The NA62 experiment – Results from 2014 Pilot Run

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on behalf of the NA62 Collaboration

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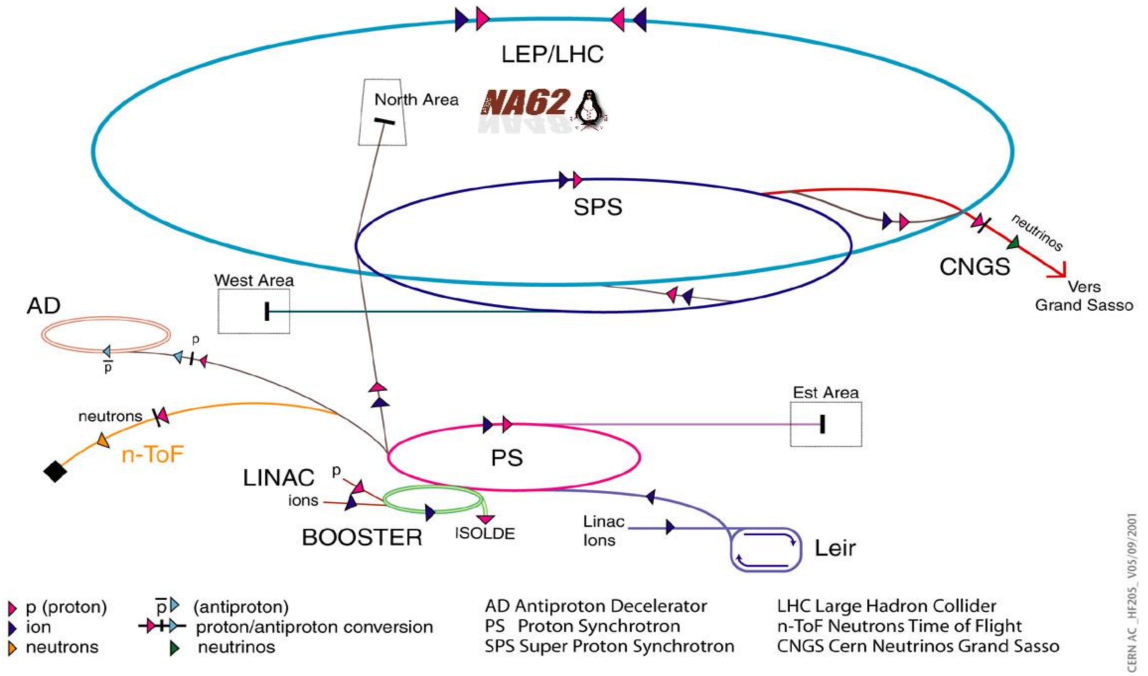
The NA62 experiment

- Fixed target experiment at the North Area of CERN SPS.
- Kaons in flight decay technique
- Main goal: Measurement of BR($K^+ \to \pi^+ \nu\nu$) with 10% accuracy, collection O(100) SM events in 3 years data taking
- The NA62 Collaboration – 13 countries, 32 institutions, 238 participants

(Belgium, Bulgaria, Canada, Czech Republic, Germany, Italy, Mexico, Romania, Russia, Slovakia, Switzerland, United Kingdom, USA)



December 2008: NA62 Approval

2009-2012: detector R&D

October 2012: Technical Run (partial layout)

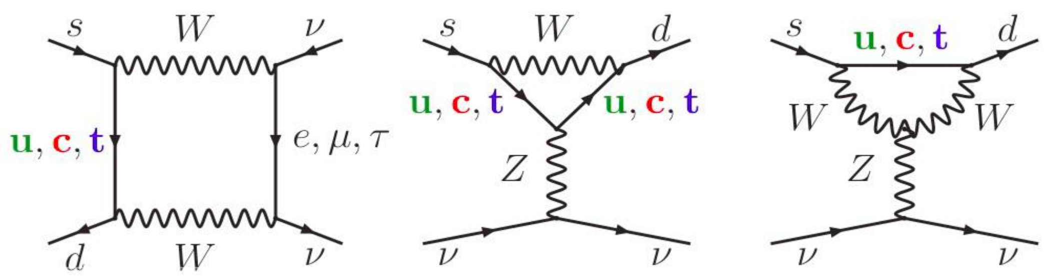
2013-2014: detector installation

October 2014: Pilot Run (full layout)

2015 – 2016 – 2017 Physics Runs

Motivations for $K^+ \to \pi^+ \nu \bar{\nu}$ study

Box and penguin (one-loop) diagrams



- FCNC processes forbidden at tree-level
- CKM suppressed (BR ~ $|V_{ts} * V_{td}|^2$)
- Extraction of $|V_{td}|$ with a few % non-parametric uncertainty
- Sensitivity to New Physics (NP)

Contributions to the BR ratio:

- (dominant) t-quark part (NLO QCD, 2-loop EW corrections);
- (small) c-quark part (NNLO QCD, NLO EW corrections);
- Long Distance (LD) correction;
- Hadronic matrix element extracted from well-known decay BR($K^+ \to \pi^0 e^+ \nu$)

Extremely precise theoretical predictions:

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$$
$$BR(K^0 \to \pi^0 \nu \bar{\nu}) = (3.00 \pm 0.30) \times 10^{-11}$$

Uncertainty:

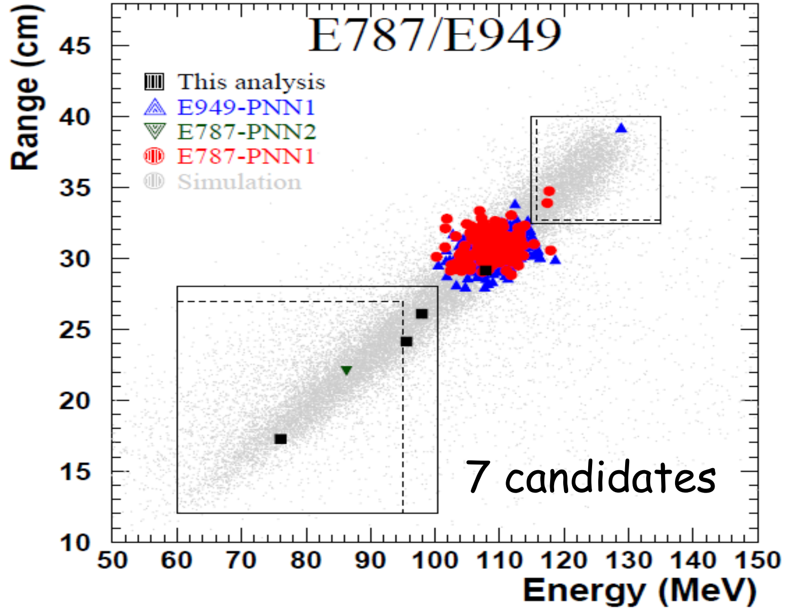
- CKM parametric, dominated by V_{cb}

SM predictions: [A.J, Buras, D. Buttazzo, J. Girrbach-Noe and R, Knegjens, arXiv:1503.02693]

Experimental status and $K \to \pi\nu\bar{\nu}$ sensitivity to New Physics

E787/E949 experiment @ BNL
(stopped kaon technique)

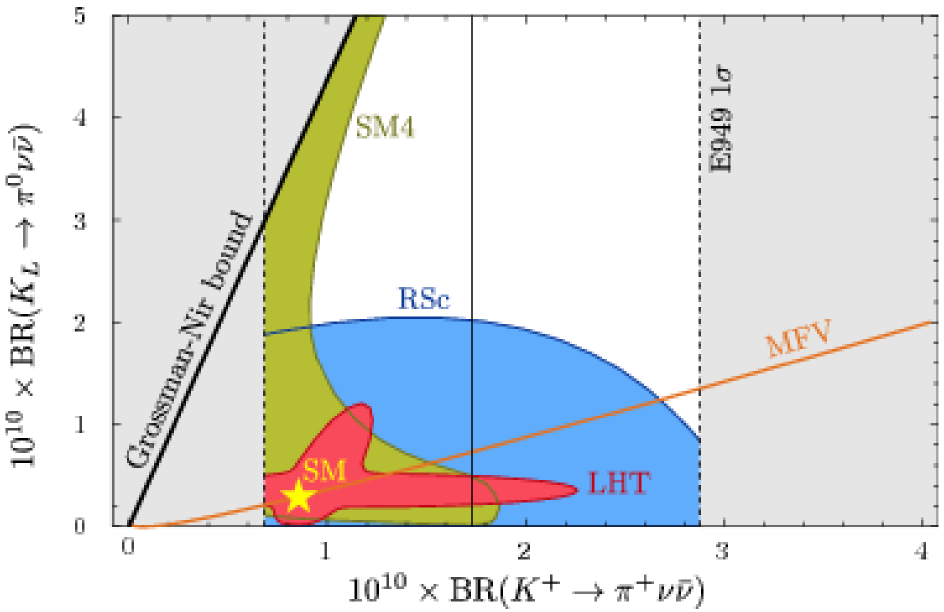
$BR(K^+ \to \pi^+ \nu\bar{\nu})_{THEORY} = (0.91 \pm 0.07) \times 10^{-10}$
$BR(K^+ \to \pi^+ \nu\bar{\nu})_{exp} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$



[E787/E949, Phys.Rev.Lett.101, 191802, 2008]

Searches for NP in $K \to \pi\nu\bar{\nu}$:

- Complementary to LHC
- Several scenarios possible
- Measurements of charged and neutral mode will allow to discriminate between different NP scenarios



Grey: ruled out
SM: Standard Model
SM4: SM with 4th generation
RSc: custodial Randall-Sundrum
LHT: littlest Higgs with T-parity
MFV: minimal flavor violation

D. Straub @ CKM-2010
arXiv: 1012.3893

Requirements to the NA62

- Goal: 10% precision branching ratio measurement of $K^+ \to \pi^+ \nu \bar{\nu}$
  - ✓ O(100) SM $K^+ \to \pi^+ \nu \bar{\nu}$ events (3 years of data)

- Requirements
  - ✓ Statistics: BR(SM) ~9 x 10^{-11}
    - Kaon intensity (3 years): **10^{13} K^+ decays**
    - Detector Acceptance: **~10%**
  - ✓ Systematics:
    - Signal purity: >10^{12} background rejection (<20% bgr)
    - <10% precision background measurement

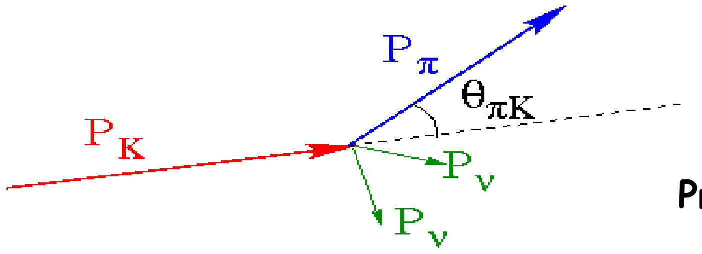
  ⇒ Signal / BGR ~ 10

- Technique
  - ✓ "High" momentum K^+ beam (75Gev/c)

Experimental strategy

- **Signal**

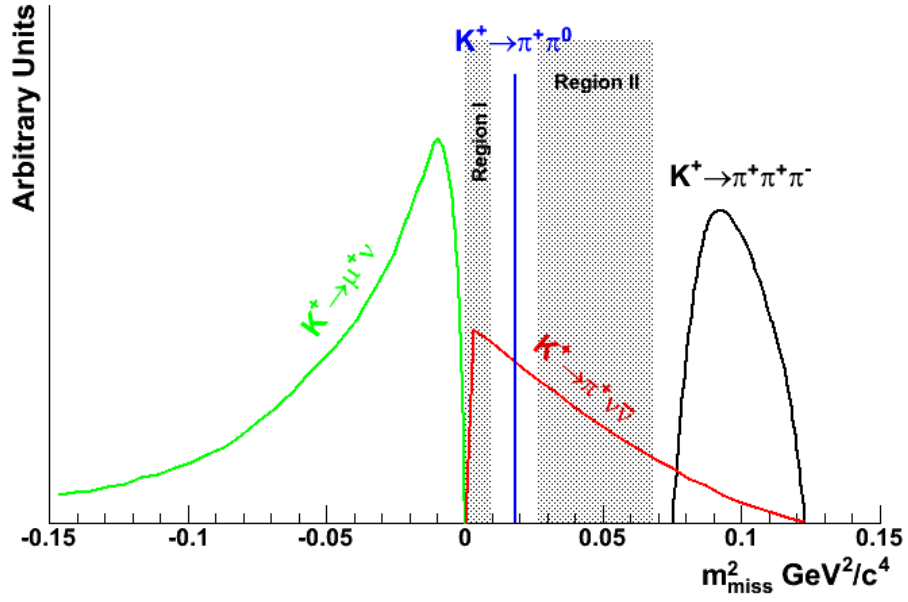
Main kinematic variable: $m^2_{miss} = (P_K - P_{\pi^+})^2$



Precise timing needed !

$$m^2_{miss} \cong m^2_K\left(1-\frac{|P_\pi|}{|P_K|}\right)+m^2_\pi\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\theta^2_{\pi K}$$

The signals are measured in two regions (I and II)



Background

- K^+ decay modes
- Accidental single track matched with a K-like track
- Beam-gas and upstream interactions

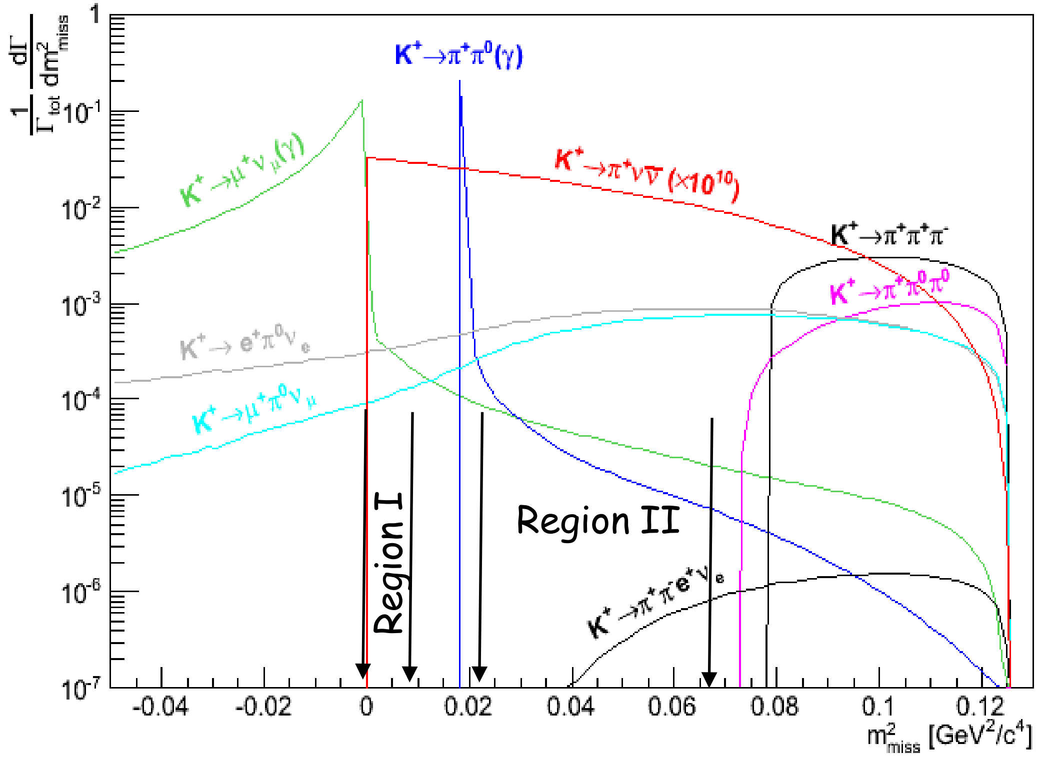
Signal signature:

- Incoming high momentum(75 GeV/c) K^+
- Outcoming low momentum(<35 GeV/c) π^+ in time with the incoming K^+

Region I : $0 < m^2_{miss} < 0.01\ GeV^2/c^4$
Region II: $0.026 < m^2_{miss} < 0.068\ GeV^2/c^4$

Background rejection

- K^+ positive identification (CEDAR)
- π/μ separation (RICH)
- π /e separation (E/p)



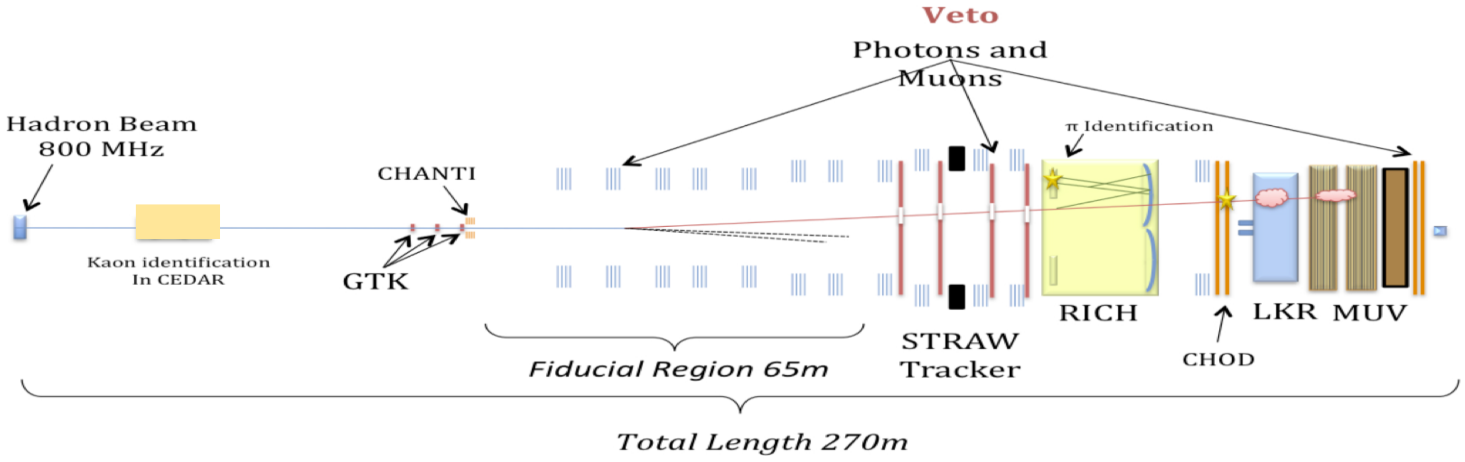
Decay	BR [%]	Rejection
$K^+\to\mu^+\nu(K_{\mu2})$	63.5	μ-ID+kinematics
$K^+\to\pi^+\pi^0(K_{2\pi})$	20.66	γ-veto+kinematics
$K^+\to\pi^+\pi^+\pi^-$ $K^+\to\pi^+\pi^0\pi^0$	1.76 5.59	Multi-trk+kinematics γ-veto+kinematics

Decay	BR [%]	Rejection
$K^+\to\pi^0e^+\nu$ (K_{e3})	5.07	e-ID+kinematics
$K^+\to\pi^0\mu^+\nu$ $(K\mu_3)$	3.35	μ-ID+γ-veto
$K^+\to\mu^+\nu\gamma(K\mu_{2g})$	6.2×10^{-3}	γ-veto+kinematics
$K^+\to\pi^+\pi^-e^+\nu$ (K_{e4})	4.25×10^{-5}	e-ID+multi-trk
$K^+\to\pi^+\pi^-\mu^+\nu$ $(K\mu_4)$	1.4×10^{-5}	Multi-trk+kinematics

NA62 beam line & detector

Beam line

- SPS primary beam 400 GeV/c, ~3x10^{12} p per pulse on target
- Secondary (unseparated) hadron beam 75 GeV/c, ~780 M particles/s (p/K/π)
- 4.8x10^{12} K decays/year



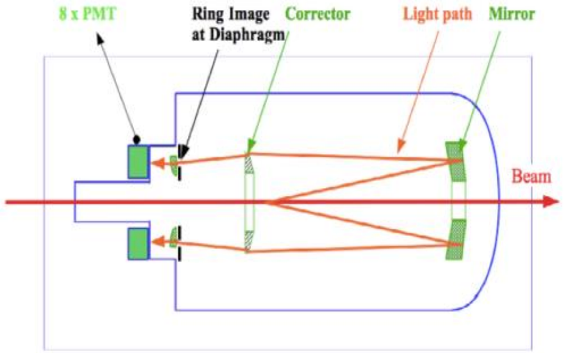
- The CEDAR – differential Cerenkov counter
  - K^+ components in the beam
- GTK – Gigatracker → 3 Si micro-pixel station
  - Time, direction and momentum of the beam particle
- The STRAW Tracker → 4 Chambers inside high vacuum (~10^{-6}) tank
  - Coordinates and momentum of secondary charged particles from decay volume
- The RICH detector → 17m long radiator filled with Ne gas at 1 atm,
- The MUV – Muon-Veto Detectors → 2-part hadron calorimeter, iron and a transversally-segmented hodoscope
  - Separate pions and muons between 15 and 35 Gev/c

- System of Photon-Veto detectors - hermetic coverage 0-50 mrad angles from the decay region
  - The LKR – high resolution Liquid Krypton electro-magnetic calorimeter
  - IRC and SAC– Intermediate Ring and Small-Angle Calorimeters
  - 12 annular photon-veto LAV detectors
- Counters CHANTI and charge-particle hodoscope CHOD
- High-performance trigger and Data-acquisition (TDAQ) system

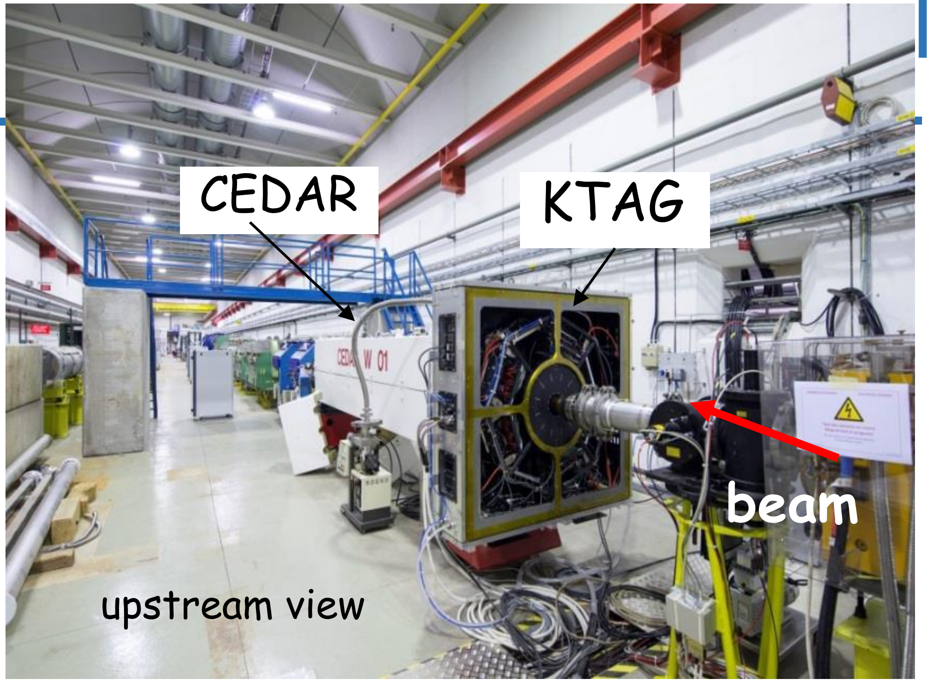
Kaon Identification System

Secondary (unseparated) 75 GeV/c hadron beam: total rate ~ 750MHz
Main components: ~ 72% π+, ~ 6% K+, ~ 22% p

Cherenkov kaon tagger



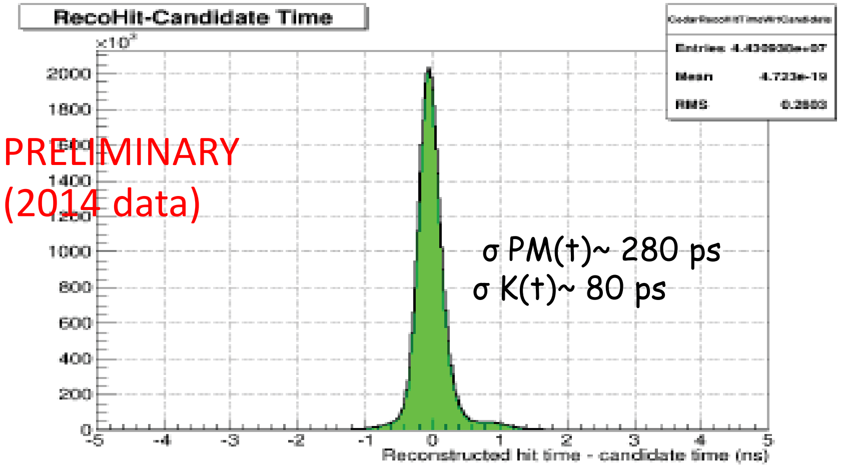
- ChErenkov Differential Achromat Ring focus counter /CEDAR/ with Kaon TAGging detecto
- N_2 inside CEDAR
- external optics, PMs, front-end, readout
- 8 PM stations (8 PM readout)



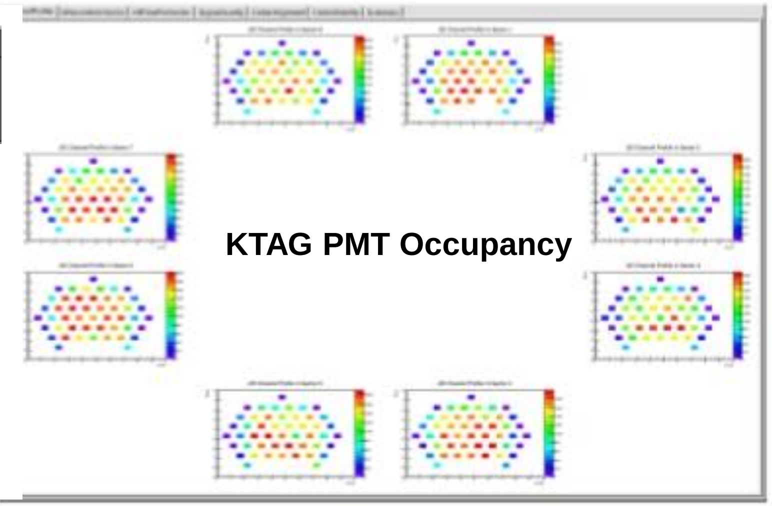
Kaon ID system (CEDAR-KTAG) requirements:

- operation with ~ 45MHz kaon flux
- at least 95% K+ ID efficiency, below 0.1% mis-tagging probability
- < 100ps time resolution on K+ crossing time
- radiation hardness (up to 1 Gy/year)

Readout and detector fully commissioned



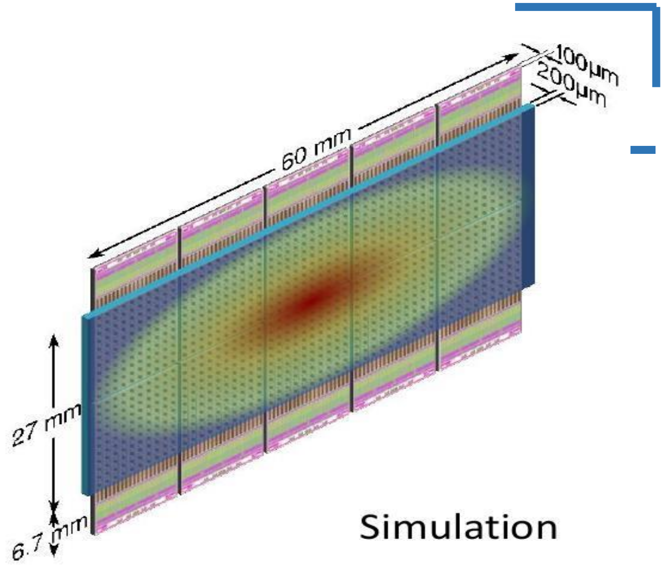
PM occupancy



Spectrometers –

beam & charged decay products

Gigatracker (GTK) – beam spectrometer

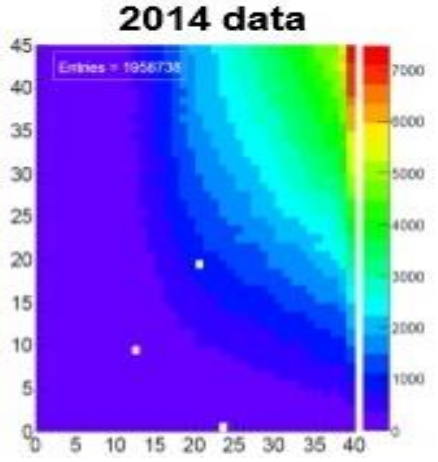


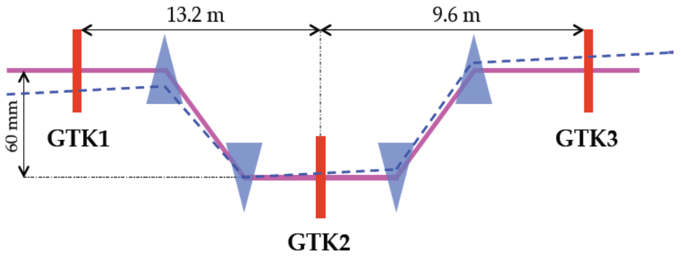
Pixel spectrometer to measure Kaons' momenta

- 3 Si pixel stations (4 achromat magnets), 10 chip/station, 18K pixel/station
- Station dimensions: 60(X)x27(Y) mm^2 (active area), thickness<0.5 mm(0.5% X_0)

Requirements:

- Stand 750 MHz total rate (140 KHz/pixel in the center)
- 200 ps/station resolution
- σX,Y ~16 μrad, ΔP/P < 0.4%

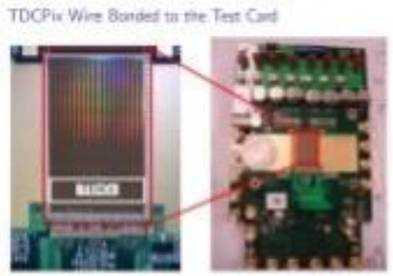


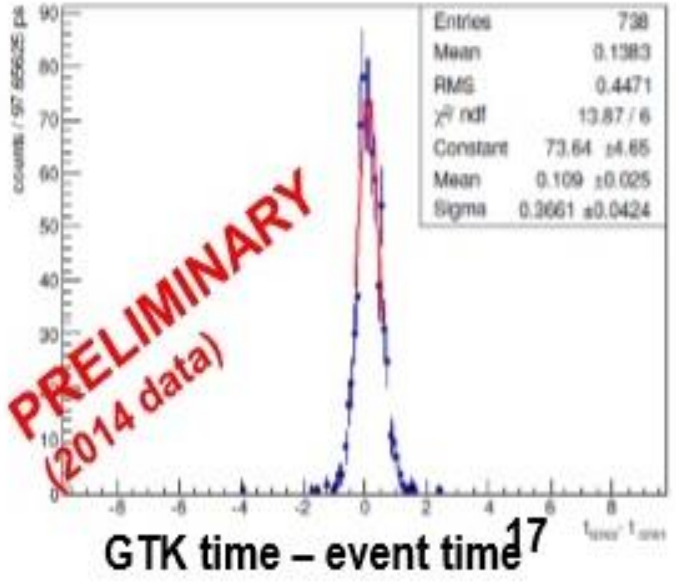


2014 Pilot run

- ✓ Readout partially commissioned (1 chip/station, no trigger matching)
- ✓ 450/250 μm technology (100 μm in 2015)
- ✓ Cooling system commissioned

The TDCPix chip



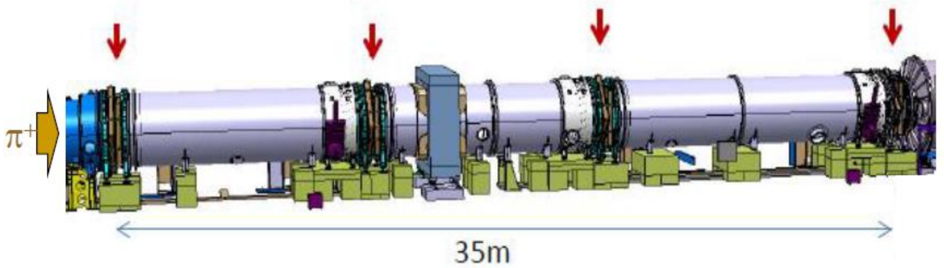


STRAW – decay products spectrometer

Momentum measurement of charged particles from K decays

- 7168 straw tubes spectrometer in vacuum
- 4 chambers, 4 views/chamber, 4 staggered layers/view, 112 Mylar straws/layer
- Material:50nm Cu+20nm Au+36μm Mylar
- Filling gas: Ar+CO_2 (70/30%)
- 0.36 T magnet after the 2nd chamber
- Readout: TDCs+CARIOCA chip+SRBs

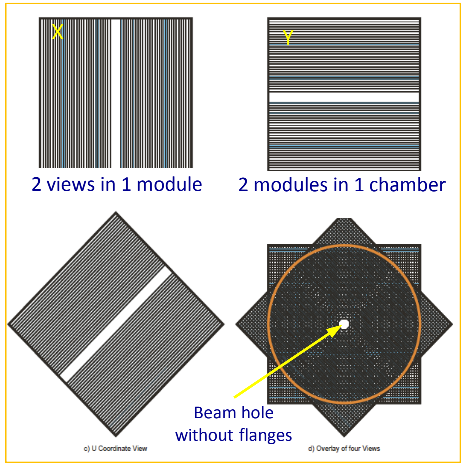
4 straw chambers in vacuum + spectrometer magnet



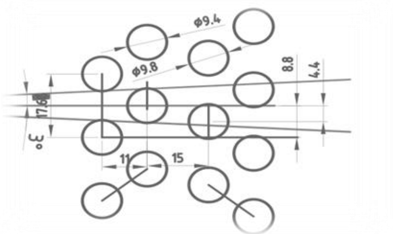
Magnet:
- B ~ 0.36T
- p_T = 270 MeV/c

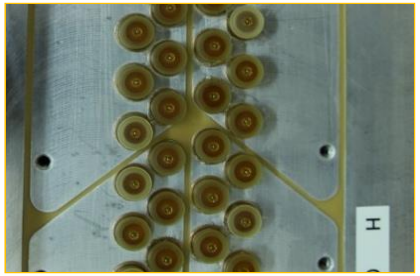
Requirements:
- ✓ high precision (special resolution ~ 130 μm/view)
- ✓ high efficiency
- ✓ low mass budget (~1.8% X_0)
- ✓ momentum resolution dp/p ~ 0.32% + 0.008%*p

Straw detector design

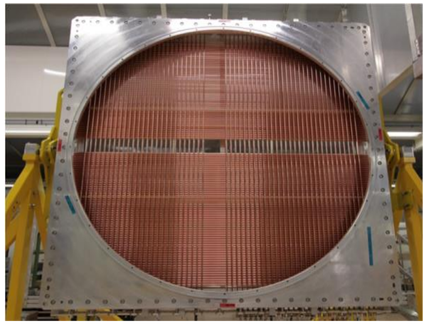


Straw view

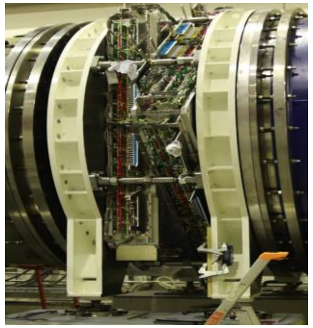




Straw module



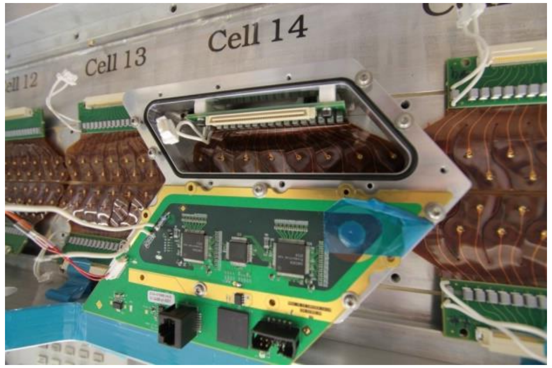
Straw chamber



STRAW – decay products spectrometer

Installation of a Straw chamber

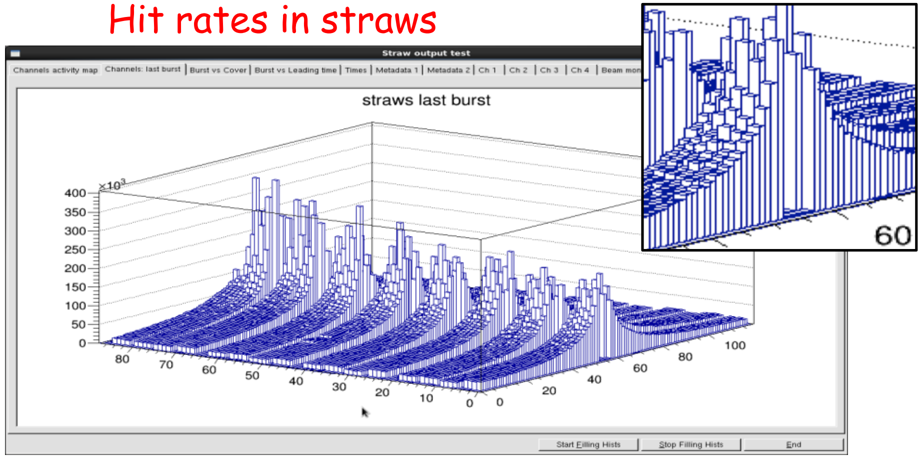
Straw cover (TDC+Carioca)



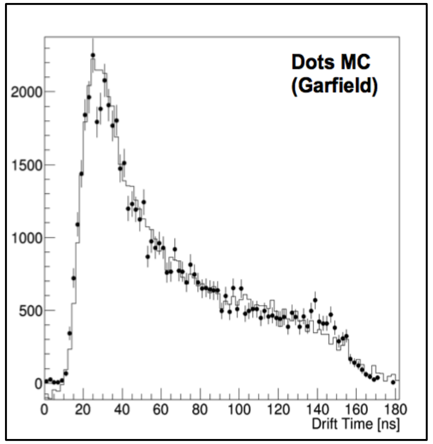
2014 Pilot run

- ✓ Triggerless readout (L0 readout in 2015)
- ✓ Detector fully commissioned

Hit rates in straws

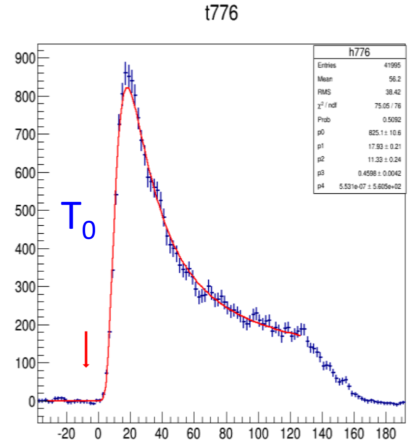


Straw trailing time (drift time)



PRELIMINARY (2014 data)

T_0 for each channel
In progress



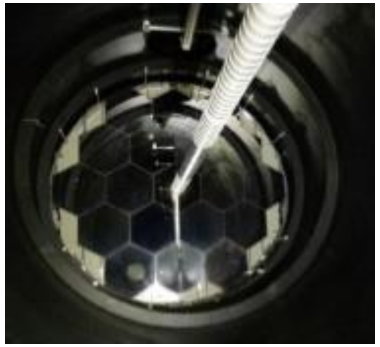
Particle Identification

RICH

Cherenkov decay particles tagger :

- 17m long vessel filled with Ne at atmospheric pressure
- Array of 20 hexagonal mirrors focusing the light to PMs
- 2 PM flanges
- 976 PMs per flange

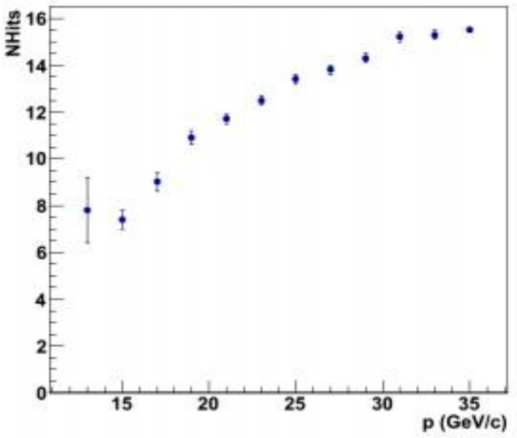
RICH mirrors



Requirements

- π/μ separation @ $5\cdot10^{-3}$ (15 < P < 35 GeV/c)
- Time resolution ~70ps

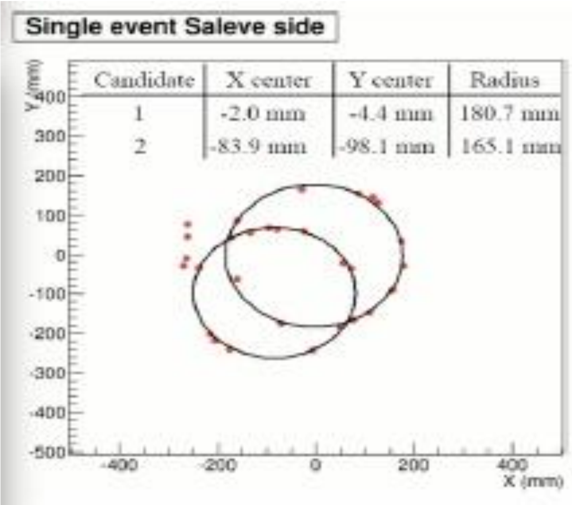
$N_{photons}$ vs particle momentum



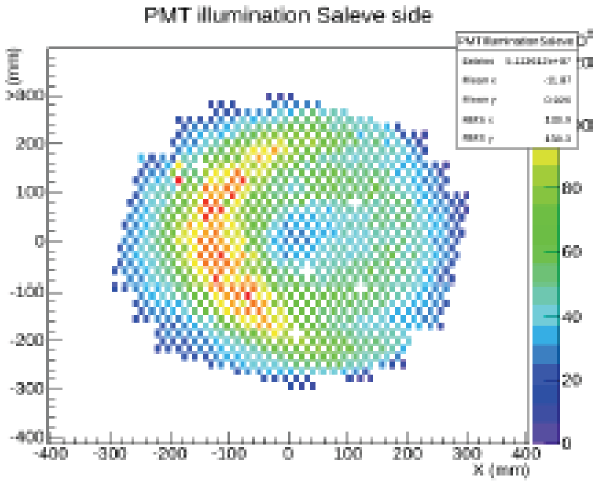
PRELIMINARY
(2014 data)

detector and readout fully commissioned

Reconstructed rings, 2014 run



RICH PM illumination in 2014



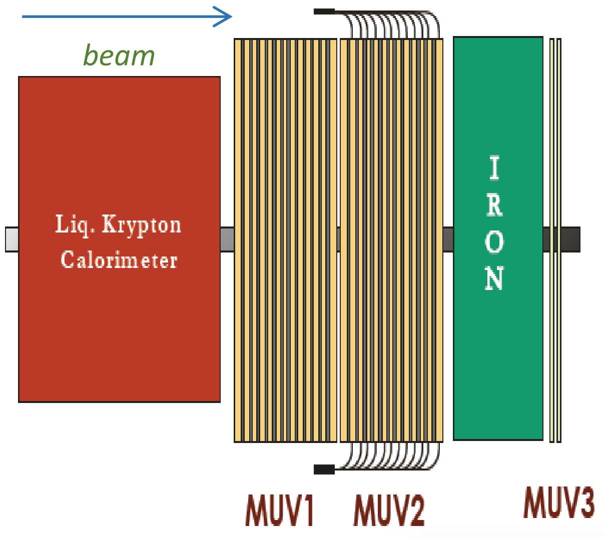
MUV

MUV 1+2 (HAC): measurement of π deposits

- Iron/scintillation sandwich
- 2 modules of iron/scintillator plates (88+176 channels)
- Readout: PMs+CREAM boards
- MUV2 reused from NA48

2014 Pilot run

✓ 1 module commissioned in 2014

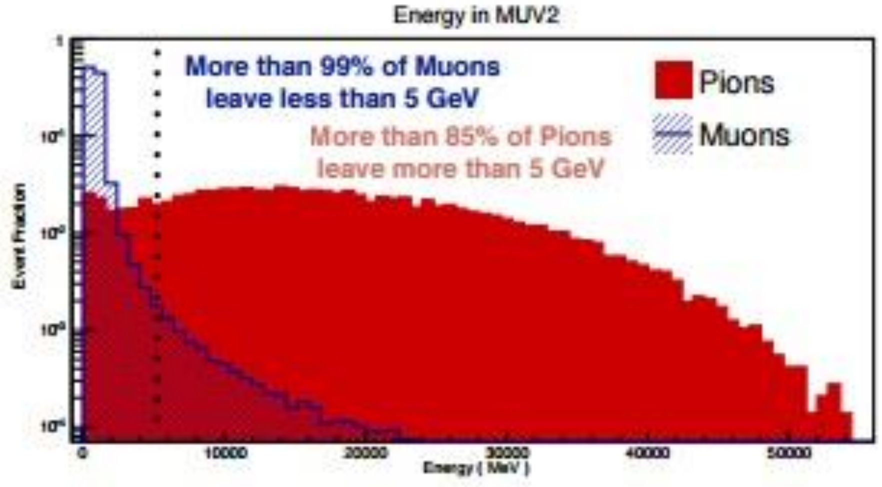


MUV3: μ tagging

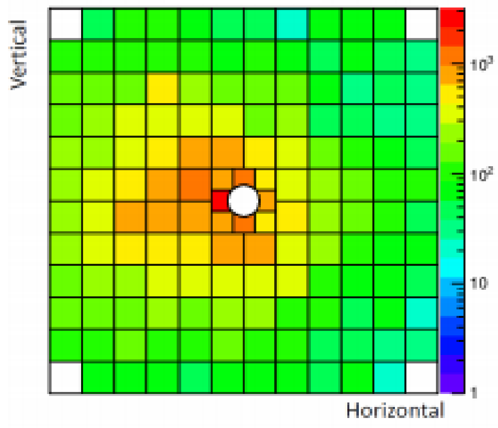
- Fast muon veto plane
- 148 scintillator tiles (2PMs per tile)
- < 500 ps time resolution

2014 Pilot run

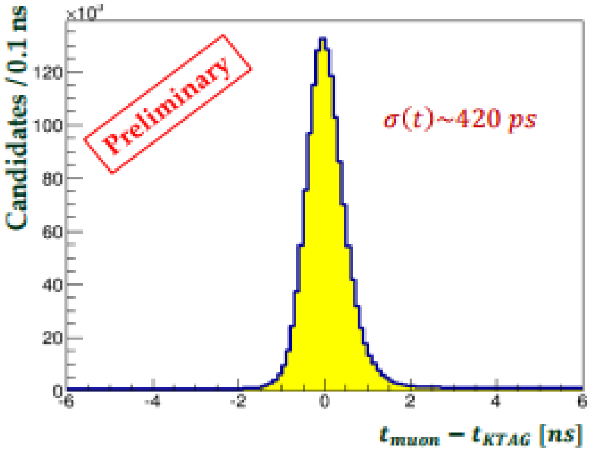
✓ Detector & RO commissioned



MUV3 illumination in 2014



MUV3 resolution



Photon Vetos

LAV – Large Angular Vetos

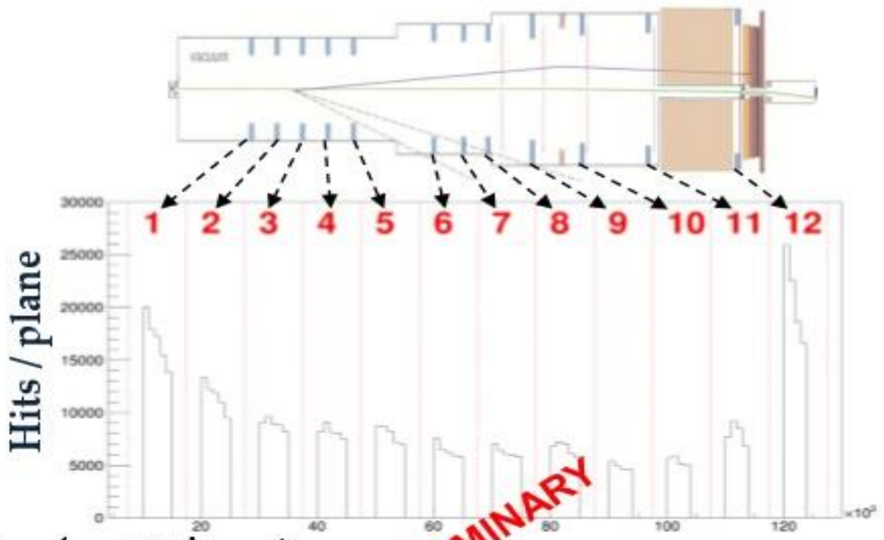
Particle veto @ large angle (8.5-50 mrad)

- 12 veto stations along the beamline, OPAL crystals reused
- 5/4 staggered rings/station, 32 crystals/ring
- Signal (Cherenkov light) read by PMs and discriminated using

Requirements:

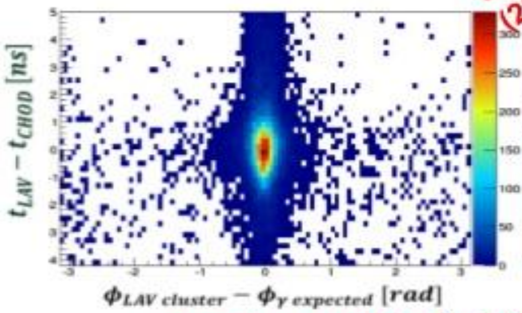
- ✓ $10^{-3}/10^{-4}$ inefficiency on photons up to 150 MeV
- ✓ ~1 ns time resolution
- ✓ Rate at full intensity 1 MHz

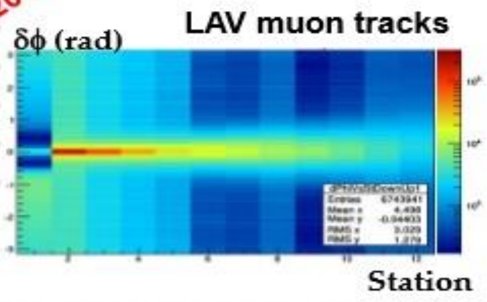
detector and readout fully commissioned



$t_{LAV} - t_{exp.}$ vs. $\phi_{LAV} - \phi_{exp.}$

PRELIMINARY (2014 data)





γs and μs predicted in LAVs using straw information

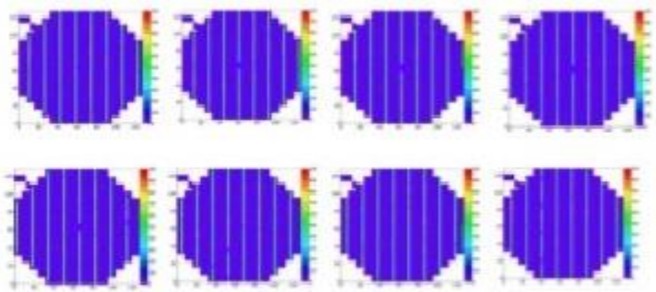
LKr – electromagnetic calorimeter

Forward veto (1-8.5 mrad),
precision measurement of EM energy deposits

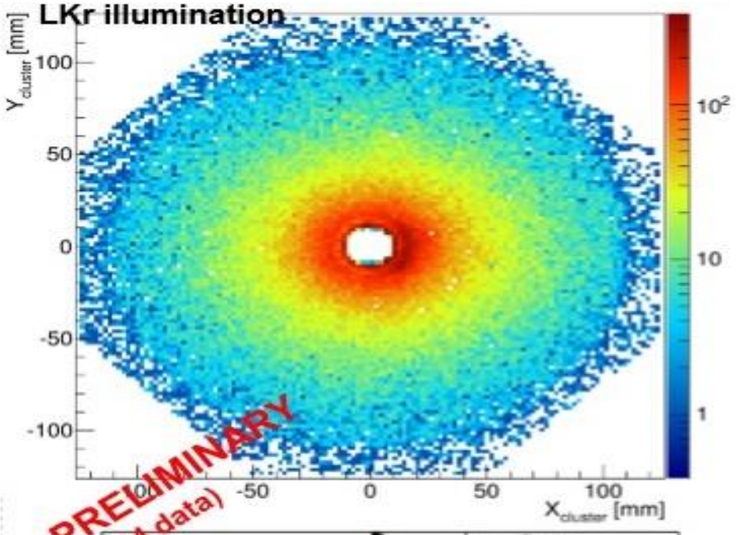
- 10 m^3 Liquid Krypton calorimeter
- 1.25 m deep (27 X_0, 6.1 cm Molière radius)
- 13284 2x2 cm^2 cells, projecting geometry towards the kaon fiducial region
- Preamplifiers inside the LKr
- Built-in calibration system
- Detector built for NA48, new electronics (based on the CREAM board)

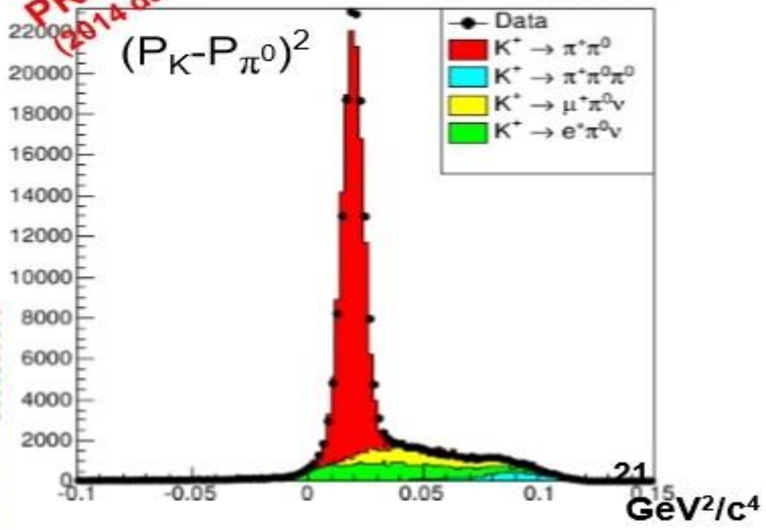
✓ < 10^{-5} inefficiency for photons with energy greater than 10 GeV
✓ Rate at full intensity 10 MHz

✓ **Detector refurbished and commissioned**
✓ **Readout fully commissioned**



LKr callibration pattern





Intermediate Ring Calorimeter & Small Angular Calorimeter

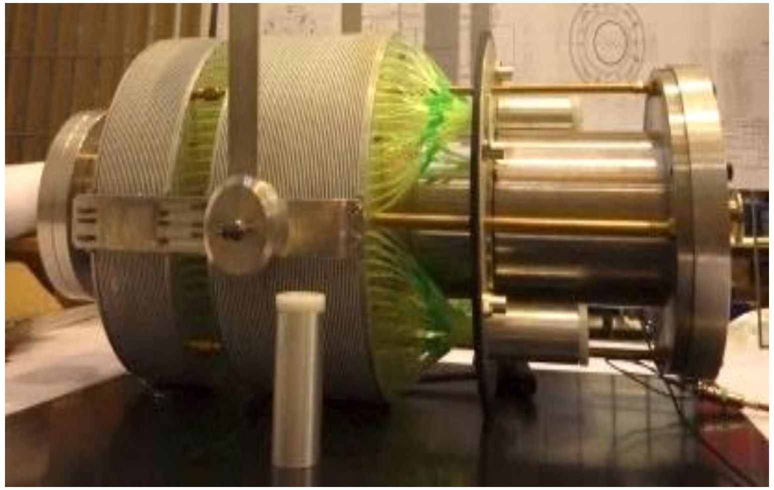
SAC & IRC: small angle veto Shashlyk calorimeters

- SAC: γ detection along the beam line (after beam deflection)
- IRC: detection of photons at very low angle in front of the LKr, radial coverage 7 cm < R < 14 cm
- WLFs+PMs used for both detectors

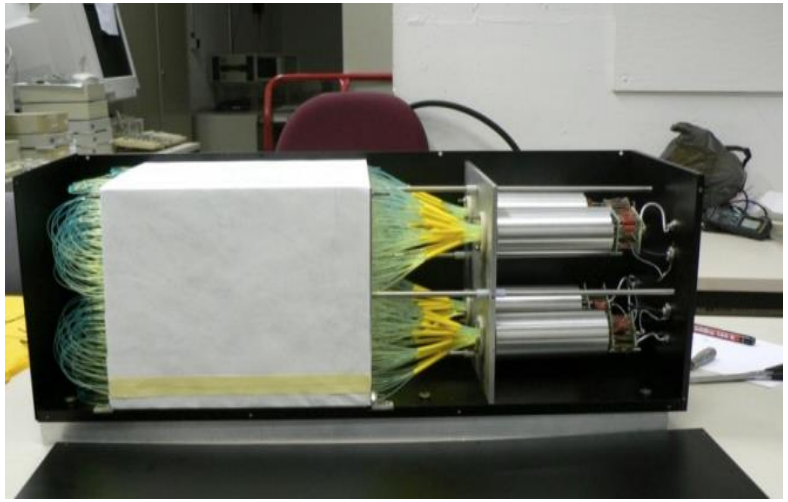
LAV + LKr + IRC + SAC:
~10^8 rejection of $\pi^0 \to \gamma\gamma$

detectors installed, readout partially commissioned

IRC



SAC

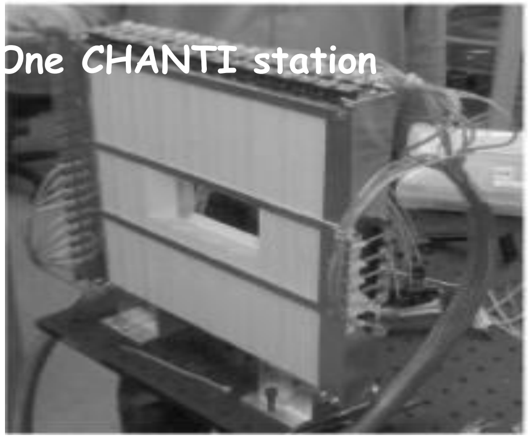


CHOD & CHANTI

CHANTI

CHANTI: detection of particles from inelastic interactions in GTK mimicking a Pion in time with a Kaon

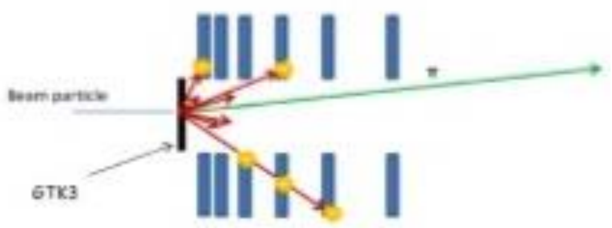
- 6 stations hermetic to charged particles between 49 and 1.31 mrad
- 22(24) scintillation bars in X(Y) for each station
- WLS fibers inside each bar, readout by SiPM on one side only (other is mirrored)
- IIs happen every 5/10[4] (GEANT studies)



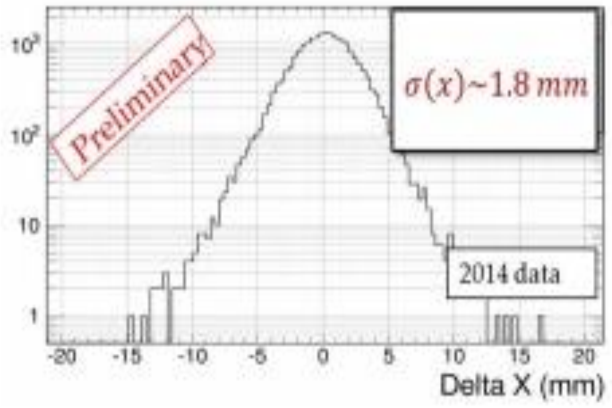
2014 Pilot run

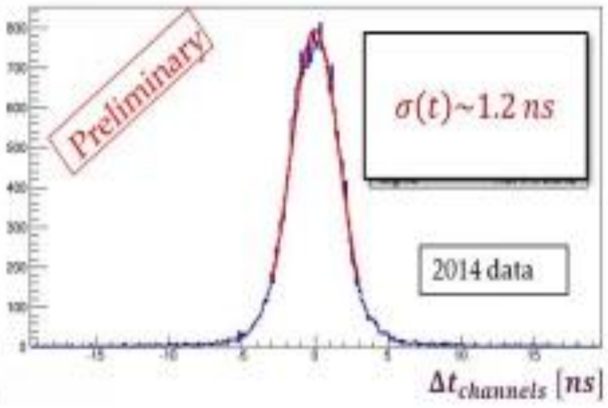
✓ detector installed and aligned, readout commissioned

CHANTI layout

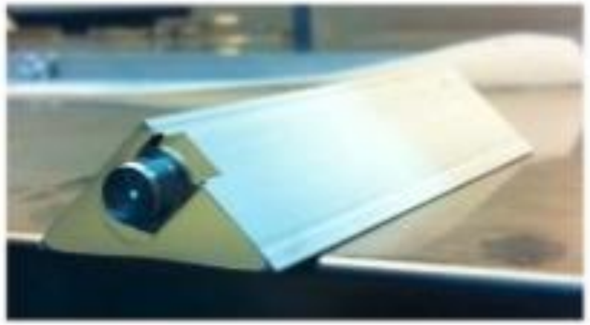


CHANTI X and time resolution





CHANTI scintillator bar



CHOD – charged particle hodoscope

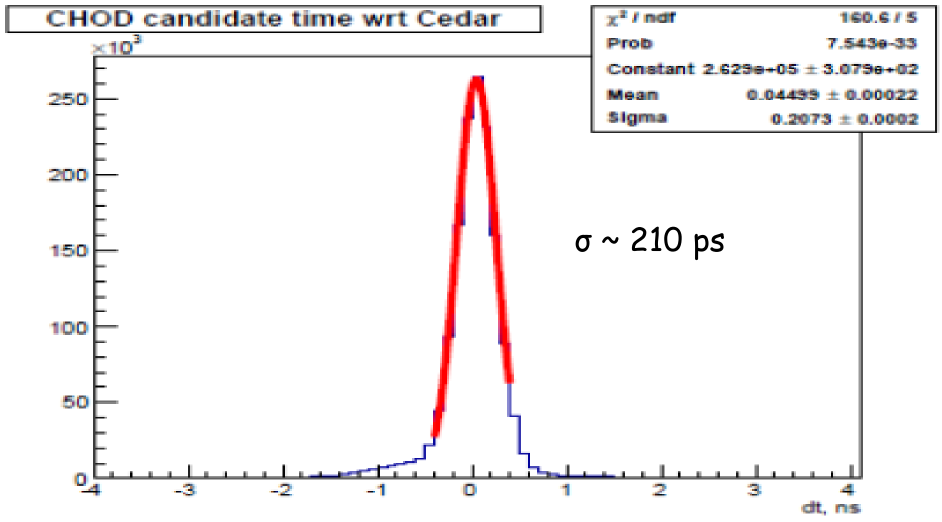
CHOD: detection tracks with precise measurements of the arrival time and impact point

- 2 planes with scintillator slabs
- 64 slabs per plane
- X/X_0 ~5% per plane

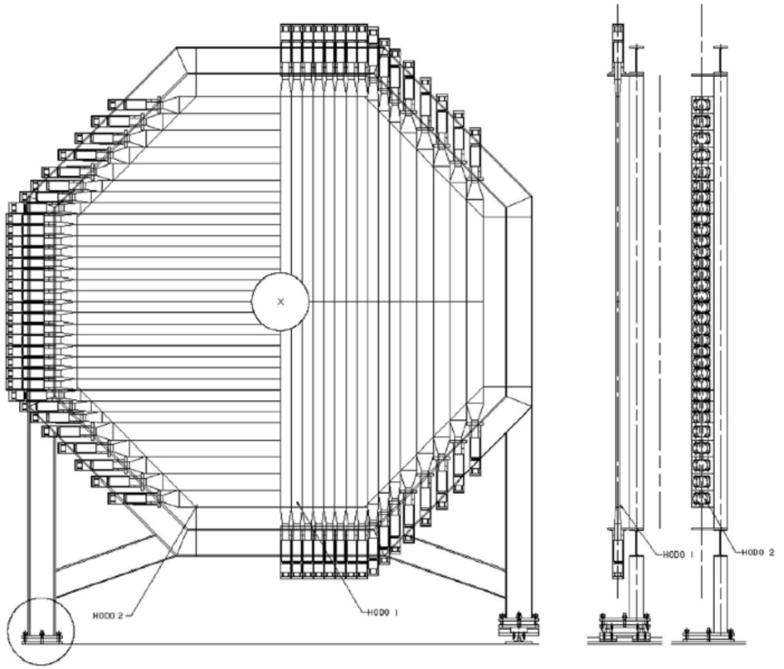
Requirements:

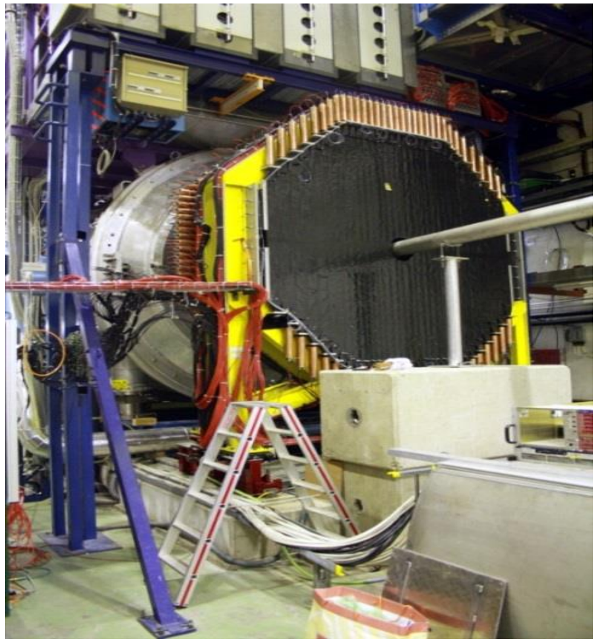
✓ Time resolution with impact point correction $\sigma_t < 400$ps

CHOD time resolution



σ ~ 210 ps





2014 Pilot run

✓ Readout and detector fully commissioned

2014 Pilot Run:

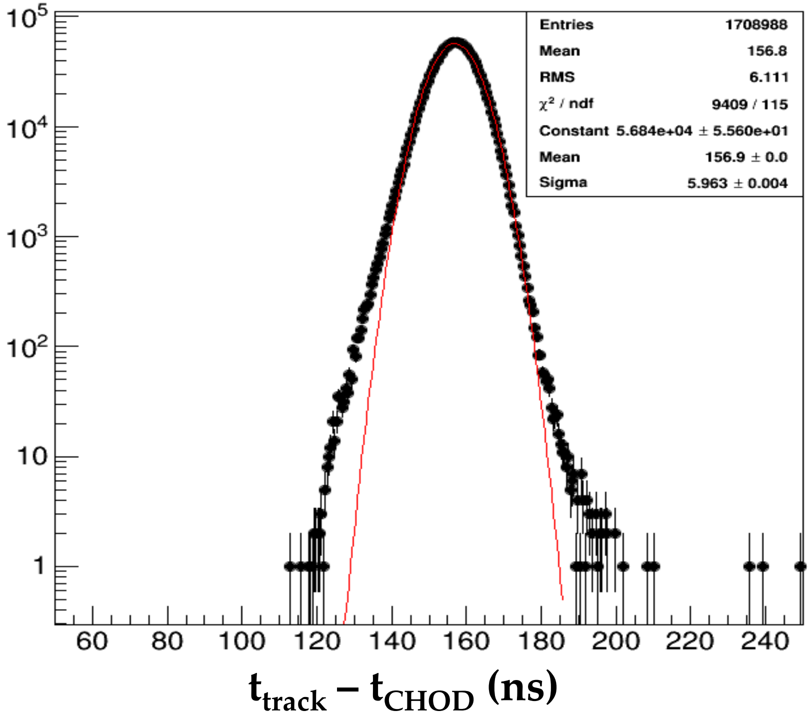
- two weeks of data taking at stable conditions
- 5% of the nominal intensity
- Preliminary time alignments and calibrations

Data analysis from 2014 Pilot Run

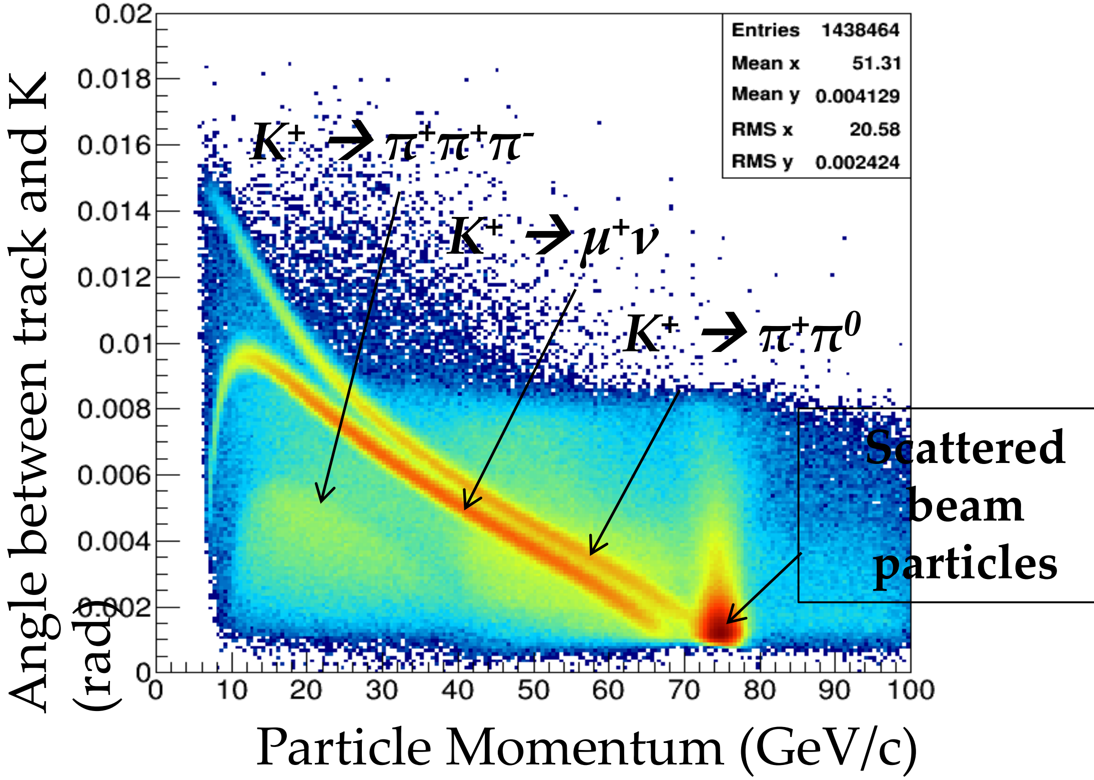
First look at the 2014 data - Single Track Events

Events with only 1 reconstructed track in the spectrometer (40 ns time window)

- 10^2 muon rejection at trigger level
- KTAG rejects kaon BGR



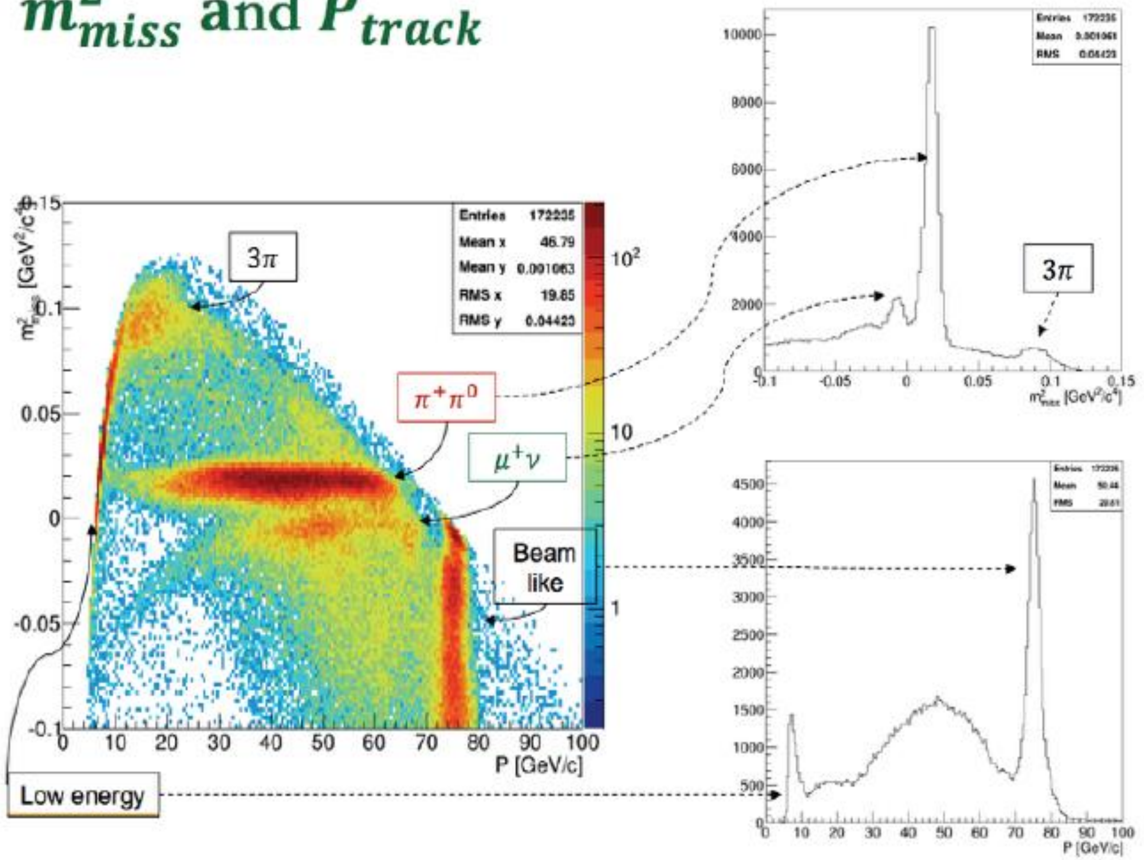
RMS = 6 ns



- Spectrometer + kaon momentum and direction assumption.
- 4 chamber tracks.

First look at the 2014 data

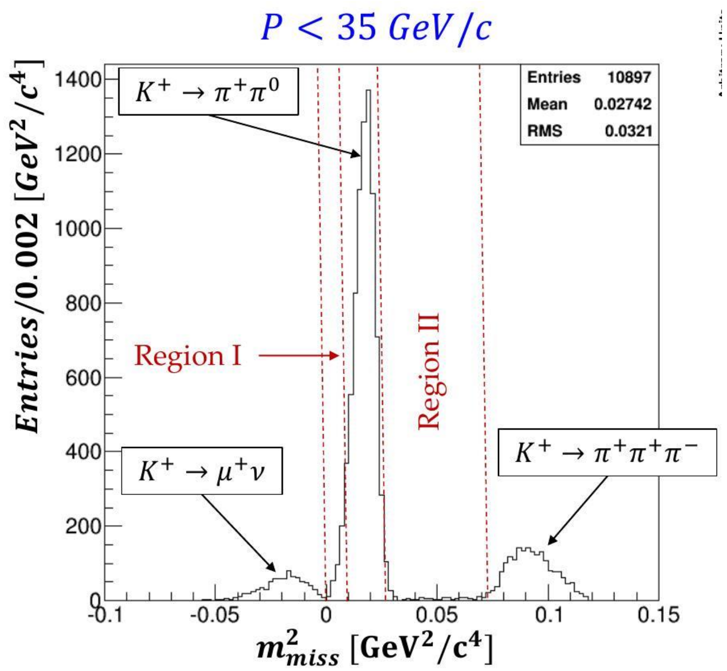
m^2_{miss} and P_{track}



- Kaon selected in time with CHOD and Spectrometer track + geometrical acceptance
- Vertex in fiducial region
- 15 < P < 35 GeV/c

Resolution of the $\pi^+\pi^0$ peak - $5*10^{-3}$ GeV^2/c^4

(vs. $3*10^{-3}$ GeV^2/c^4 in MC)



Conclusion

- **The NA62 experiment 2014 pilot run has been successful**, the majority of detectors and readout systems has been commissioned

- **Nominal intensity beam in 2015-2017** for full physics runs (first run has just started)

Main Goal:

- collect O(100) SM $K^+ \to \pi^+ \nu\bar{\nu}$ events
- measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) with ~10%

Further goals:

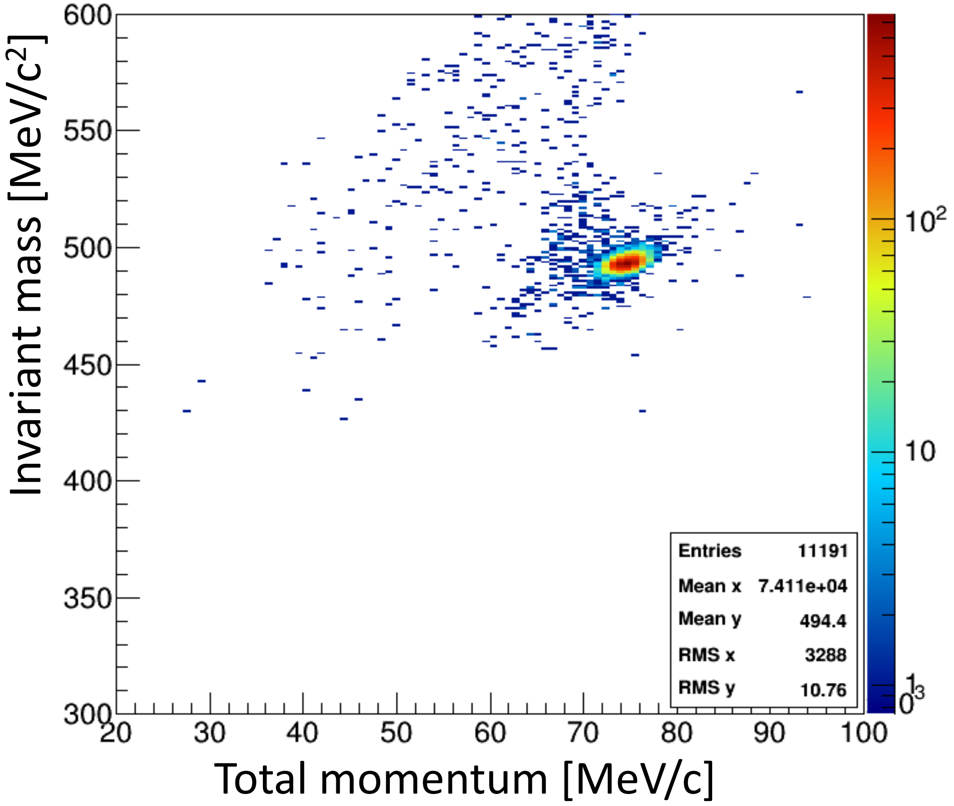
- Extraction $|V_{td}|$ with ~10% accuracy
- Probe several New Physics scenarios in $K^+ \to \pi^+ \nu\nu$
- Probe New Physics in similar processes (e.g. $K^+ \to \pi^+ X$)

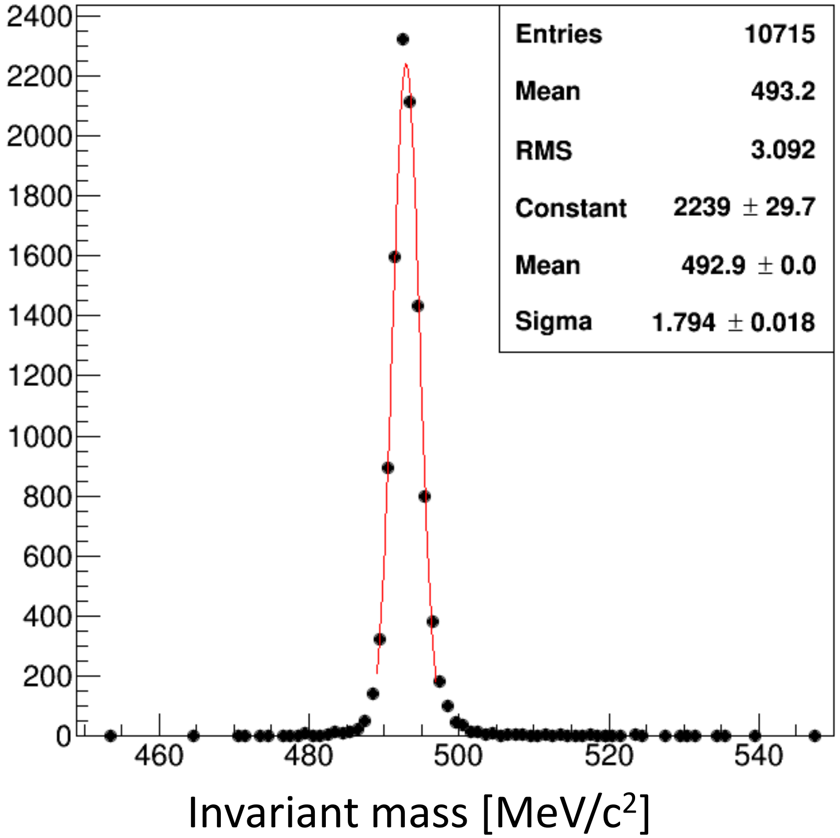

THANK YOU!

Spares

First look of 2014 data – Three track events

- Selection of $K^+ \to \pi^+\pi^+\pi^-$
- 2 positive and 1 negative charge. 3-track vertex (analytical). 4 chamber tracks.





- Invariant mass resolution: 0.9 MeV/c²
- Invariant mass average: 493.657 MeV/c²) (PDG - 493,667 (MeV/c²)

The NA62 goals

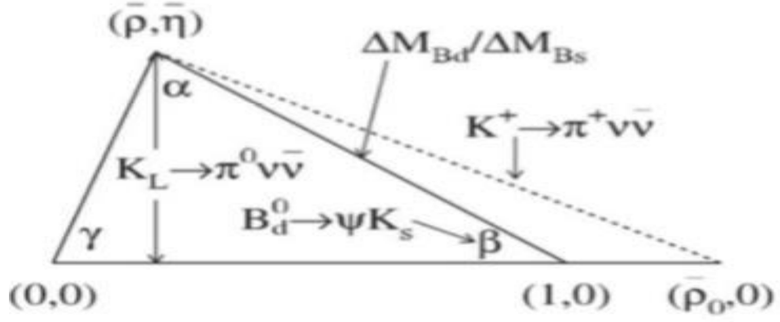
Main goal:

- Collect O(100) SM signal events in 3 years data taking
- Measure BR($K^+ \to \pi^+ \nu\nu$) with 10% precision

Further goals:

- Extraction $|V_{td}|$ with ~10% accuracy
- Probe several New Physics scenarios in $K^+ \to \pi^+ \nu\nu$
- Probe New Physics in similar processes (e.g. $K^+ \to \pi^+ X$)

Independent determination of unitary triangle for K meson system (with neutral mode)



BR($K^+ \to \pi^+ \nu\nu$)=(9.11 ± 0.72) × 10−11
[JHEP 1411 (2014) 121 [arXiv:1408.0728 [hep-ph]]
error: CKM parametric, dominated by Vcb

Beyond the baseline:

- LFV/LNV decays with 3 tracks in the final state
- Heavy neutrino searches
- π^0 decays
- Dark photon searches
- $K^+ \to \pi^+ \pi^0 \pi$ (pseudoscalar sGoldstino should exists in model with spontaneous symmetry braking, V.Rubakov)

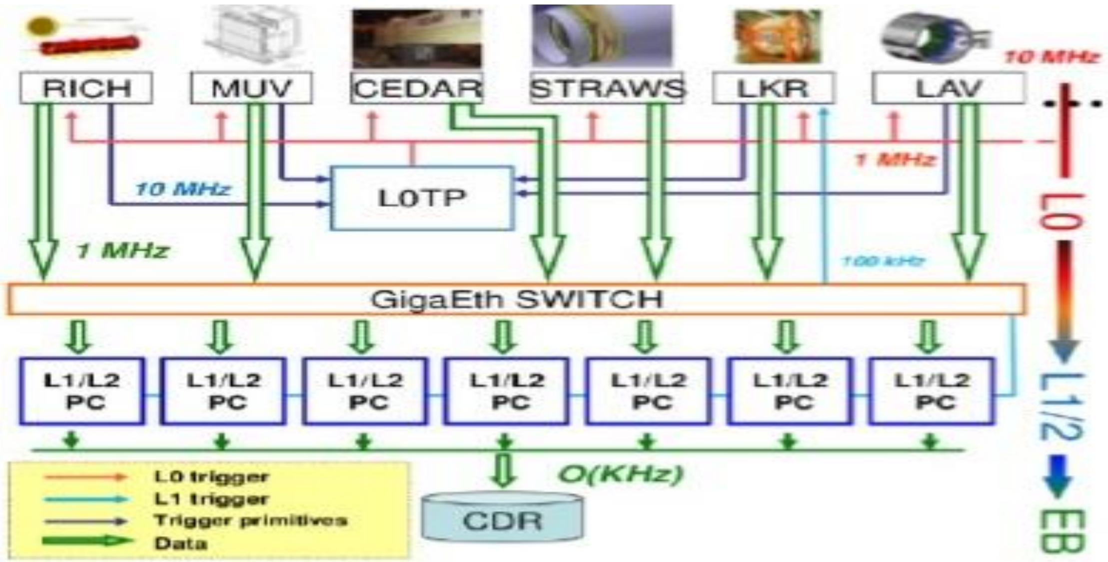
Beyond the baseline

Decay	Physics	Present limit (90% C.L.) / Result	NA62
$\pi^+\mu^+e^-$	LFV	1.3×10^{-11}	0.7×10^{-12}
$\pi^+\mu^-e^+$	LFV	5.2×10^{-10}	0.7×10^{-12}
$\pi^-\mu^+e^+$	LNV	5.0×10^{-10}	0.7×10^{-12}
$\pi^-e^+e^+$	LNV	6.4×10^{-10}	2×10^{-12}
$\pi^-\mu^+\mu^+$	LNV	1.1×10^{-9}	0.4×10^{-12}
$\mu^-\nu e^+e^+$	LNV/LFV	2.0×10^{-8}	4×10^{-12}
$e^-\nu\mu^+\mu^+$	LNV	No data	10^{-12}
π^+X^0	New Particle	$5.9\times10^{-11}\ m_{X^0}=0$	10^{-12}
$\pi^+\chi\chi$	New Particle	–	10^{-12}
$\pi^+\pi^+e^-\nu$	$\Delta S\neq\Delta Q$	1.2×10^{-8}	10^{-11}
$\pi^+\pi^+\mu^-\nu$	$\Delta S\neq\Delta Q$	3.0×10^{-6}	10^{-11}
$\pi^+\gamma$	Angular Mom.	2.3×10^{-9}	10^{-12}
$\mu^+\nu_h, \nu_h\to\nu\gamma$	Heavy neutrino	Limits up to $m_{\nu_h}=350\ MeV$	
R_K	LU	$(2.488\pm0.010)\times10^{-5}$	>×2 better
$\pi^+\gamma\gamma$	χPT	<500 events	10^5 events
$\pi^0\pi^0e^+\nu$	χPT	66000 events	$O(10^6)$
$\pi^0\pi^0\mu^+\nu$	χPT	-	$O(10^5)$

The TDAQ system

The NA62 trigger system is based on 3 trigger levels:

- L0: based on "trigger primitives" from a configurable number of detectors
  - Fixed latency (~1 ms)
  - FPGA based
  - L0TP receives the primitives, takes the L0 decision and sends the L0 signal
  - **Reduction factor**: 10 MHz →1 MHz
- L1: data from most detectors acquired by L1 PCs and used to take the L1 decision
  - Whole event analysed by L1 PCs
  - LKr data not sent @ L1 level
  - Max latency: ~1 s
  - **Reduction factor:** 1 MHz →100 KHz
- L2: final decision taken with data from all detectors available
  - Max latency ~ spill length
  - **Reduction factor:** 100 KHz →20 KHz



2014 Pilot run

- ✓ Data collected at 20% nominal intensity
- ✓ Trigger primitives partially commissioned

INPUT TRIGGER PRIMITIVES

L0 trigger processor (L0TP)

- Altera DE4 test board, StratixIV onboard
- Max input rate from detectors: 10 MHz
- Max L0T output rate: 1 MHz
- 6 Eth. ports to receive trigger