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

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

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

2016:
- 40% of nominal intensity $\rightarrow$ $5 \times 10^{11}$ $K^+$ decays

2017-18:
- 60% of nominal intensity $\rightarrow$ $8 \times 10^{12}$ $K^+$ decays

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

Expected Background:
$0.15 \pm 0.09_{\text{stat}} \pm 0.01_{\text{syst}}$

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

arXiv:1811.08508 (accepted by PLB)
The NA62 Detector

Primary beam: CERN SPS protons
• 400 GeV/c
• $3.3 \times 10^{12}$ ppp

Secondary beam:
• unseparated positive beam $\pi(70\%)/K(6\%)/p(23\%)$
• $p_K = 75$ GeV/c ($\Delta p/p \sim 1.1\%$)
• Nominal beam rate = 750 MHz@GTK
• $K^+$ rate $\approx 45$ MHz
• $\sim 5$ 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

Talk by L. Federici

[NA62 Detector Paper: 2017 JINST 12 P05025]
NA62 and RICH requirements

• Signal
\[ \text{BR}_{\text{SM}} = (0.84 \pm 0.10) \cdot 10^{-10} \]

\[ K^+ \xrightarrow{\bar{\nu}} \pi^+ \nu \]
\[ K^+ \xrightarrow{\bar{\nu}} \pi^+ \pi^0 \]
\[ K^+ \xrightarrow{\bar{\nu}} \pi^+ \pi^- \]

• Background

<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 strategy
  - Kinematics
  - Particle ID
  - Photon/Muon rejection
  - \( 15 < P_{\pi^+} < 35 \text{ GeV/c} \)

• Keystones
  - O(100 ps) timing between subdetectors
  - O(10^4) kinematic rejection
  - \( >10^7 \) Muon rejection
  - \( >10^7 \) \( \pi^0 \) suppression

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

NA62 Requirements
  - O(10%) signal acceptance
  - \( 10^{13} \) Kaon decays in fiducial volume
  - O(10^{12}) background rejection

\[ m^2_{\text{miss}} = (P_K - P_{\pi})^2 \]
The NA62 RICH layout

Vessel: ~17 m long, Neon gas
Volume ~ 200 m³

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) = 6.28 \times 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

<table>
<thead>
<tr>
<th>Gas Analysis</th>
<th>O₂ (ppmV)</th>
<th>H₂O (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>
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 MgF₂
- Average reflectivity ≈90% in λ(195-650) nm, D₀ < 4 mm

![Total reflectivity for two different coating as a function of photon energy.](image)

- 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

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

[Aluminium honeycomb support structure 5 cm thick, two halves]
Mirror alignment

**Preliminary laser alignment**
- done before vessel closing
- precision $O(500) \mu\text{rad}$ 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 $O(30) \mu\text{rad}$ 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 MISALIGNMENT**

- All mirrors within ±1mm (one point/mirror)
- Global Offset ~$O(20)$ mm
- Residual misalignment:
  → 1mm (ring center position)
  → 30 $\mu$rad (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

<table>
<thead>
<tr>
<th>Hamamatsu R7400U-03 Photomultipliers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity range 185-650 nm (420 nm peak)</td>
</tr>
<tr>
<td>Gain $1.5 \times 10^6$ at working point = 900 V</td>
</tr>
<tr>
<td>UV glass window, 16 mm Ø (photocathode 8 mm active)</td>
</tr>
<tr>
<td>Q.E. ~ 20% at peak</td>
</tr>
<tr>
<td>280 ps time jitter (FWHM)</td>
</tr>
</tbody>
</table>

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 fed 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
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
Resolution of basic variables can be compared to other RICH’s
• Clean positrons from $K^+ \rightarrow \pi^0 e^+\nu$ decays
• Single rings fully contained in RICH acceptance
• Performance after mirror alignment

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

• Ring radius resolution: gaussian width

• Single hit resolution: gaussian width of the Pull $= (R - R_{\text{exp}}) \sqrt{N_{\text{hits}} - 3}$

• Number of hits/ring: poissonian fit

Ring Radius resolution
$\langle R \rangle = 189.6 \text{ mm}$
$\sigma_R = 1.47 \text{ mm}$

Single hit resolution
$\sigma_{\text{hit}} = 4.66 \text{ mm}$

Number of hits per ring
$\langle N_{\text{hits}} \rangle = 13.8$

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

2016 DATA
Intrinsic RICH Time resolution:
Hits on Cherenkov ring divided in 2 halves → difference between time average of 2 sets

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

• Event Time resolution:
  Time Resolution of the full ring = \( 0.5 \cdot \sigma \)

RICH Time Resolution ~ 70 ps
2016 Data $\pi^+\nu\nu$ selection

**Ring Radius vs Pion candidate momentum**

```
<table>
<thead>
<tr>
<th>$R_{\text{ring}}$ [mm]</th>
<th>Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10^5</td>
</tr>
<tr>
<td>50</td>
<td>10^4</td>
</tr>
<tr>
<td>100</td>
<td>10^3</td>
</tr>
<tr>
<td>150</td>
<td>10^2</td>
</tr>
<tr>
<td>200</td>
<td>10</td>
</tr>
<tr>
<td>250</td>
<td>0</td>
</tr>
<tr>
<td>300</td>
<td>0</td>
</tr>
</tbody>
</table>
```

- 1-track sample

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

```
<table>
<thead>
<tr>
<th>$M_{\text{RICH}}$ [GeV/c^2]</th>
<th>Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10^5</td>
</tr>
<tr>
<td>0.05</td>
<td>10^4</td>
</tr>
<tr>
<td>0.1</td>
<td>10^3</td>
</tr>
<tr>
<td>0.15</td>
<td>10^2</td>
</tr>
<tr>
<td>0.2</td>
<td>10</td>
</tr>
<tr>
<td>0.25</td>
<td>0</td>
</tr>
</tbody>
</table>
```

- $\pi^+$
- $\mu^+$
- $e^+$

**Equation:**

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

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

- 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:
  $$2.1 \cdot 10^{-3} \mu^+ \text{ efficiency vs } 82\% \pi^+ \text{ efficiency}$$
**K^+ \rightarrow \pi^+\nu\bar{\nu} event in the RICH**

**Kinematic selection of signal regions:**

$m_{miss}^2 = (P_K - P_{\pi})^2$ with the $m_{\pi}$ hypothesis

- $K^+ \rightarrow \pi^+\pi^-\pi^0$
- $K^+ \rightarrow \pi^+\nu\bar{\nu}$
- $K^+ \rightarrow \mu^+\nu$

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

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

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

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

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

**2016 DATA**

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, successfully running since then
- **RICH performance very close to expectations**
- **NA62 was approved up to 2018** with the main goal of measuring \( \text{BR}(K^+ \rightarrow \pi^+\nu\nu) \)
- **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