta p/p \sim 1\%$)
- $\pi^+(70\%) / K^+(6\%) / p(24\%)$
- nominal intensity $33 \times 10^{11}$ ppp (750 MHz@GTK)
The NA62 Detector

Primary SPS proton beam
- \( p = 400 \text{ GeV/c}, 10^{12} \text{ p/s} \)
- 3.4 s effective spill

Secondary positive beam
- \( p_K = 75 \text{ GeV/c} \) (\( \Delta p/p \sim 1\% \))
- \( \pi^+(70\%) / K^+(6\%) / p(24\%) \)
- nominal intensity \( 33 \times 10^{11} \text{ ppp} \) (750 MHz@GTK)

Decay region
- Fiducial decay region 60 m
- \( K^+ \) decay rate \( \sim 5 \text{ MHz} \)
- Vacuum \( 10^{-6} \text{ mbar} \)

Secondary beam Detectors

- Target
- KTAG
- GTK
- Kaon ID
- Beam tracker
- CHANT
- Decays
- CHOD
- MUV0
- MUV1,2
- MUV3
- SAC
- HASC
- LKr
- RICH
- IRD
- LKr
- E.M. calorimeters
- (forward and small angles)

Decay Region

- Primary SPS proton beam
- Secondary positive beam
- Decay region
- Secondary beam Detectors
The NA62 Detector

Primary SPS proton beam
- p = 400 GeV/c, $10^{12}$ p/s
- 3.4 s effective spill

Secondary positive beam
- $p_K = 75$ GeV/c ($\Delta p/p \approx 1\%$)
- $\pi^+(70\%) / K^+(6\%) / p(24\%)$
- nominal intensity $33 \times 10^{11}$ ppp (750 MHz@GTK)

Decay region
- Fiducial decay region 60 m
- $K^+$ decay rate $\sim 5$ MHz
- Vacuum $10^{-6}$ mbar

Main Detectors
- Tracking: Si-pixel beam tracker (GTK) + Straw tracker in vacuum (STRAW)
- PID: Cherenkov for $K^+$ beam (KTAG) and for decay products (RICH)
- Hermetic veto: calorimeters + muon veto system for $\gamma/\mu$ detection

Secondary positive beam detectors

- Target
- KTAG
- GTK
- Kaon ID
- Beam tracker
- CHANT
- Beam guard ring
- Decay volume
- Vacuum
- STRAW spectrometer
- MUV0
- CHOD
- MUV1,2
- Iron
- Muon Veto and Hadron Calorimeters
- SAC
- IRC
- LKr
- E.M. calorimeters (forward and small angles)
- HASC
- Dump
- Decay Region
- Decay region detectors
- Secondary beam detectors
- NA62 Detector Paper:
  JINST 12 (2017) P050250
The NA62 Detector

**Primary SPS proton beam**
- \( p = 400 \text{ GeV}/c, 10^{12} \text{ p/s} \)
- 3.4 s effective spill

**Secondary positive beam**
- \( p_K = 75 \text{ GeV}/c \) (\( \Delta p/p \sim 1\%) \)
- \( \pi^+ (70\%) / K^+ (6\%) / p (24\%) \)
- nominal intensity \( 33 \times 10^{11} \text{ ppp} \) (750 MHz@GTK)

**Decay region**
- Fiducial decay region 60 m
- \( K^+ \) decay rate \( \sim 5 \text{ MHz} \)
- Vacuum \( 10^{-6} \text{ mbar} \)

**Main Detectors**
- **Tracking**: Si-pixel beam tracker (GTK) + Straw tracker in vacuum (STRAW)
- **PID**: Cherenkov for \( K^+ \) beam (KTAG) and for decay products (RICH)
- **Hermetic veto**: calorimeters + muon veto system for \( \gamma/\mu \) detection

**Secondary beam Detectors**
- Beam tracker
- Beam guard ring

**Kaon ID**

**Secondary beam**
- \( p \) beam

**Target**
- KTAG
- GTK

**Beam guard ring**
- CHAN

**Normalised coincidences**
- \( N_C = 5 \)
- \( N_C = 6 \)
- \( N_C = 7 \)
- \( N_C = 8 \)
The NA62 Detector

**Primary SPS proton beam**
- $p = 400\text{ GeV/c}, 10^{12}\text{ p/s}$
- 3.4 s effective spill

**Secondary positive beam**
- $p_K = 75\text{ GeV/c} \ (\Delta p/p \sim 1\%)$
- $\pi^+(70\%) / \ K^+(6\%) / p(24\%)$
- nominal intensity $33 \times 10^{11}\text{ ppp}$ (750 MHz@GTK)

**Decay region**
- Fiducial decay region 60 m
- $K^+$ decay rate ~5 MHz
- Vacuum $10^{-6}\text{ mbar}$

**Main Detectors**
- **Tracking**: Si-pixel beam tracker (GTK) + Straw tracker in vacuum (STRAW)
- **PID**: Cherenkov for decay products (RICH)
- Hermetic veto: calorimeters + muon veto system for $\gamma/\mu$ detection

---

NA62 Detector Paper:
JINST 12 (2017) P050250
**K^+ → π^+νν measurement strategy**

- **Signal:**
  \[ m^2_{\text{miss}} = (P_K - P_\pi)^2 \]

- **Background:** K^+ decays, beam activity

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ^+ν (K_{μ2})</td>
<td>63.5%</td>
</tr>
<tr>
<td>π^+π^0 (K_{π2})</td>
<td>20.7%</td>
</tr>
<tr>
<td>π^+π^+π^-</td>
<td>5.6%</td>
</tr>
</tbody>
</table>

- **Experimental principles**
  - Kinematics
  - Particle ID
  - Photon/Muon rejection
  - 15 < P_{π^+} < 35 GeV/c

- **Keystones**
  - O(100 ps) time coincidence
  - O(10^4) kinematic rejection
  - >10^7 muon rejection
  - >10^7 π^0 rejection
**K^+ \rightarrow \pi^+\nu\bar{\nu} measurement strategy**

- **Signal:**
  \[ m_{\text{miss}}^2 = (P_K - P_p)^2 \]

- **Background:** \( K^+ \) decays, beam activity

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu^+\nu ) (( K_{\mu2} ))</td>
<td>63.5%</td>
</tr>
<tr>
<td>( \pi^+\pi^0 ) (( K_{\pi2} ))</td>
<td>20.7%</td>
</tr>
<tr>
<td>( \pi^+\pi^+\pi^- )</td>
<td>5.6%</td>
</tr>
</tbody>
</table>

- **Experimental principles**
  - Kinematics
  - **Particle ID**
  - Photon/Muon rejection
  - 15 < \( P_{\pi^+} < 35 \) GeV/c
  - **O(100 ps) time coincidence**
  - O(\( 10^4 \)) kinematic rejection
  - >\( 10^7 \) muon rejection
  - >\( 10^7 \pi^0 \) rejection
RICH requirements

Muon contamination < 1% in the pion sample for 15 < p < 35 GeV/c
Time resolution ~100 ps
L0 trigger signal for charged particles

Mirror Mosaic (17 m focal length)

Vessel: ~17 m long, Neon gas

2 × 976 PMTs
RICH vessel and radiator

Vacuum proof tank in construction steel

- 17 m long, overall volume ~ 200 m³
- 4 cylindrical sections of different lengths and decreasing diameter
- Beam pipe (Ø 168 mm) going through
- Thin Al entrance and exit windows
- No purification/recirculation system
- 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

Neon gas radiator slightly above atmospheric pressure

- refractive index \((n-1) = 62.8 \times 10^{-6}\) at \(\lambda = 300\) nm
- Cherenkov threshold \(p = 12.5\) GeV/c for pions
- good light transparency, low chromatic dispersion
- low atomic number, \(\theta_{\text{c,max}} = 11.2\) mrad

<table>
<thead>
<tr>
<th>Gas Analysis</th>
<th>(\text{O}_2) (ppmV)</th>
<th>(\text{H}_2\text{O}) (ppmV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 2015</td>
<td>100</td>
<td>~350</td>
</tr>
<tr>
<td>June 2017</td>
<td>70-80</td>
<td>~100</td>
</tr>
<tr>
<td>December 2017</td>
<td>93</td>
<td>~500</td>
</tr>
<tr>
<td>June 2018</td>
<td>73</td>
<td>566</td>
</tr>
</tbody>
</table>
Photodetection system

Cherenkov light reflected by mirrors is collected by 1952 PMTs in two spots

- Two aluminium disks placed at the upstream endcap
- Winston cones with Al mylar to optimize light collection
- Compact hexagonal packing, 18 mm pixel size
- Quartz windows separate Ne from air
- Custom made HV divider
- No PM replaced after 2014

**Hamamatsu R7400U-03 Photomultipliers**

- Sensitivity range 185-650 nm (420 nm peak)
- Gain $1.5 \times 10^6$ at working point = 900 V
- UV glass window, 16 mm Ø (8 mm active)
- Q.E. ~ 20% at peak
- 280 ps time jitter (FWHM)
The RICH HV System

- 4 CAEN Mainframes SY1527 (16 slots)
- 14 A1733N (12 ch), 15 A1535SN(24 ch)
- 4 PM feeded by one HV ch
- 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
RICH Front-end and TDAQ Electronics

**RICH front-end**
- Custom-made boards (current amplifiers with differential output)
- NINO chips discriminators
- 64 boards, 32 ch. per board (4 NINO each)

**RICH read-out**
- 128 channels TDC Boards (TDCB), 4 CERN HPTDC each
- 5 TEL62 mother boards, FPGA based, 4 TDCBs each
  - 4 boards for the 1952 PMTs
  - 1 board for multiplicity read-out: L0 trigger
- Trigger primitives built in parallel with read-out
RICH mirror system

- Mosaic of 20 spherical mirrors, 2.5 cm thick glass
- 18 hexagonal mirrors, 2 semi-hex, 35 cm side
- Radius of curvature (34 ± 0.2) m, D₀ < 4 mm
- Al coating + thin dielectric film MgF₂
  - uniform performance without losses in far UV
- Average reflectivity ~90% (λ = 195-650 nm)

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

- Mosaic of 20 spherical mirrors, 2.5 cm thick glass
- 18 hexagonal mirrors, 2 semi-hex, 35 cm side
- Radius of curvature \((34 \pm 0.2)\) m, \(D_o < 4\) mm
- Al coating + thin dielectric film MgF\(_2\)
  - uniform performance without losses in far UV
- Average reflectivity \(\sim 90\%\) (\(\lambda = 195-650\) nm)

Reflectivity as a function of photon energy. Each line represents a single mirror.
RICH mirror mechanics

Aluminium honeycomb support structure 5 cm thick, two halves

- Each mirror hangs on a back dowel
- Two thin Al ribbons keep the mirror in equilibrium and allow its orientation
- A third vertical ribbon avoids rotations
- Remote control of mirror orientation through 38 piezo motors
- Some defective piezos repaired during 2015-2016 shutdown
- Movement system now perfectly working
Mirrors pre-aligned with laser before closing vessel (no beam pipe)

Final alignment with tracks reconstructed by the spectrometer during data taking: first precise mirror alignment with 2016 data

- Semi-hexagonal mirrors used as reference
- Select rings fully contained in a single mirror
- Compare the position of the ring center on the PM plane with the position predicted by track extrapolation
- Align each mirror using piezo-motors

All mirrors aligned within ± 1 mm with respect to the reference (1 cross/mirror)

Residual misalignment:
- 1 mm in terms of ring centre position
- 30 μrad in terms of mirror angular orientation
Final alignment with tracks reconstructed by the spectrometer during data taking: first precise alignment with 2016 data

- Mirrors used as reference
- Semi-hexagonal mirrors used as reference
- Select rings fully contained in a single mirror
- Compare the position of the ring center on the PM plane with the position predicted by track extrapolation
- Align each mirror using piezo-motors

Details in Viacheslav Duk talk at this conference

All mirrors aligned within ± 1 mm with respect to the reference (1 cross/mirror)

Residual misalignment:
- 1 mm in terms of ring centre position
- 30 µrad in terms of mirror angular orientation
RICH basic performance

Clean positrons from $K^+ \rightarrow \pi^0 e^+\nu$ decays (2016 data)

Single rings fully contained in RICH acceptance

- **Ring radius resolution**: gaussian width
- **Ring center resolution**: gaussian width of difference between measured and expected ring centre position
- **Single hit resolution**: gaussian width of the pull distribution:
  
  $\text{Pull} = (R - R_{\text{exp}}) \sqrt{(N_{\text{hits}} - 3)}$

- **Number of hits/ring**: $\langle N_{\text{hits}} \rangle = 13.8$, poissonian fit

---

**Ring radius resolution**

- $\langle R \rangle = 189.6 \text{ mm}$
- $\sigma_R = 1.47 \text{ mm}$

**Number of hits/ring**

- $\langle N_{\text{hits}} \rangle = 13.8$

---

**Single hit resolution**

- $\sigma_X = 2.96 \text{ mm}$
- $\sigma_Y = 2.92 \text{ mm}$

**Ring center resolution**

- $\sigma_{\text{hit}} = 4.66 \text{ mm}$
RICH basic performance

Clean positrons from $K^+ \rightarrow \pi^0 e^+ \nu$ decays (2016 data)

Single rings fully contained in RICH acceptance

- **Ring radius resolution**: gaussian width
- **Ring center resolution**: gaussian width of measured and expected ring centre position
- **Single hit resolution**: gaussian width of the pull distribution
  \[
  \text{Pull} = (R - R_{\text{exp}}) \sqrt{N_{\text{hits}} - 3}
  \]
- **Number of hits/ring**: poissonian fit

- $\langle N_{\text{hits}} \rangle = 13.8$
- $\langle R \rangle = 189.6 \text{ mm}$
- $\sigma_R = 1.47 \text{ mm}$
- $\sigma_X = 2.96 \text{ mm}$
- $\sigma_Y = 2.92 \text{ mm}$
- $\sigma_{\text{hit}} = 4.66 \text{ mm}$

Details in Viacheslav Duk talk at this conference Wednesday 1/8
RICH performance – time and track slope

2016 data, π⁺ν̅ν analysis (preliminary results)

- Precise mirror alignment
- n of hits/ring monitored using positrons
- PM’s aligned vs KTAG time: ring $\sigma_t \sim 80$ ps
- RICH ring - spectrometer track
  - matched comparing ring centre and flight direction

**Resolution (X, Y) of RICH-STRAW slope difference:** $\sim 160-170 \mu$rad

- Similar contributions from STRAW and RICH
- Test beam measurement of RICH Cherenkov angle resolution: $\Delta \theta_C \approx 50 \mu$rad

**Difference between the (x, y) track slopes of STRAW and RICH**

Time difference between CHOD candidate and RICH ring candidate

\[ \sigma = 260 \text{ ps} \]
\[ \sigma_{\text{CHOD}} \approx 250 \text{ ps} \]
\[ \sigma_{\text{RICH}} \approx 80 \text{ ps} \]
2016 data, $\pi^+\nu\nu$ analysis (preliminary results)

- Charged pion selection in the RICH: likelihood function for a ring under a pre-defined particle mass hypothesis

Particle mass computed from $R$ (RICH) and $P_\pi$ (STRAW)

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

$P_\pi$: pion momentum, $n$: refractive index
$R$: ring radius, $f$: mirror focal length.

Cherenkov ring radius as a function of pion candidate momentum. Electrons, pions and muons can be clearly distinguished.
RICH performance – PID

2016 data, $\pi^+\nu\bar{\nu}$ analysis (preliminary results)
- Track driven Likelihood particle ID discriminant
- Particle mass extracted using track momentum
- PID performance: RICH and calorimeter combined

RICH PID: pion (left scale) and muon (right scale) efficiency after pion-ID vs pion momentum

$2.5 \cdot 10^{-3}$ $\mu^+$ efficiency $\text{vs}$ 75% $\pi^+$ efficiency

$\Rightarrow > 10^7$ muon rejection
RICH performance – PID

2016 data, π⁺νν analysis (preliminary results)

- Track driven Likelihood particle ID discriminant
- Particle mass extracted using track momentum
- PID performance: RICH and calorimeter combined

More details on RICH in π⁺νν data analysis in Roberta Volpe talk at this conference Wednesday 1/8

RICH PID: pion efficiency vs muon (right scale) efficiency after pion and π⁺ vs pion momentum

- 2.5 \times 10^{-3} \mu^+ efficiency vs 75% \pi^+ efficiency

⇒ > 10^7 muon rejection
**$K^+ \to \pi^+\nu\bar{\nu}$ analysis results**

$K$ decay events in the fiducial decay region

$K^+ \to \pi^+\pi^+\pi^-$

$K^+ \to \pi^+\mu^+\nu$

$K^+ \to \mu^+\nu$

$K^+ \to \pi^+\pi^+\nu$

Two signal regions, three background regions

**$m^2_{miss} = m^2_{miss}(\text{STRAW GTK}) = (P_K - P_p)^2$**

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

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

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

**BR measurement – Upper Limits**

$BR_{NA62}(K^+ \to \pi^+\nu\bar{\nu}) < 11 \cdot 10^{-10}$ (90% CL)

$BR_{NA62}(K^+ \to \pi^+\nu\bar{\nu}) < 14 \cdot 10^{-10}$ (95% CL)
The $K^+ \rightarrow \pi^+\nu\bar{\nu}$ event in the RICH

Pion track at the RICH mirror plane

Ring reconstruction at the PM plane

Area illuminated by the Cherenkov light
Conclusions

- The NA62 RICH detector has been installed in 2014 and commissioned in 2014-2015
- Refurbished in 2015-2016 winter shutdown (piezo repair), smoothly running since then
- The RICH performances are very close to expectations
- One $K^+ \rightarrow \pi^+ \nu \nu$ event has been observed by NA62 with the 2016 data analysis
- $O(20)$ SM events are expected from 2017-2018 data
- NA62 was approved up to 2018 with the main goal of measuring $BR(K^+ \rightarrow \pi^+ \nu \nu)$
- In addition, a broad program of rare decay measurements, hidden sector particles and LF/LN violation searches has been pursued.
- **Run 3 (2021-2023):** opportunity for NA62 to complete the BR measurement
- The NA62 RICH will be maintained in working conditions for the next NA62 program

References:
- $K^+ \rightarrow \pi^+ \nu \nu$ : *First Result from the NA62 Experiment*, G. Ruggiero, EP CERN Seminar, 27/03/2018
- *Pion-muon separation with a RICH prototype for the NA62 experiment*, B. Angelucci et al., NIM A621, 205-211 (2010).