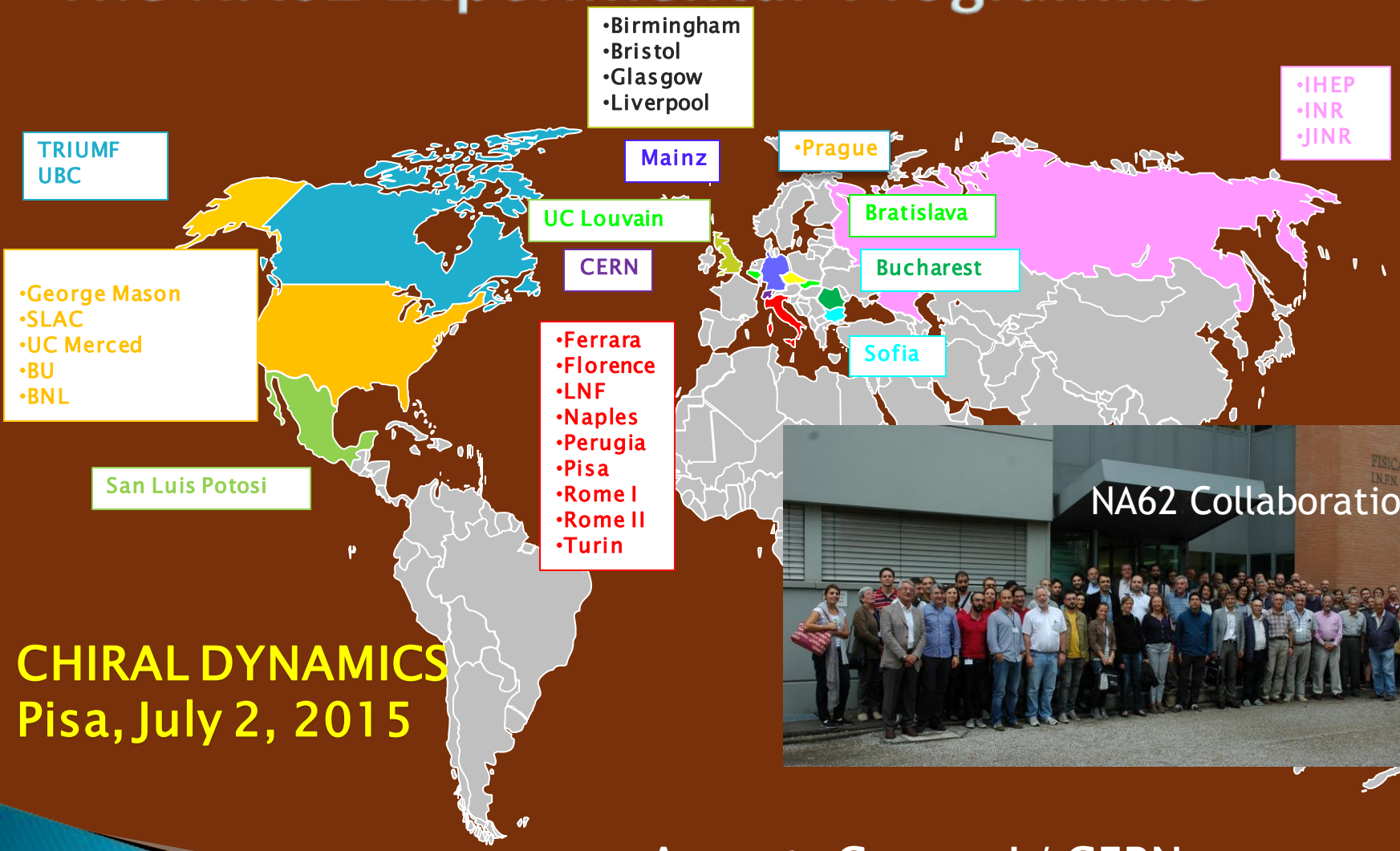
Kaons at CERN:
The NA62 Experimental Programme



CHIRAL DYNAMICS
Pisa, July 2, 2015

Augusto Ceccucci / CERN

NA62 GOAL

- We aim to measure to 10% or better

$$Br(K^+ \to \pi^+ \nu\bar{\nu})$$

with in-flight kaon decays

- State of the art:

Decay	Branching Ratio ($\times 10^{10}$)	
	Theory (SM)	Experiment
$K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$	0.911 ± 0.072 [1]	$1.73^{+1.15}_{-1.05}$ [2]

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

[2] AGS-E787/E949 PRL101 (2008) 191802, arXiv:0808.2459

CHARGED K BEAMS

"Stopped"

- Work in Kaon frame
- High Kaon purity (Electro-Magneto-static Separators)
- Compact Detectors

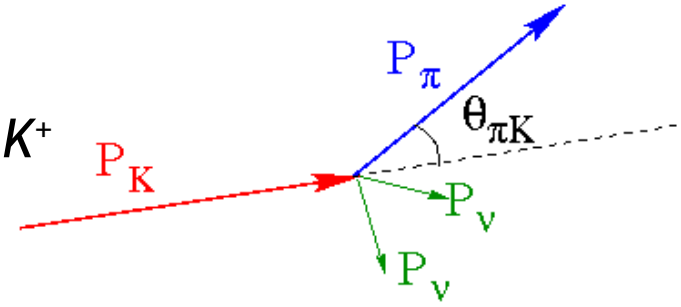
"In-Flight"

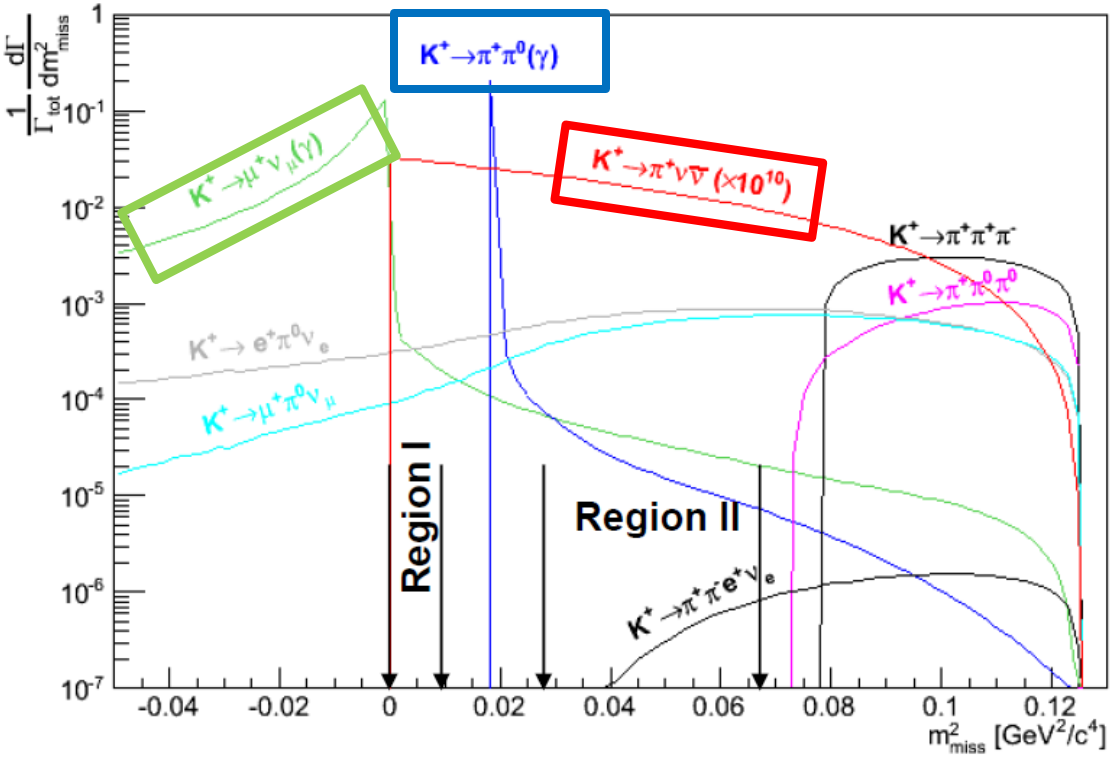
- Decays in vacuum (no scattering, no interactions)
- RF separated or Unseparated beams
- Extended decay regions

Exp	Machine	Meas. or UL 90% CL	Notes
	Argonne	$< 5.7 \times 10^{-5}$	Stopped; HL Bubble Chamber
	Bevatron	$< 5.6 \times 10^{-7}$	Stopped; Spark Chambers
	KEK	$< 1.4 \times 10^{-7}$	Stopped; $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
E787	AGS	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$	Stopped
E949	AGS	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	Stopped; PPN1+PPN2
NA62	SPS		In-Flight; Unseparated

NA62 IN-FLIGHT TECHNIQUE

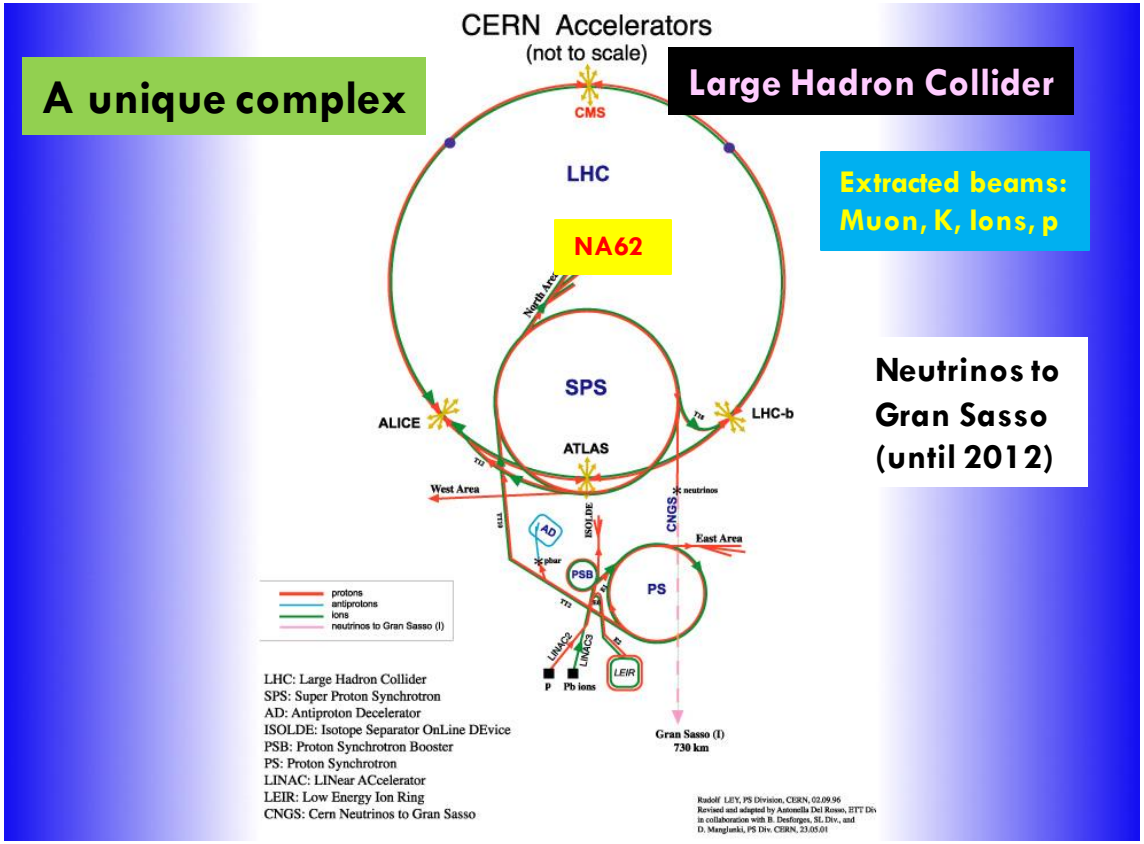
- Calorimetry to veto extra particles
- Very light trackers to reconstruct the K^+ and the π^+ momenta
- Full particle identification



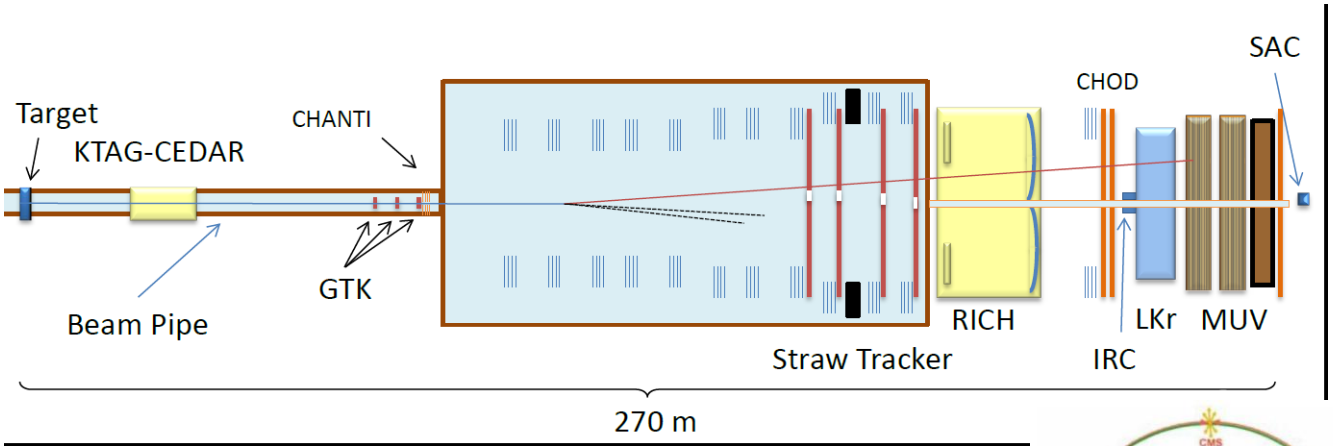


$$m^2_{miss} = (P_K - P_{\pi^+})^2$$

CERN ACCELERATORS

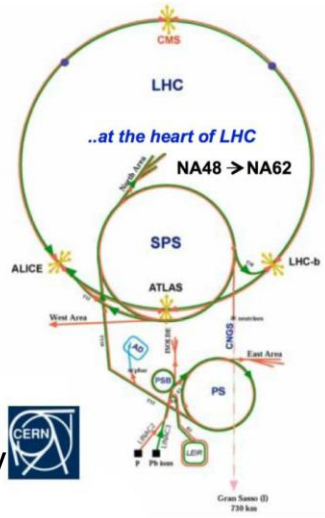


NA62 SCHEMATIC LAYOUT



10^{12} / s protons from SPS (400 GeV/c) on Be target (~1 λ)

750 MHz secondary beam: 75 GeV/c
- **Positive polarity**
- **Kaon fraction ~6%**
- **Δ p/p ~ 1%**
- **Useful kaon decays ~10% (5 MHz)**



NA62 is designed for a specific "silver bullet" measurement. This requires high beam rate, full PID, hermetic coverage, very light, high-rate tracking and state-of-the-art trigger and DAQ. It paves the way to a broad physics program

$K^+ \to \pi^+ \nu\bar{\nu}$ Analysis Sensitivity (MC)

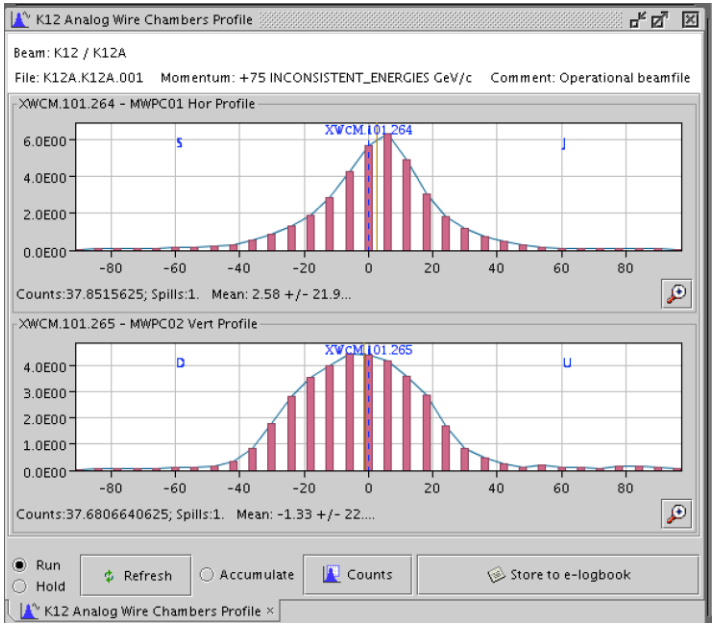
Decay	event/year
$K^+ \to \pi^+ \nu\nu$ [SM] (flux 4.5×10^{12})	45
$K^+ \to \pi^+ \pi^0$	5
$K^+ \to \mu^+ \nu$	1
$K^+ \to \pi^+ \pi^+ \pi^-$	< 1
$K^+ \to \pi^+ \pi^- e^+ \nu$ + other 3 tracks decays	< 1
$K^+ \to \pi^+ \pi^0 \gamma$(IB)	1.5
$K^+ \to \mu^+ \nu \gamma$(IB)	0.5
$K^+ \to \pi^0 e^+(\mu^+) \nu$, others	negligible
Total background	< 10

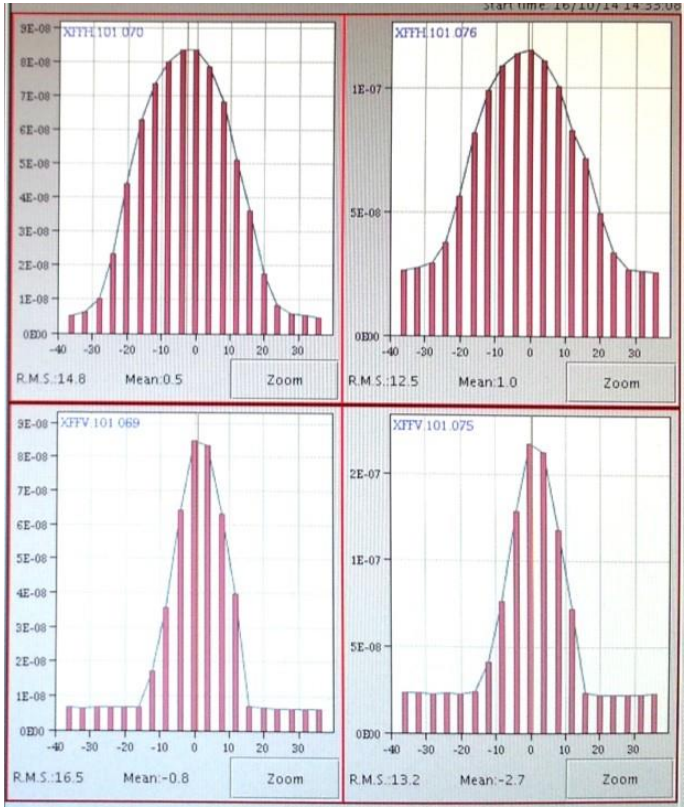
NA62 EXPERIMENT IN ECN3

- Picture taken just before starting taking data 2014
- Beam time 2014: October 6 – December 15
- >100 TB of data
- Resume data taking on June 22, 2015 until CERN Long Shutdown 2

NA62 BEAM PROFILES

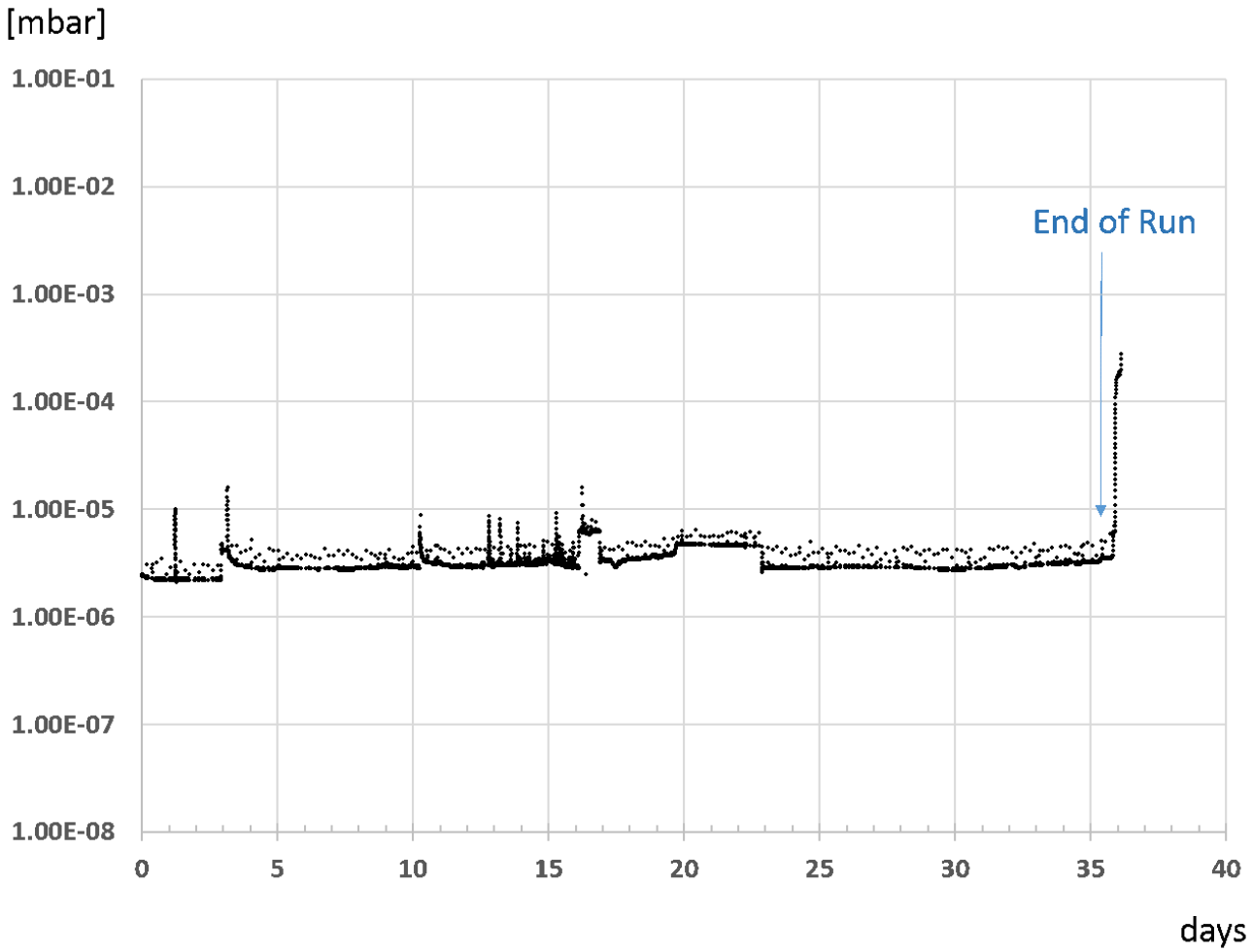
Beam profile measured by MWPC at the end of the dump tunnel. The spot size is as calculated.





Horizontal (top) and vertical (bottom) profiles before (left) and after (right) the KTAG counters measured with FISC counters. These profiles are now symmetric as expected

VACUUM IN DECAY TANK



Very satisfactory performance

NA62 DETECTOR STATUS

View of ECN3

LAV 1-5 in TTC8

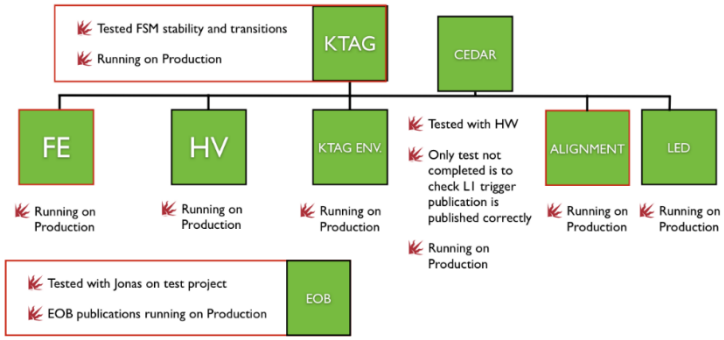
NA62 DETECTOR STATUS

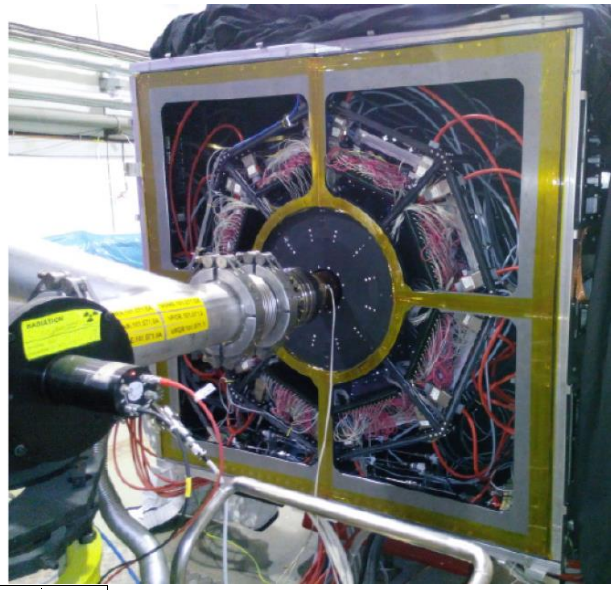
RICH Straw 4 and LAV11

Straw3 - LAV10 - MNP33 -
Straw2 - LAV9

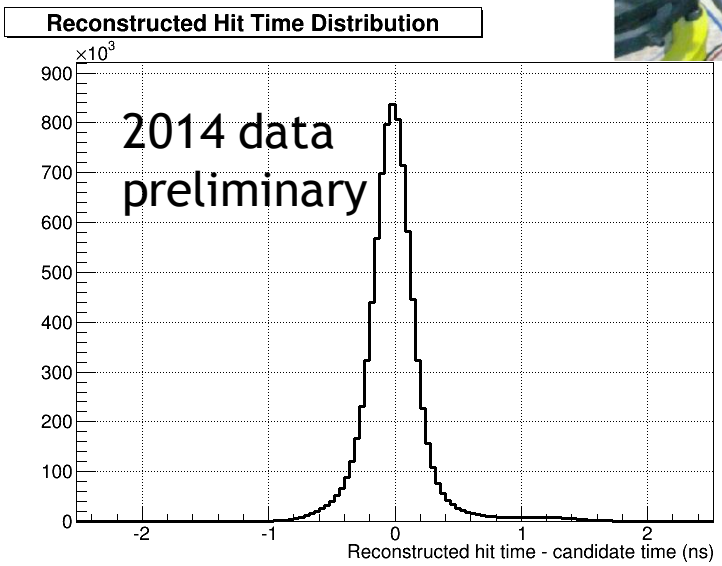
KTAG

Birmingham, Bristol, Liverpool





Kaon timing



$\sigma_{PM}(t) \sim 280\ ps$

$\langle N_{PM} \rangle \sim 18$

$\sigma_K(t) < 80\ ps$

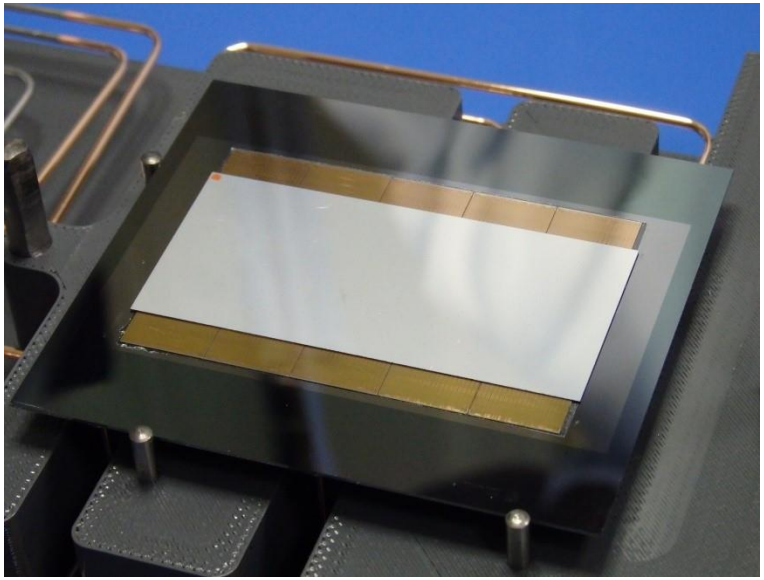
Reconstructed hit time – candidate time [ns]

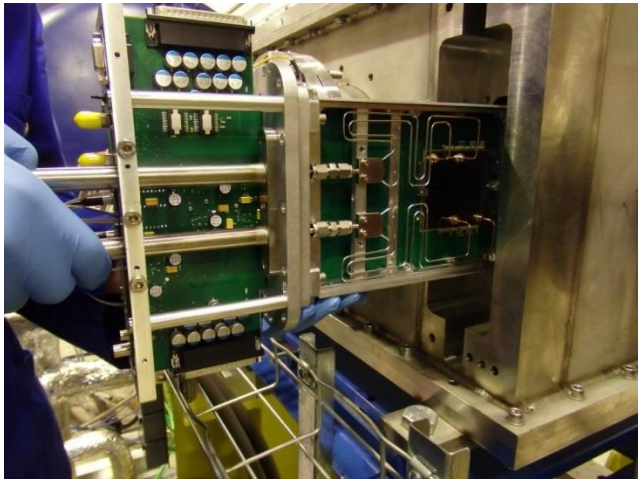
GIGATRACKER ACHIEVEMENTS

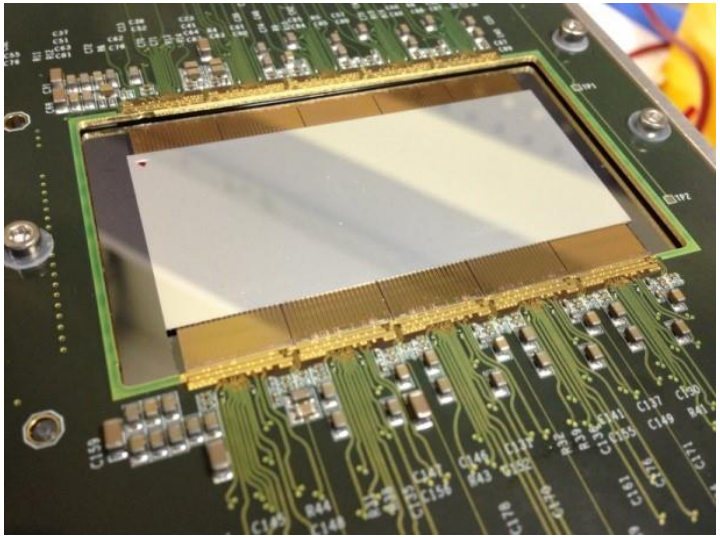
- The ASIC chip,TDCpix, has been fully characterized
- Bump-bonding of six sensors with different TDCpix thickness (450, 250 and 100 microns has been achieved)
- First carrier board was designed and fabricated
- Micro-channel cooling was achieved
- Mechanical integration
- Cooling plant constructed, installed and commissioned
- DAQ cards installed and tested
- Data acquired in “zero bias mode” and merged into stream with the other NA62 detectors

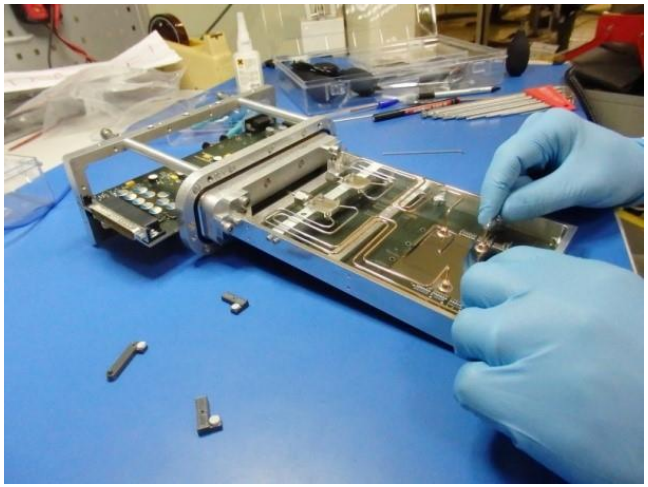
GIGATRACKER (GTK)

CERN (PH-DT, PH-ESE, PH-SME, EN,…)
Ferrara, Louvain-la-Neuve, Torino



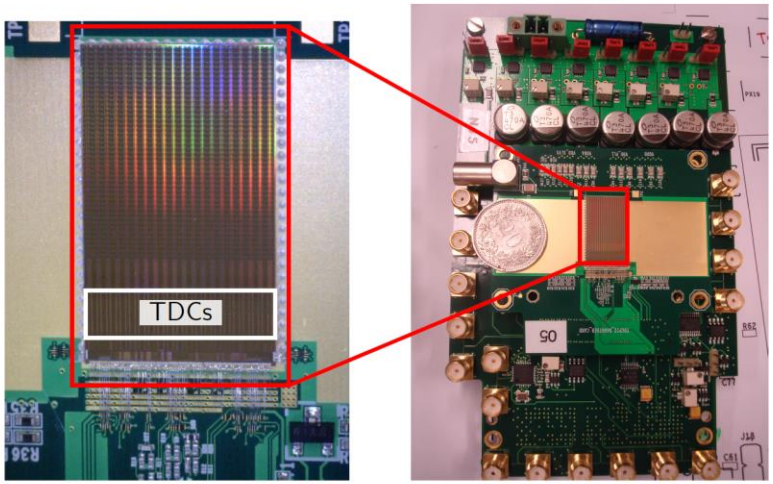






GTK READ OUT CHIP

TDCPix Wire Bonded to the Test Card



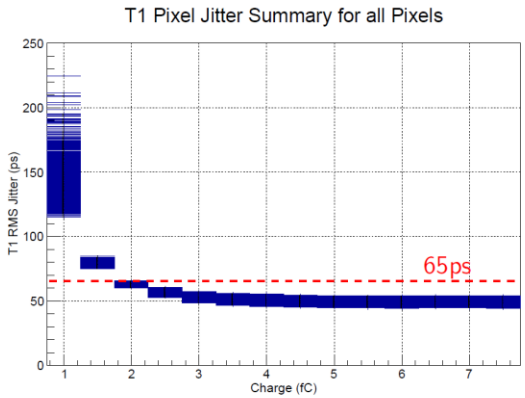
TDCPix

130 nm CMOS IBM

CERN
PH-ESE Design

Excellent performance
Major breakthrough for NA62

Full Chain Behaviour



- trigger swept through full clk cycle
  - 32 phases
  - Step:100ps
- 10^4 triggers per phase
- No sensor present

$T_1(\text{RMS}) < 65\,\text{ps}$ at $2.5\,\text{fC}$

Block	Status	Remarks
Configuration	Working	5 chips tested
PLL	Working	3.2 GHz
Serialisers	Working	3.2 Gb/s
Bandgaps	Working	
Temperature Interlock	Working	
Column Biasing	Working	200 DACs
In-Pixel Threshold Trimming	Working	1800 DACs
# of bugs detected	0	

"Whole Chip" Resolution ~ 72 ps RMS

GTK COOLING


LIFT HERE
2300 Kg
TCC8 GALLERY
NA62 GIGATRACKER
COOLING SYSTEM
bicold
ENGINEERING

GTK DURING THE 2014 RUN

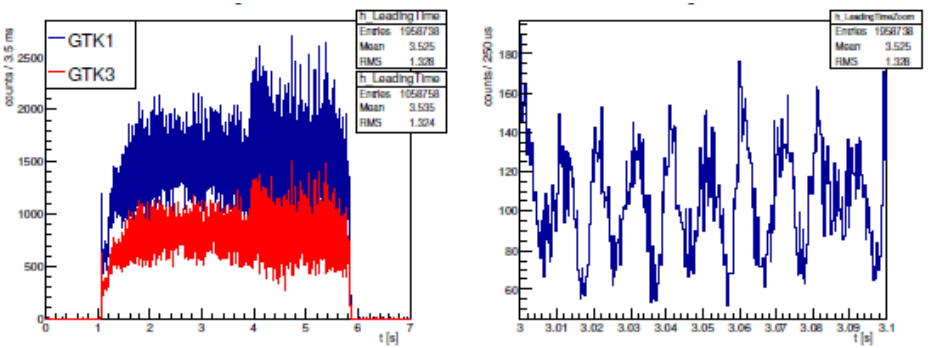
Three Stations Installed before the end of the 2014 run and partially read out

GTK position	Date of Installation	TDCPix Thickness (micron)
1	9/12/2014	450
2	11/12/2014	250
3	6/11/ 2014	450

SPS user schedule for 2014

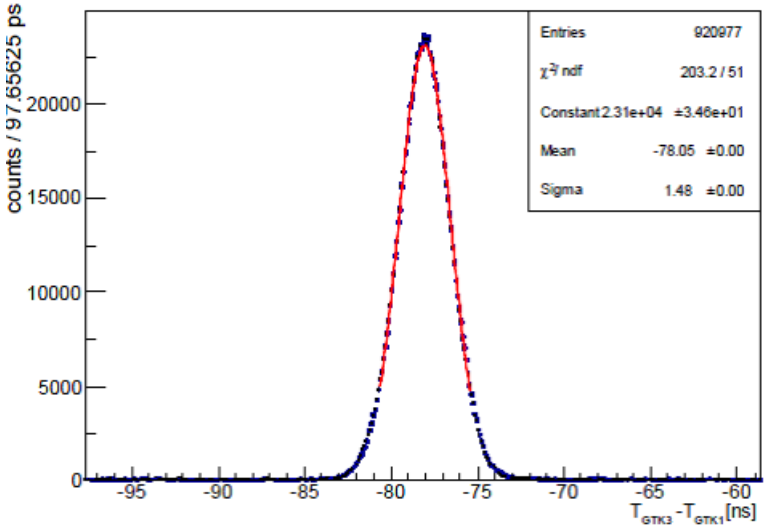
Tests on several single-chip assemblies confirms that the ASIC chip is fully functional and that the bump-bonding efficiency is better that 99%.

GTK DAQ

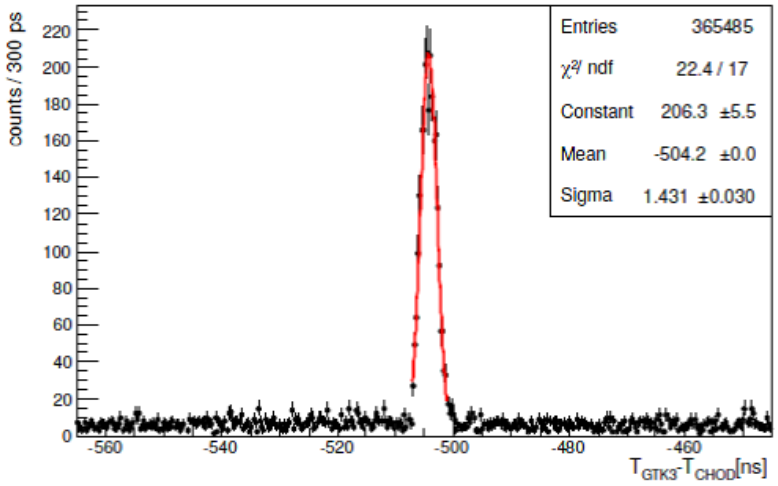


Each TDCpix sends data to one VME DAQ card
Data were reaout in “zero-bias” mode
GTK is a very powerful tool to study any beam structure / frequency

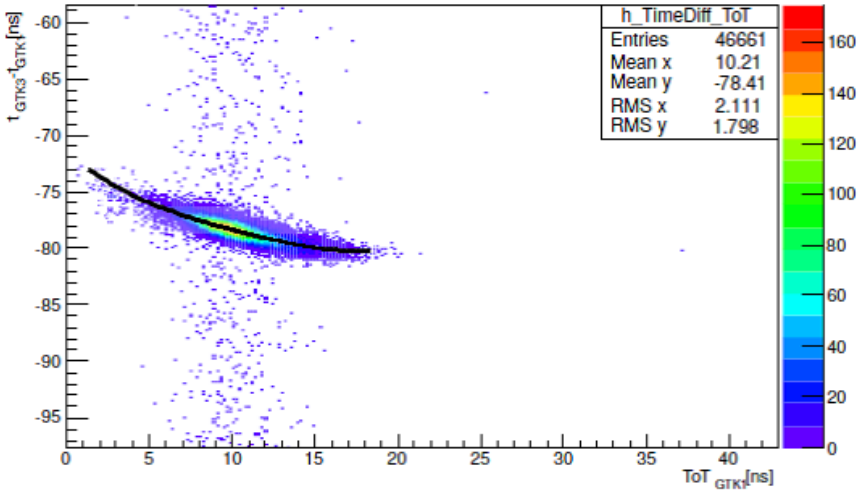
GTK ANALYSIS



GTK3 – GTK1 Before any correction



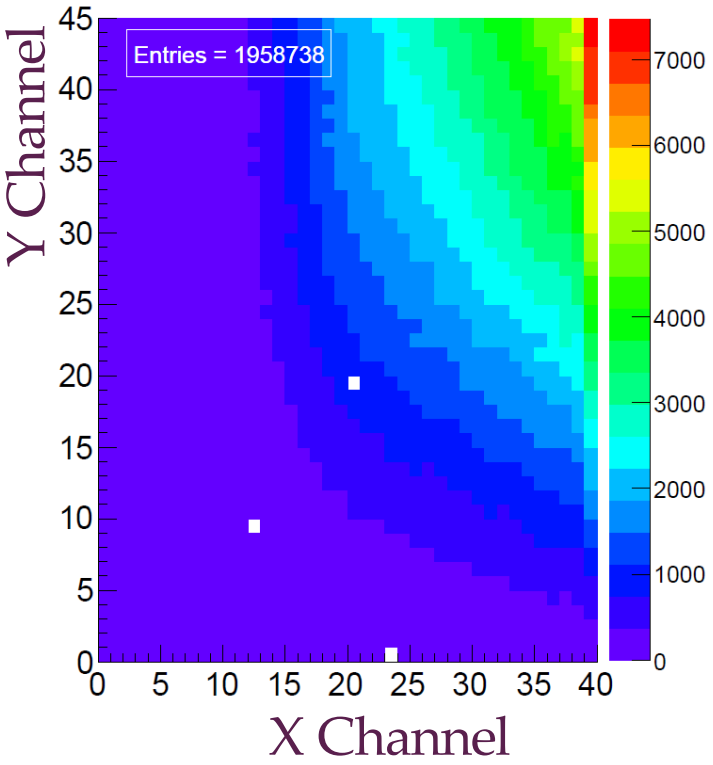
GTK3 – CHOD

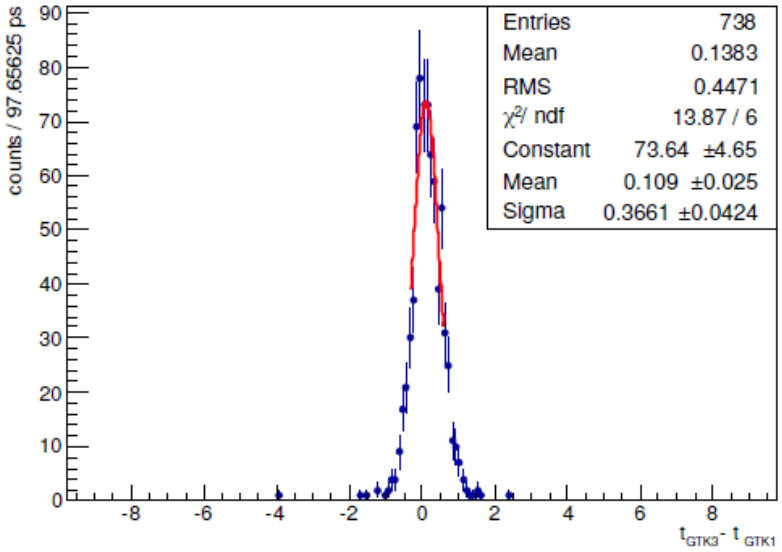


GTK3-GTK1vs. ToT GTK1 (pixel 29,33)

ToT is used to correct for The slewing of the signal

GIGATRACKER PERFORMANC





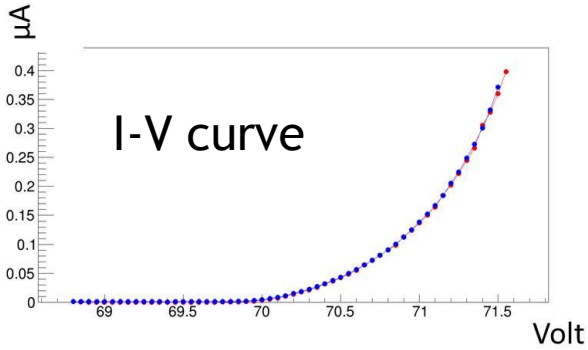
After ToT correction

Time resolution~ 260 ps /station
In line with expectations for
HV= 200 V

K12 Beam; Illumination of one GTK chip

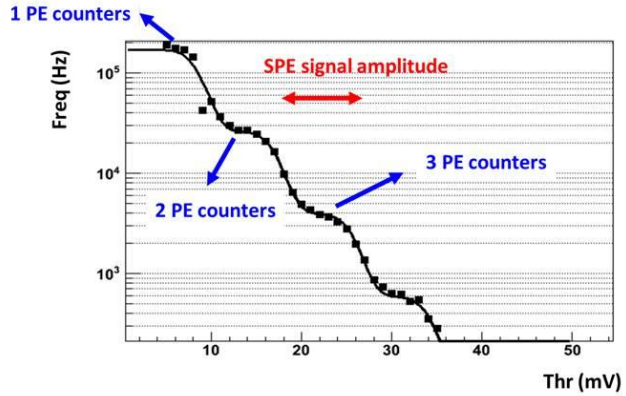
CHANTI

- The purpose of the CHANTI is to identify inelastic interactions occurring in the GTK3
- Six stations made by triangular scintillating bars read out via WLS fiber and SiPM
- 300 channels
- Installed and aligned to +/- 0.1 mm



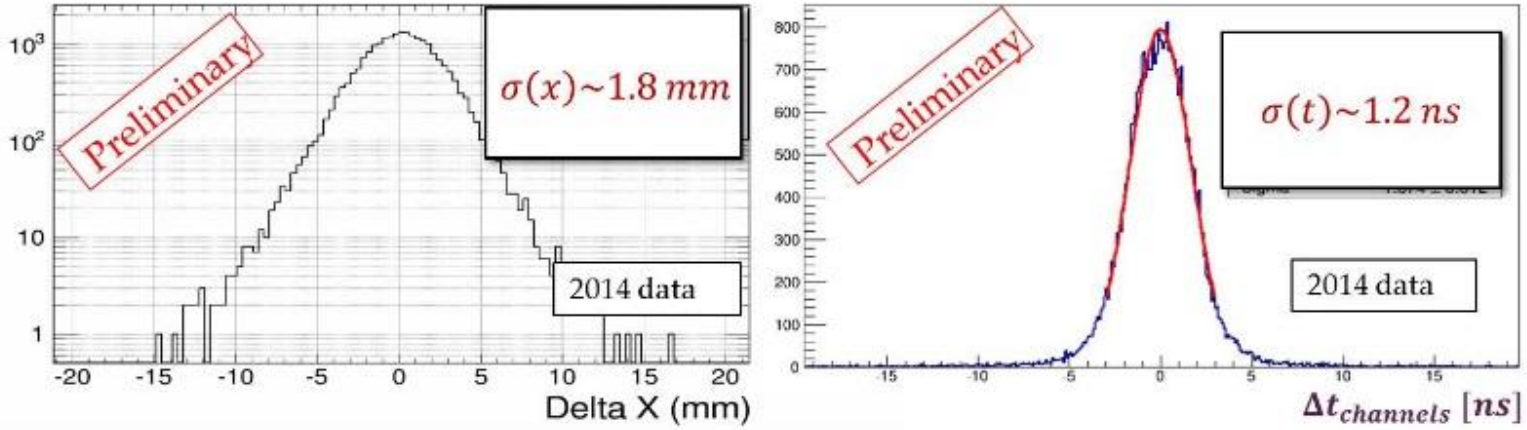
I-V curve

CHANTI Installation



Typical Threshold Scan

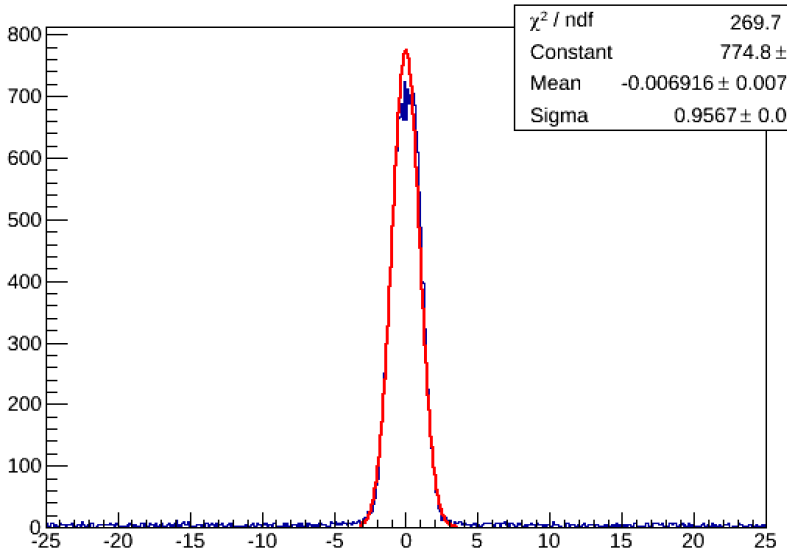
CHANTI PERFORMANCE

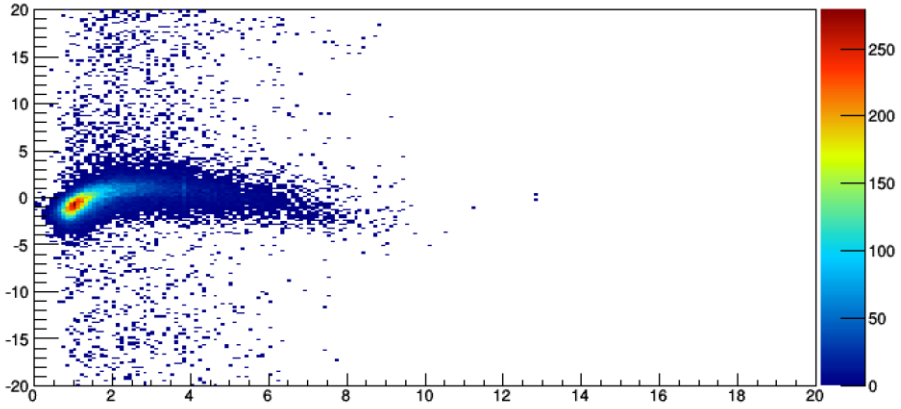


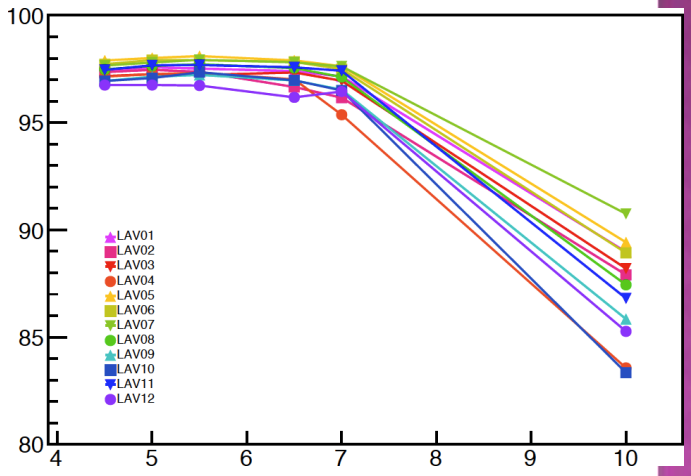
Time resolution obtained after ToT corrections

LARGE ANGLE VETOES (LAV)

Frascati, Naples, Pisa, Rome I

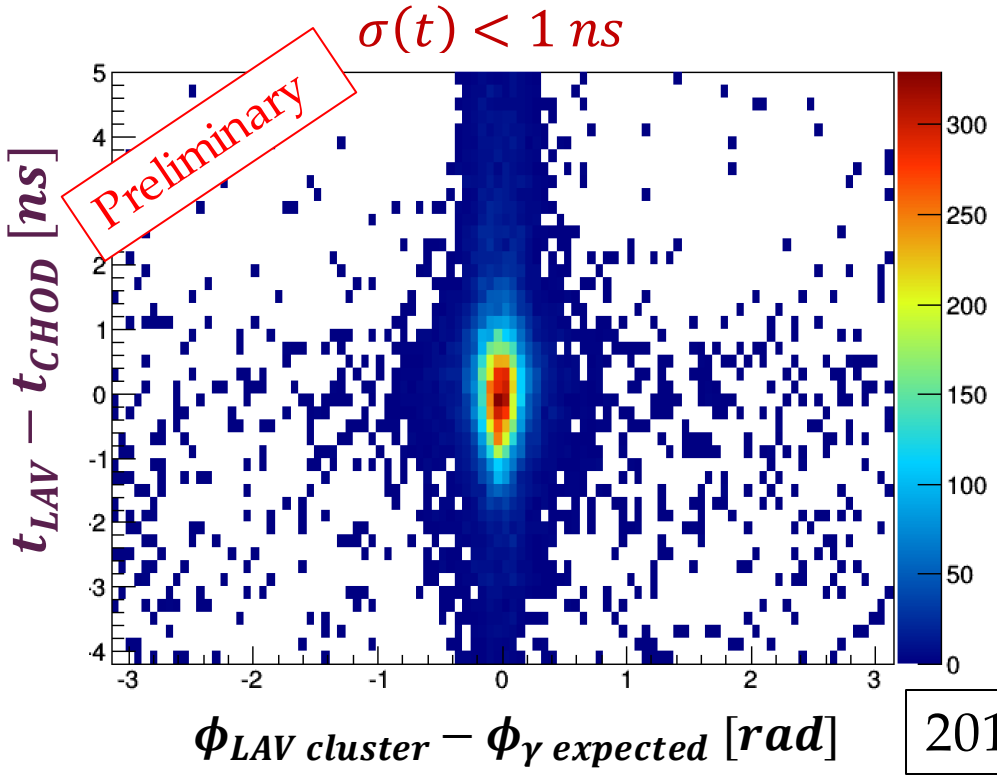




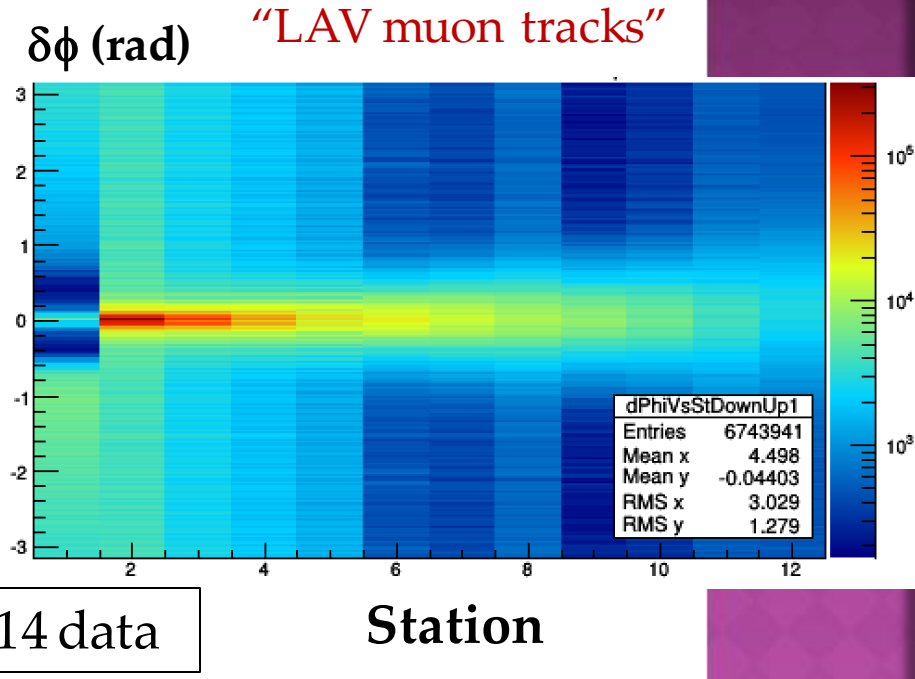


LAV SIGNALS

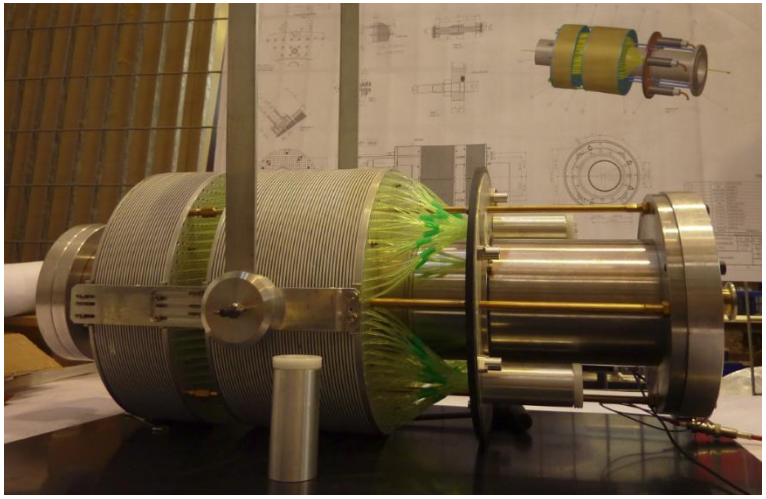
- Photons predicted in LAV match with reconstructed LAV clusters.
  - $K^+ \to \pi^+\pi^0$ reconstructed using straw spectrometer only.
  - 1 γ detected in the liquid Krypton calorimeter.
- LAVs' sensitive to muons



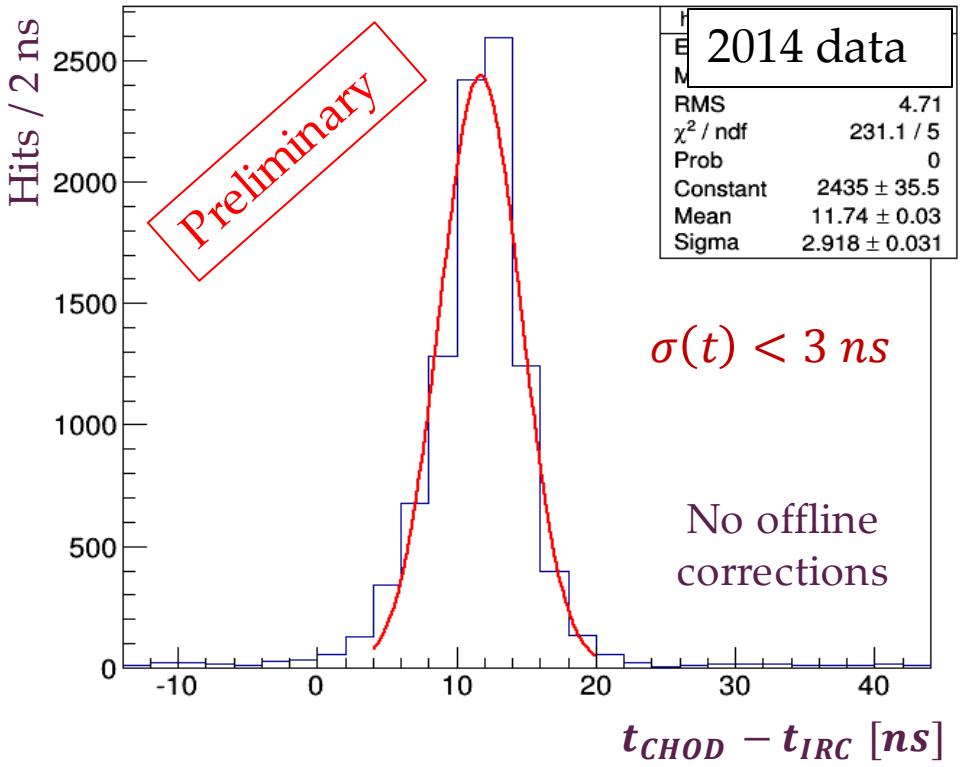
2014 data



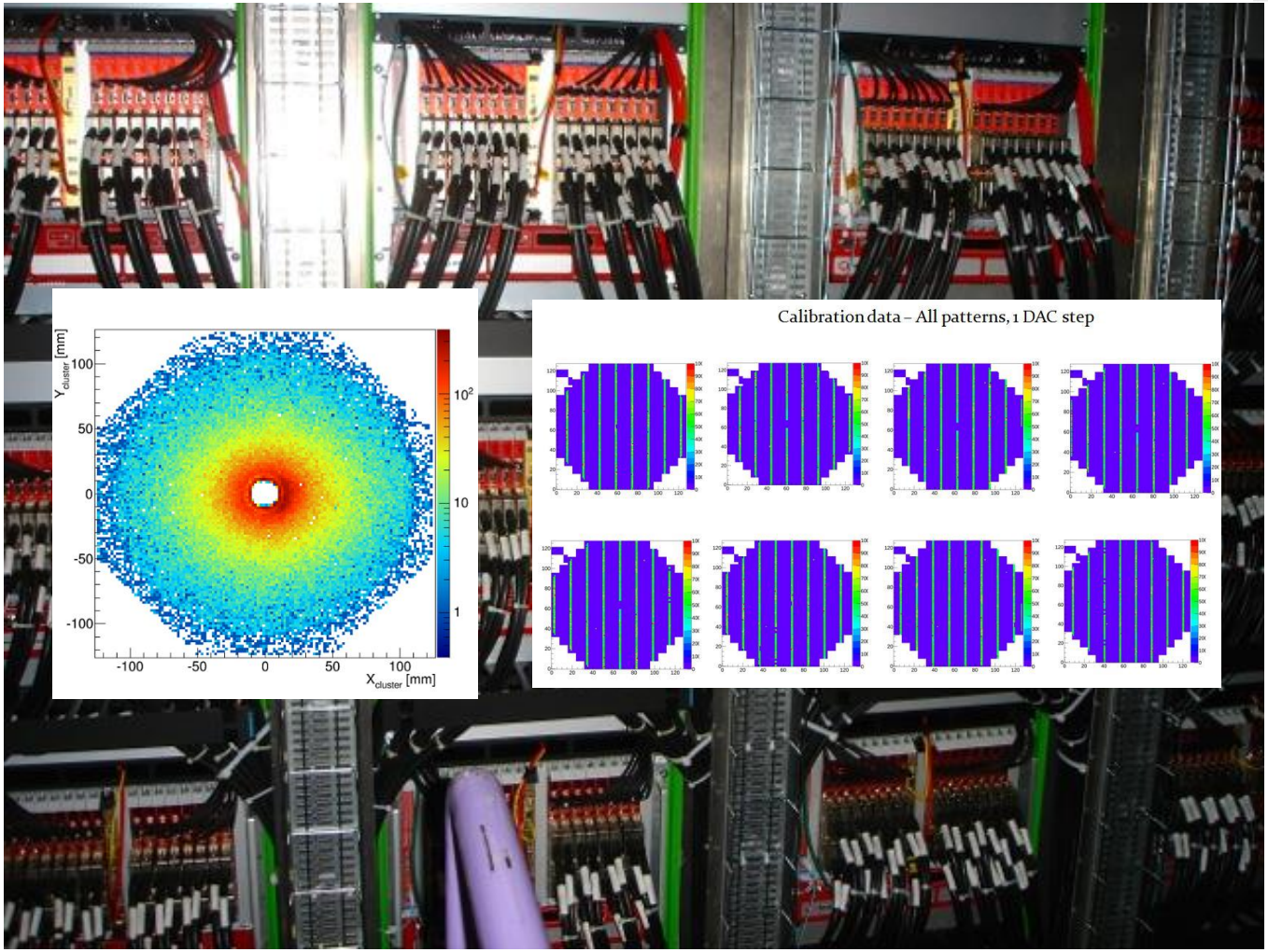
PHOTON DETECTORS: < 1 MRAD REGION



- Intermediate Ring (IRC) and Small Angle (SAC) calorimeters
- Shashlik technique (Iron and scintillating fibers)
- TDC readout
- 10^{-4} inefficiency for > 1 GeV photons
- Photon rate at full intensity < 1 MHz
- Commissioned in 2014



LIQUID KRYPTON READ OUT

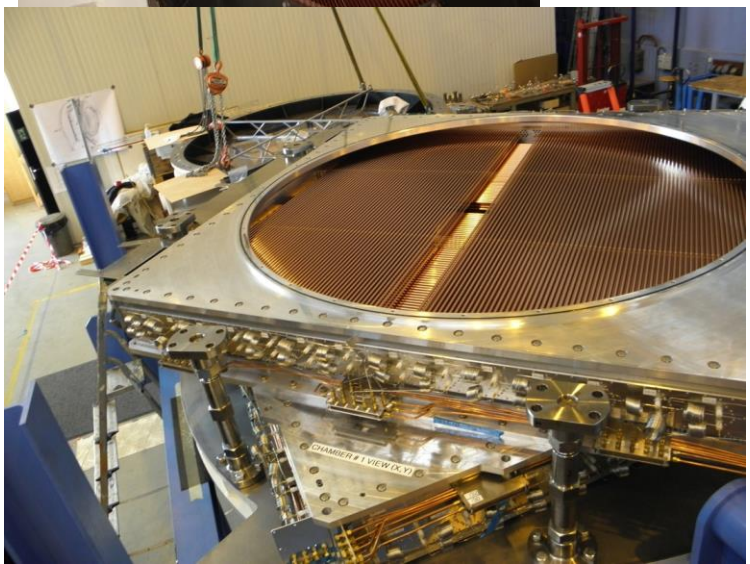


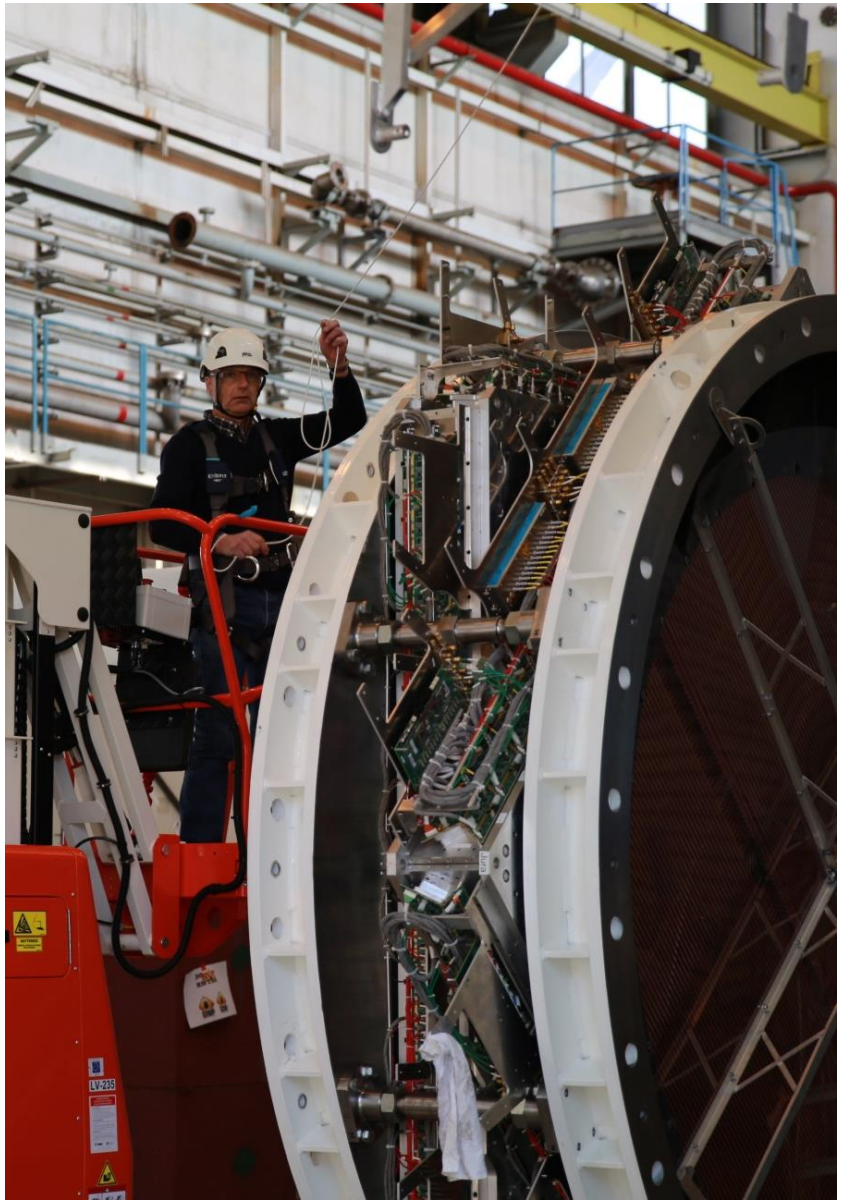
14 bit FADC, 40 Ms, 32 ch / module **432 modules, 28 VME crates**

Specifications/Tender : CERN PH-ESE,PH-SME Manufacturer: CAEN (ITALY)

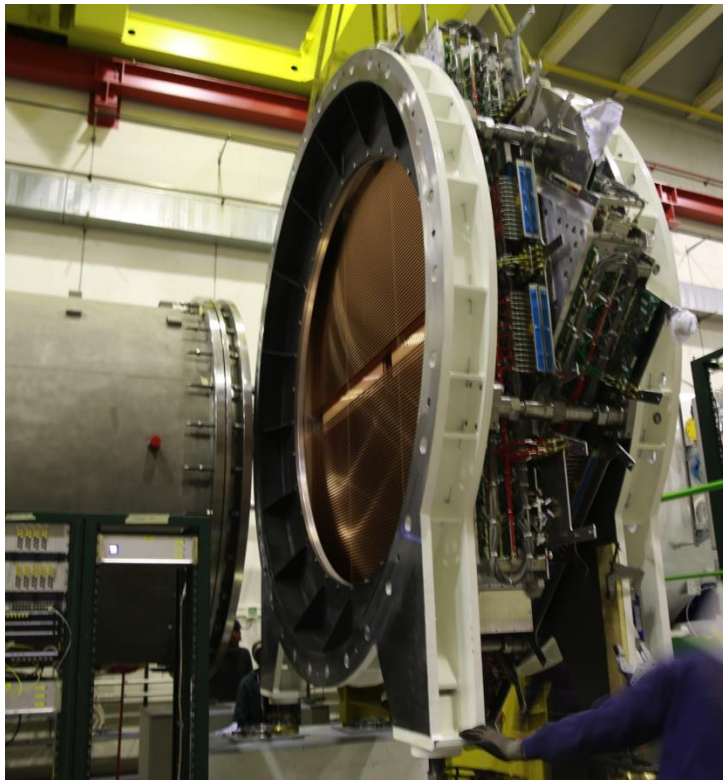
NA62 STRAW TRACKER

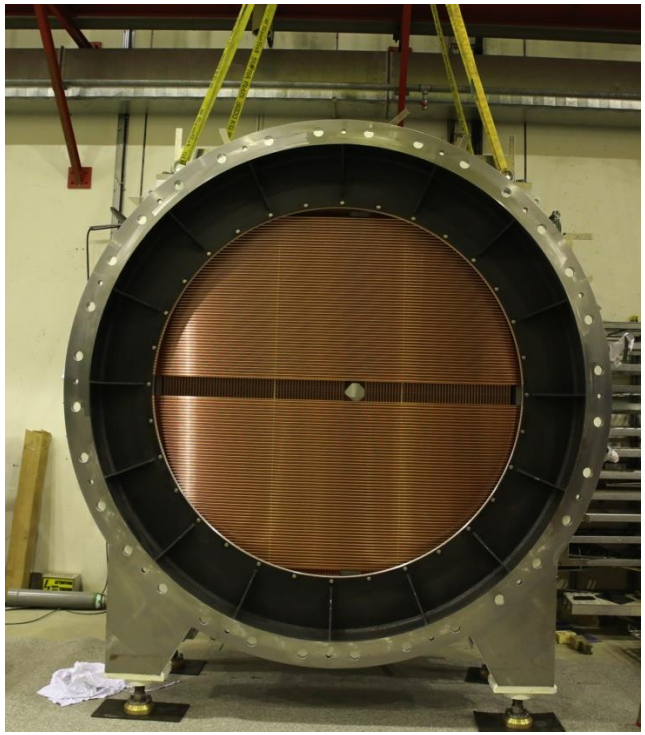
CERN (PH-DT, PH-ESE,PH-SME) - JINR





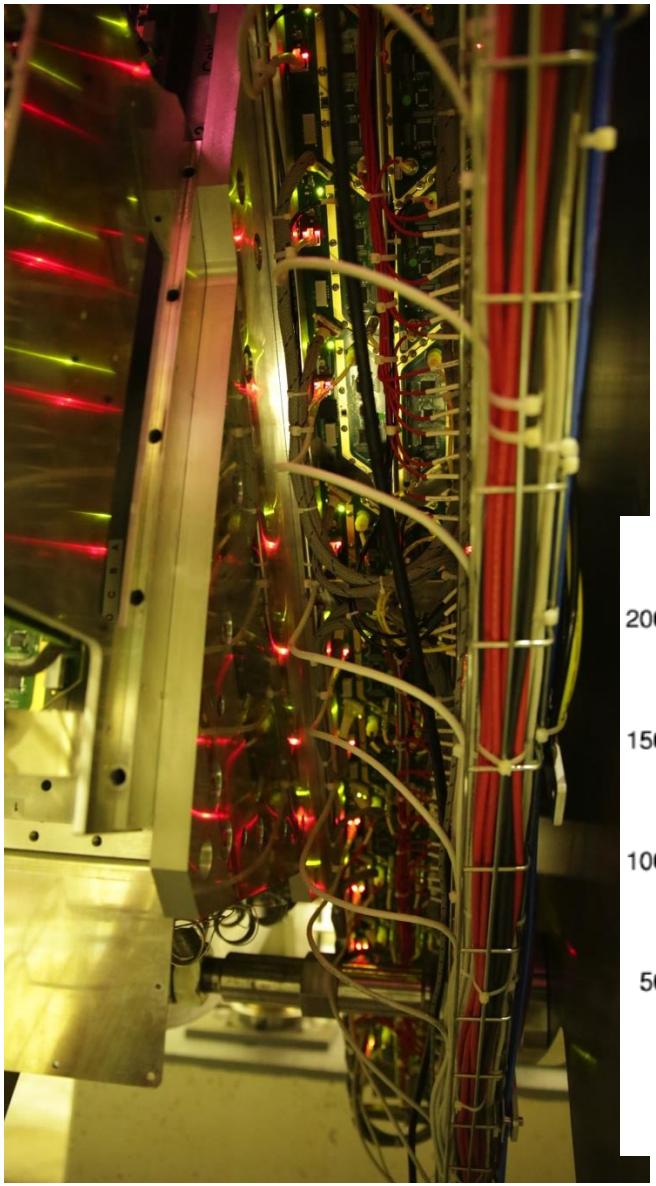
COMPLETION OF THE STRAWS

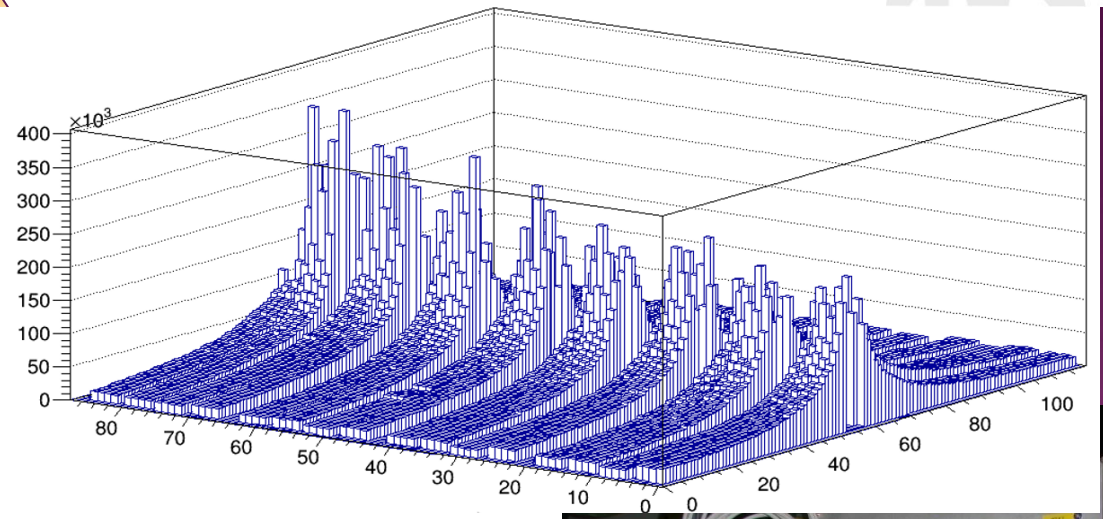


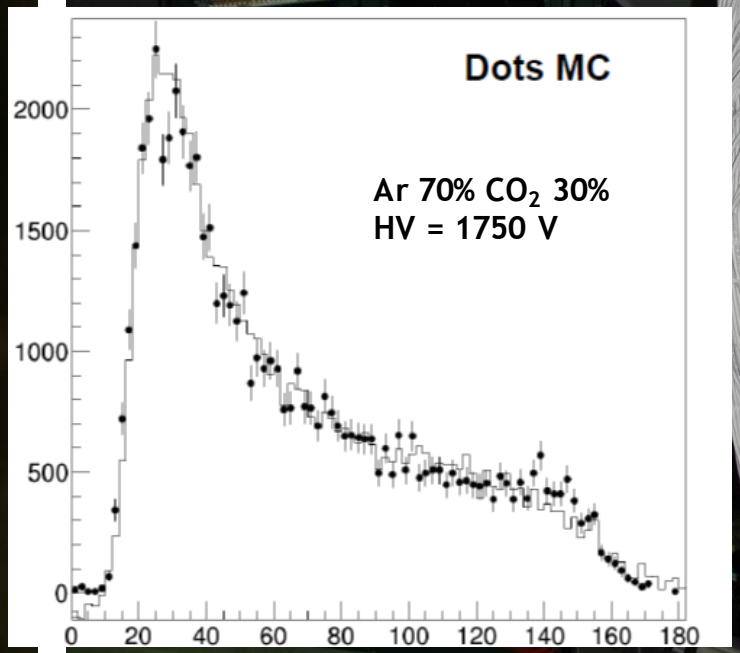


Number (Ch/Mod/ Coordinates)	Start of assembling	End of assembling	End of testing	Delivered to CERN	Assembling and testing time (months)
CH2 M1 U-V	**09.2012**	04.2013	10.2013	11.2013	14
CH2 M2 X-Y	07.2013	01.2014	02.2014	04.2014	8
CH4 M1 U-V	12.2013	02.2014	03.2014	04.2014	4
CH4 M2 X-Y	02.2014	05.2014	**06.2014**	07.2014	5

STRAW TRACKER

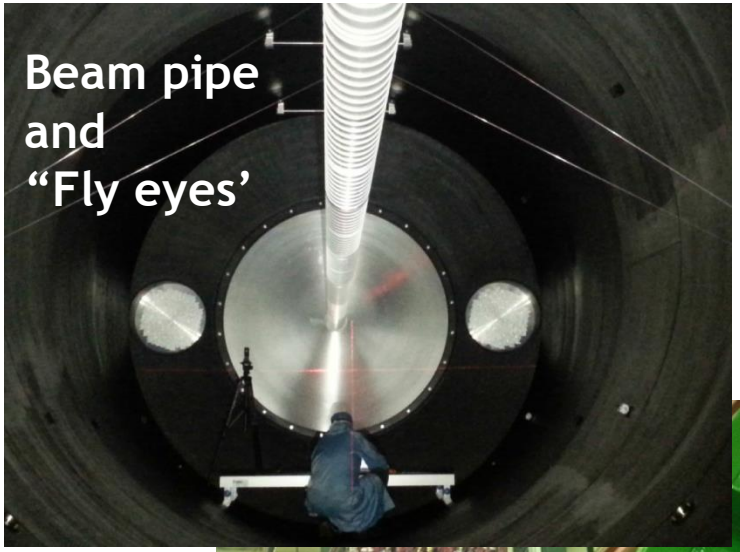


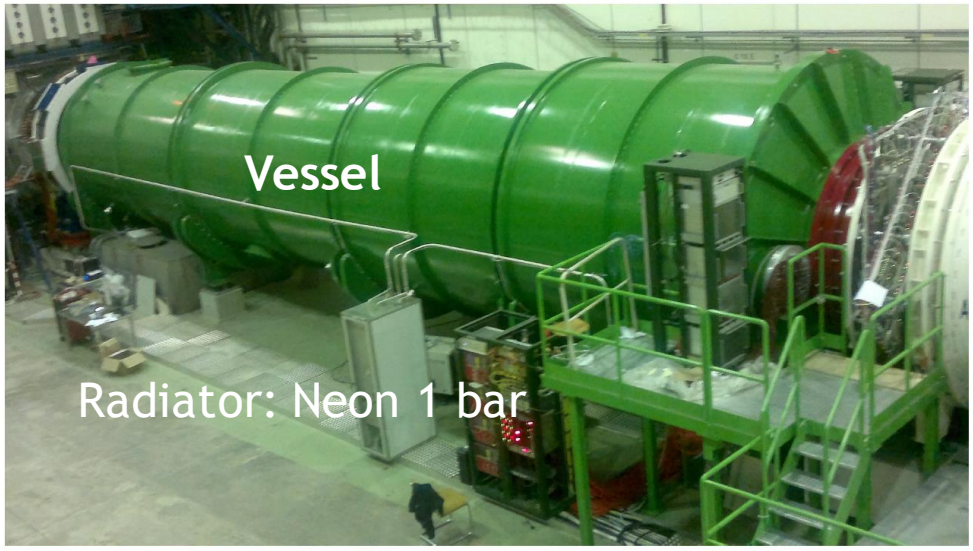


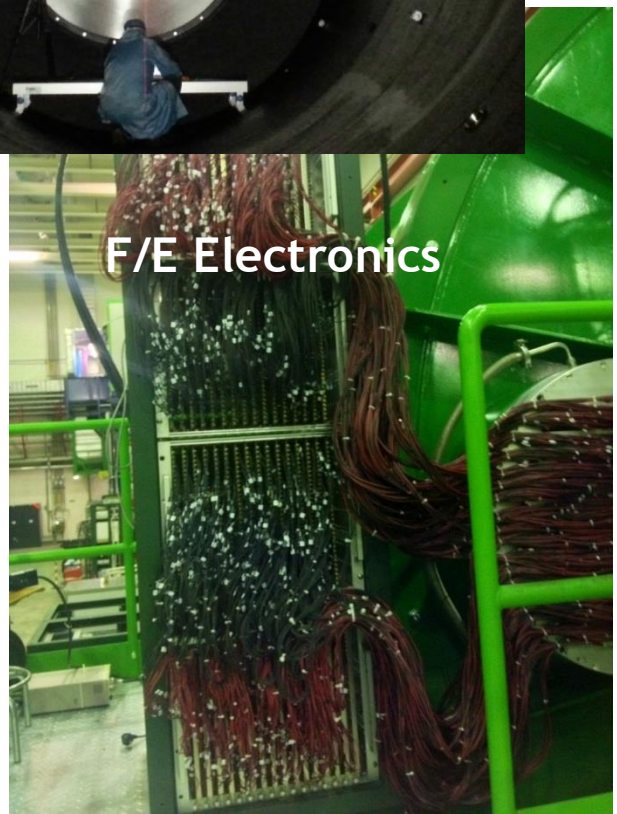


NA62 RICH

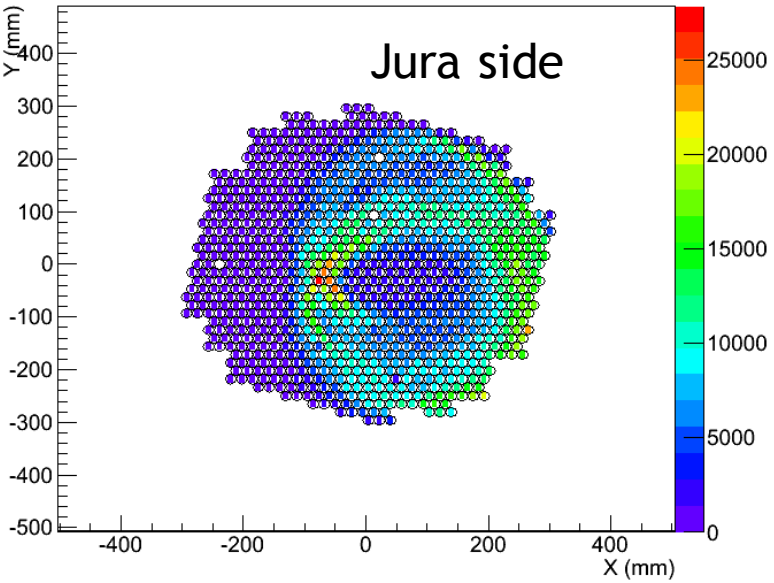
CERN (PH-DT,..), Firenze, Perugia

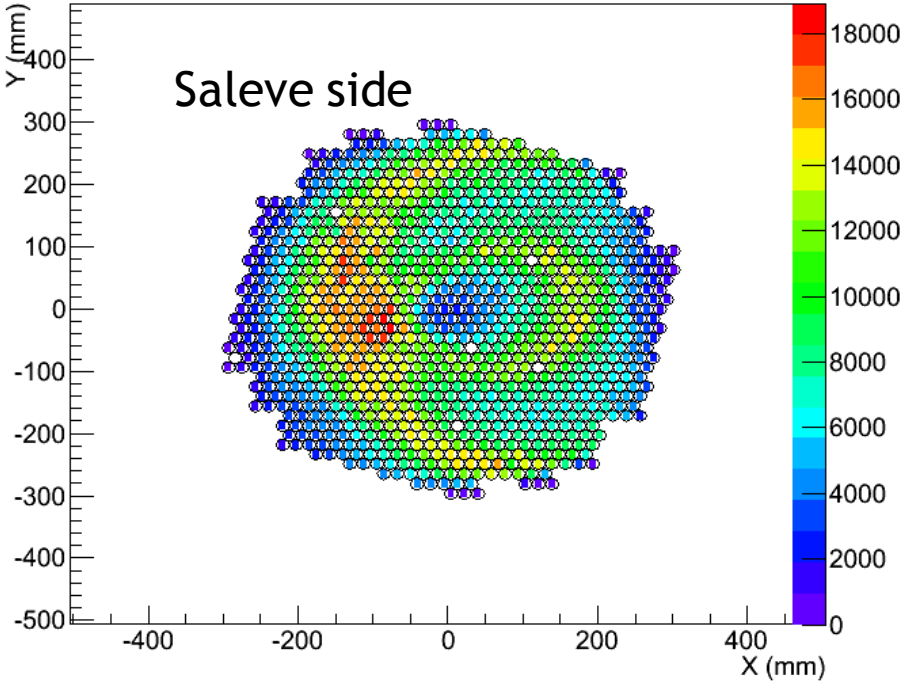






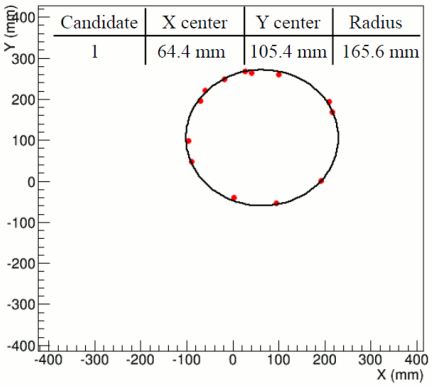
RICH COMMISSIONING





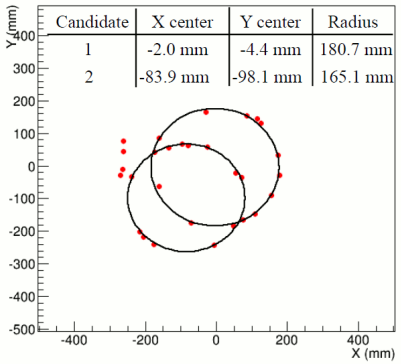
Single event Saleve side

Candidate	X center	Y center	Radius
1	64.4 mm	105.4 mm	165.6 mm



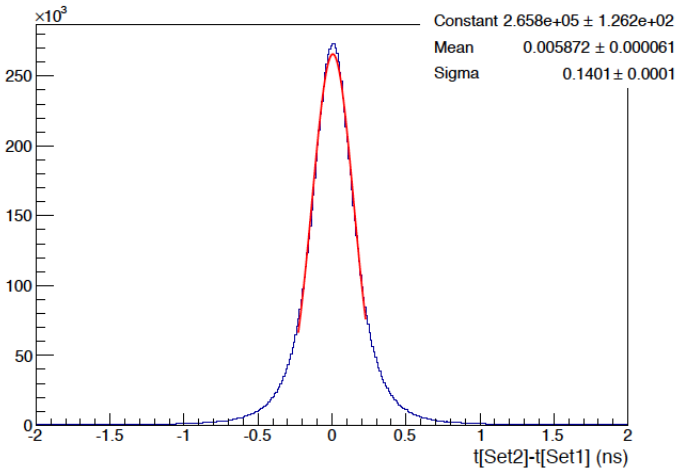
Single event Saleve side

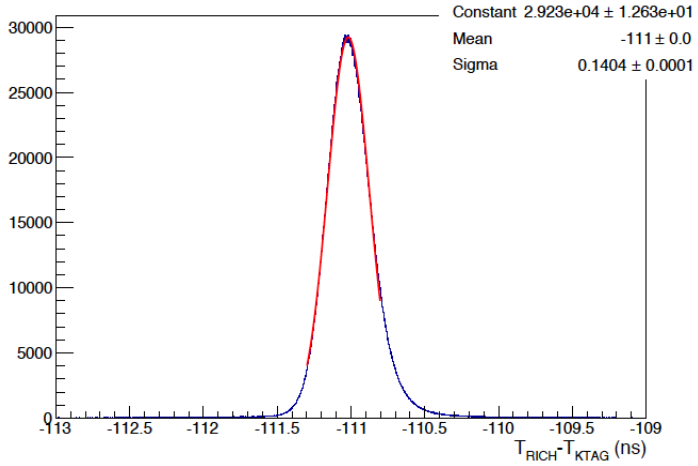
Candidate	X center	Y center	Radius
1	-2.0 mm	-4.4 mm	180.7 mm
2	-83.9 mm	-98.1 mm	165.1 mm



RICH TIME RESOLUTION

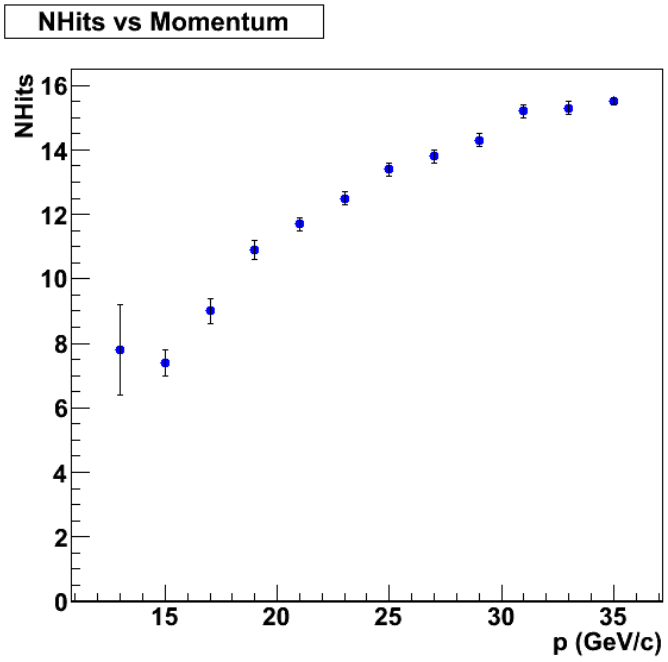
For each event, average time of half of the hits – average time of the other half σ = 140 ps = 2 times the event time resolution



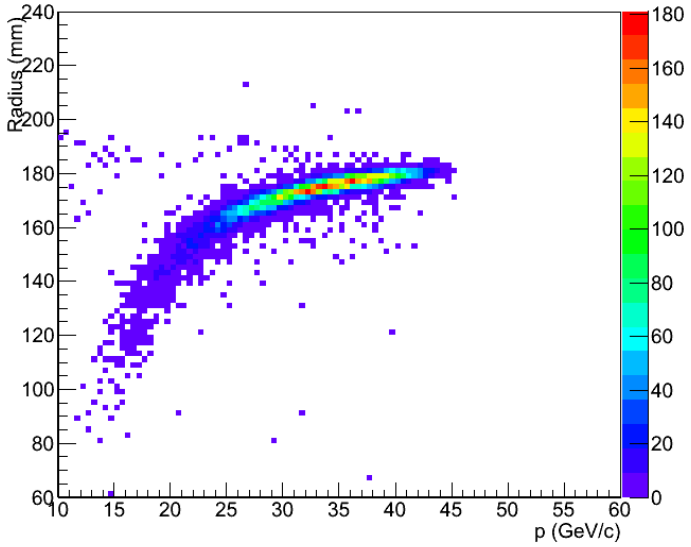


RICH event time resolution ~ 70 ps

RICH PERFORMANCE



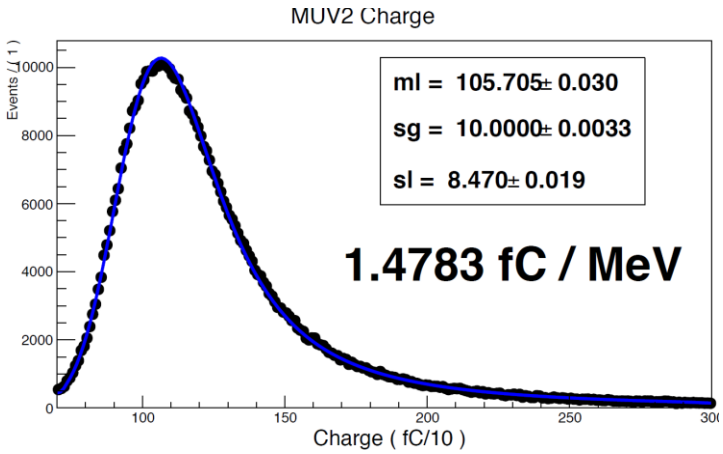
Number of hits per ring as a Function of particle momentum

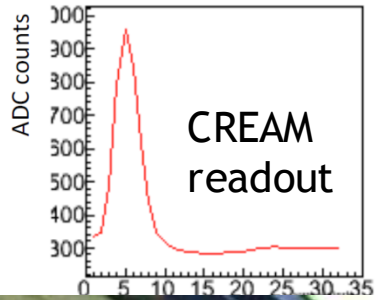


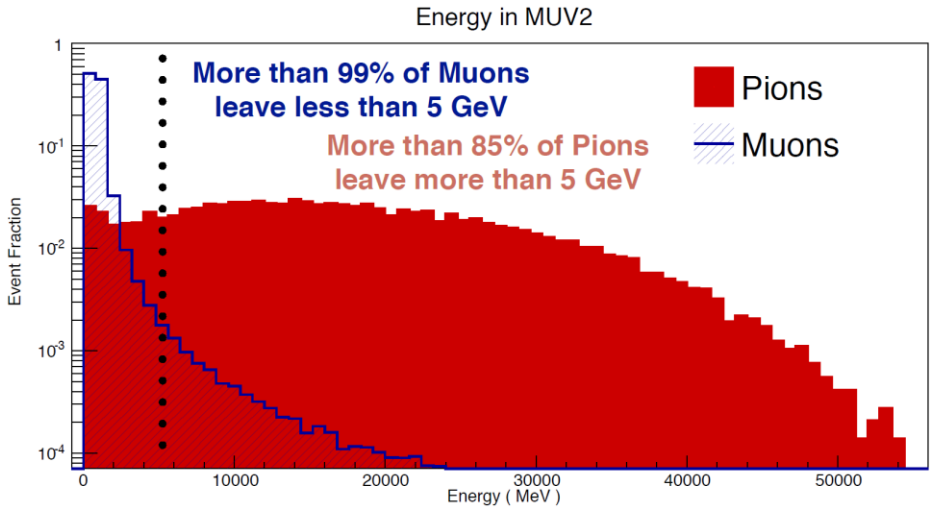
Cherenkov ring radius vs. particle momentum for $\pi^+\pi^0$ events (w/o spectrometer information)

MUV

Hadron Calorimeter (two sections)

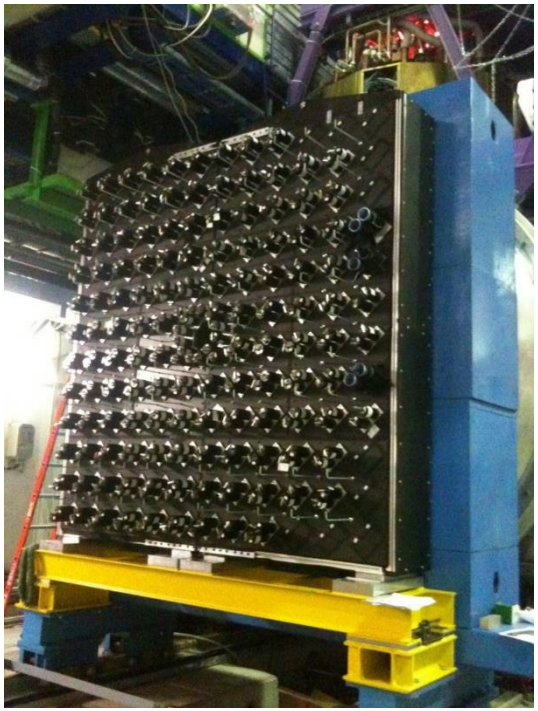


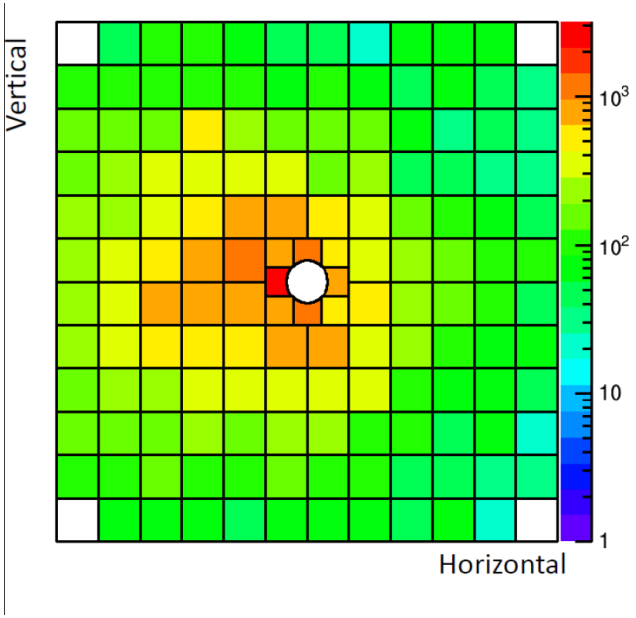


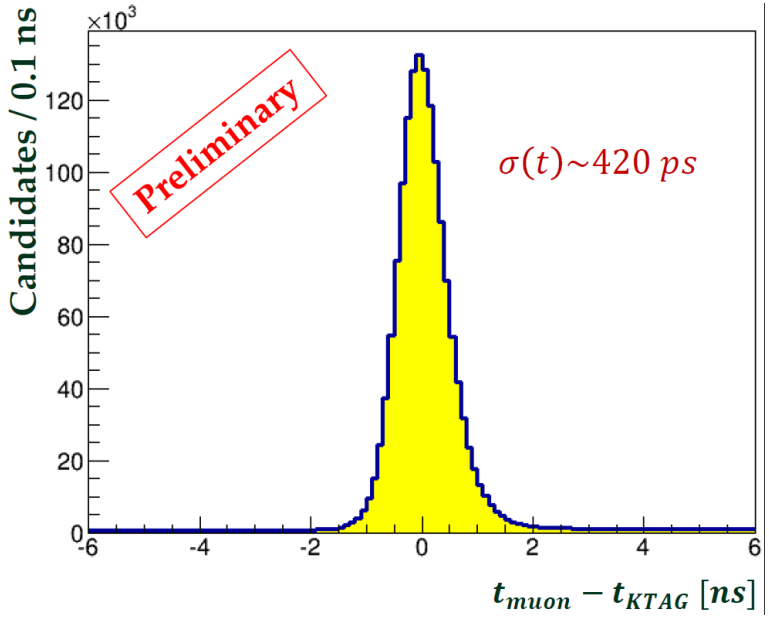


MUV

FAST Veto after iron filter







TDAQ

- Activities quite intense in 2014
  - Compromise between TDAQ test and data taking
- Common Infrastructure
  - Mostly ready well in advance of the 2014 run
- Common TDC-based TDAQ system
  - All the TDCB and TEL62 boards required were produced and installed
  - Diverted resources from firmware development to board testing
  - Firmware suited for low intensity running
  - Limitations experienced and being solved
- Online farm
  - Worked satisfactorily
  - No L1 and L2 triggers
  - Manpower issues are being addressed
- Trigger System
  - L0TP in both FPGA-based and PC-based flavours
  - TDCB-based trigger primitives generated from LAV, MUV3, RICH, CHOD
  - LKrL0 system partially deployed ($1/6^{th}$) and tested

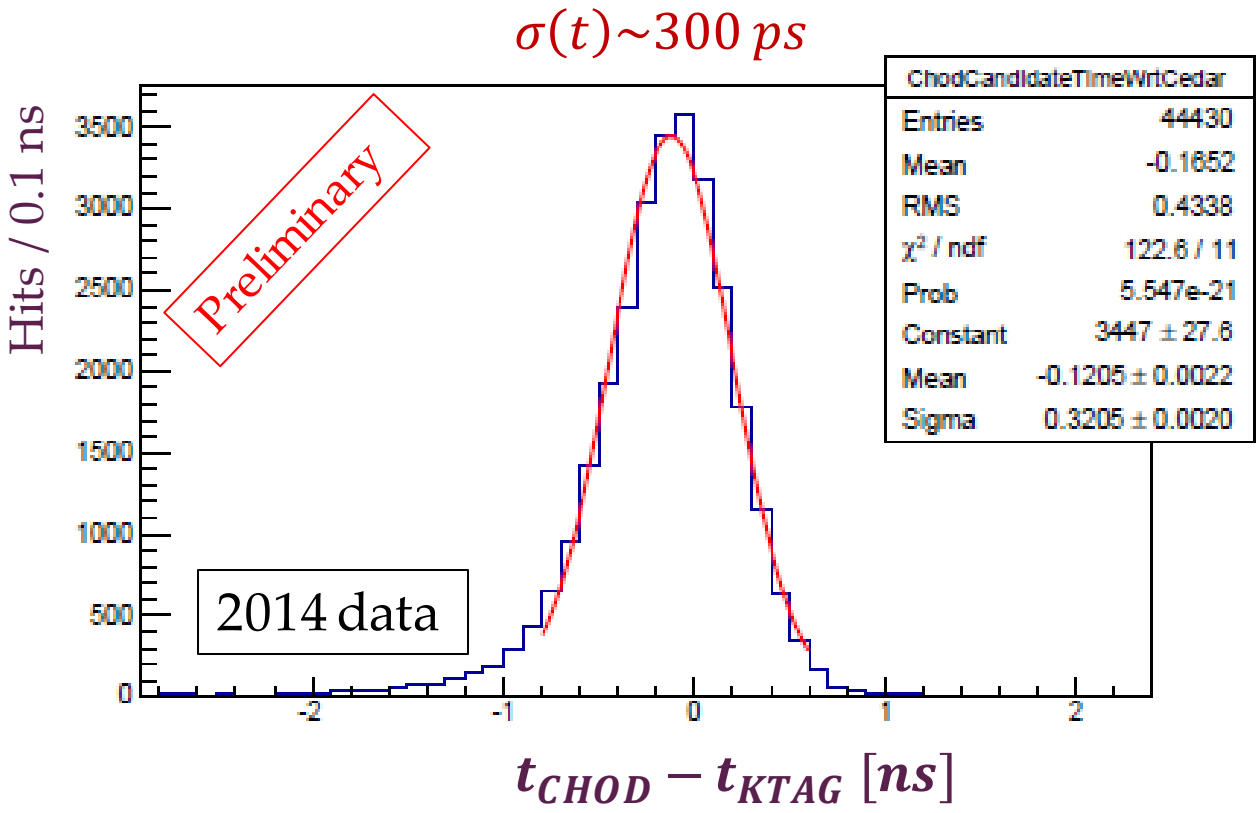
ANALYSIS OF 2014 DATA

- About two weeks of data taking with stable conditions
- Level 0 Trigger: Q1*!QX*HAC*!NHOD*!IRC+Q1/100
  - Three STRAW Chambers during the first week
  - Four Chambers during the second week
- Muon and minimum bias runs for calibration
- CERN-EP Seminar by Giuseppe Ruggiero, March 10, 2015:

  https://indico.cern.ch/event/360237/

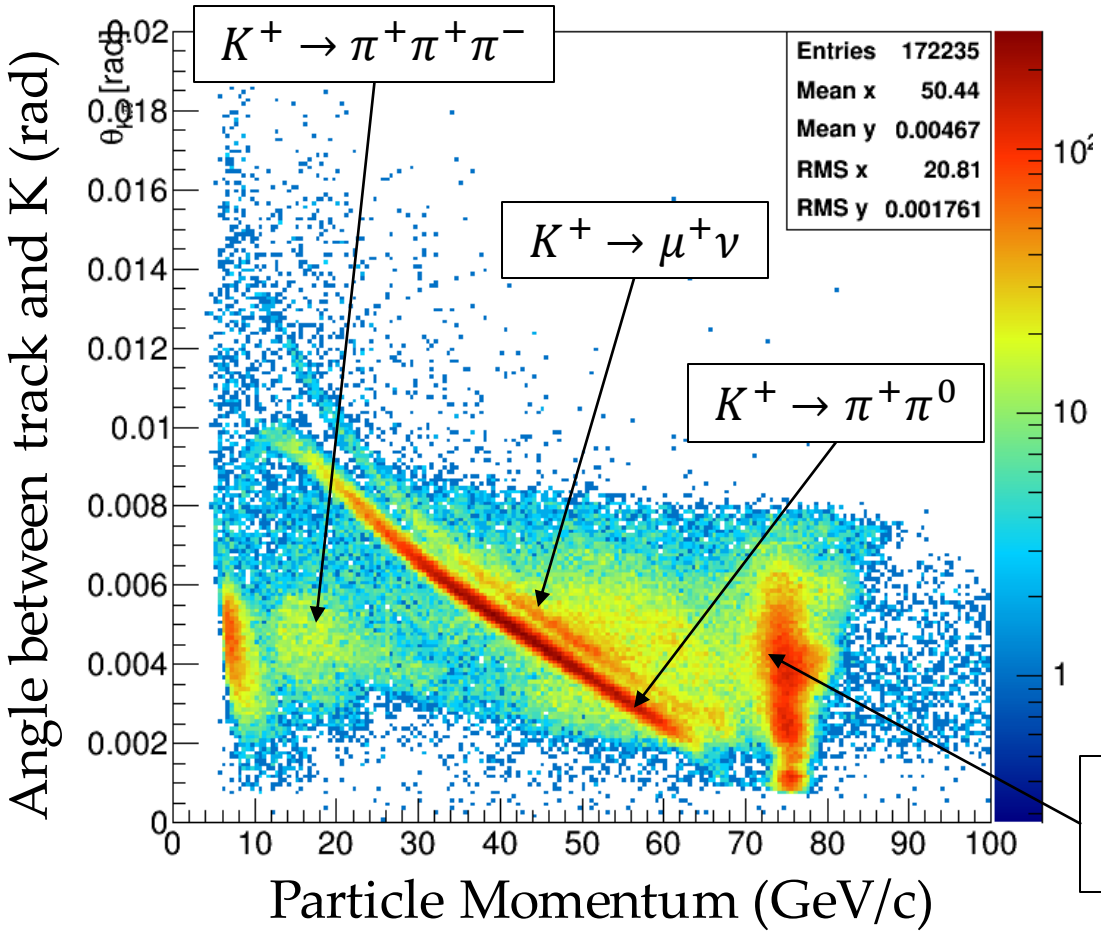
CHOD-KTAG TIMING

- Array of horizontal and vertical scintillator slabs (CHOD)

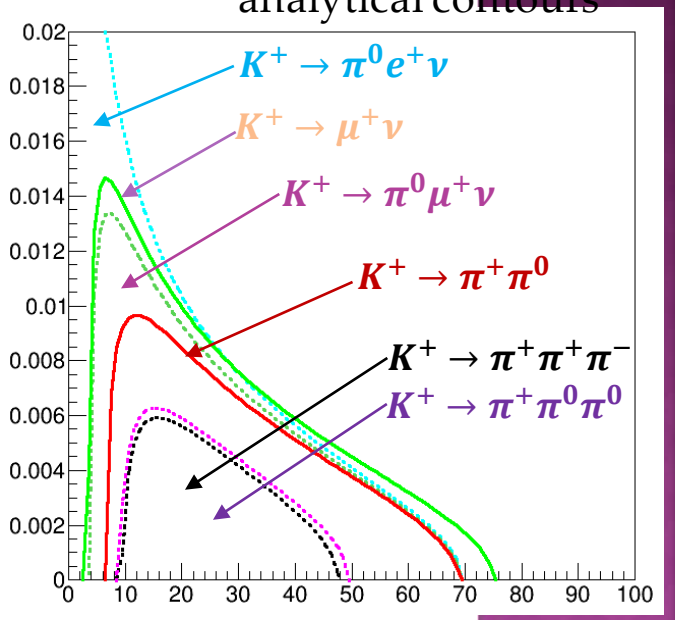


2014 DATA QUALITY

- Events with only 1 track in the spectrometer reconstructed (within 40 ns)
- 10^2 muon rejection at trigger level



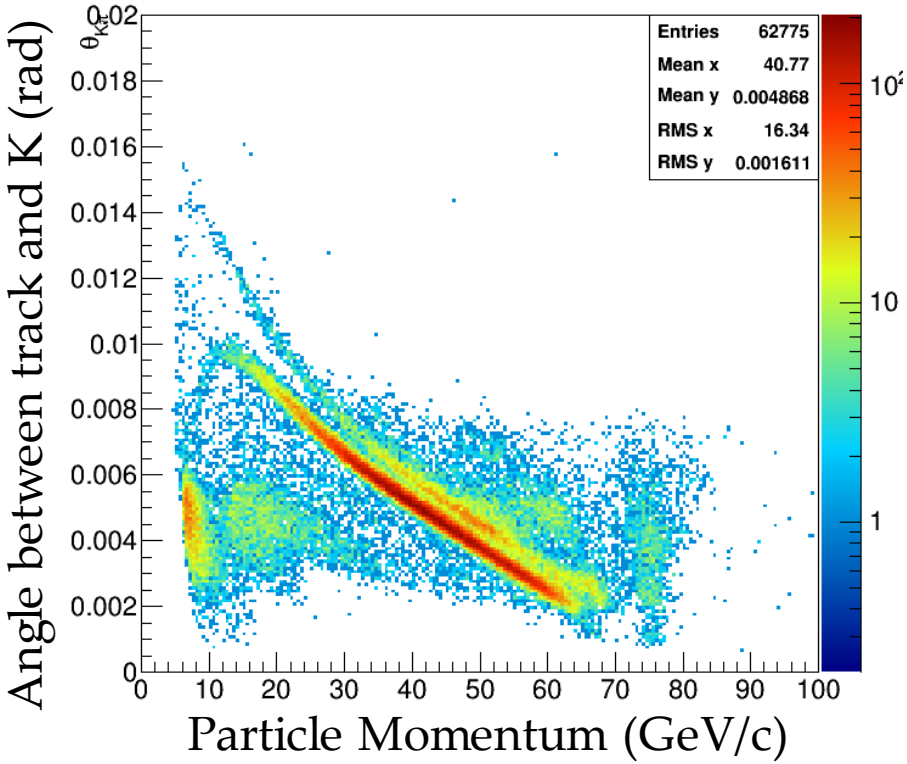
analytical contours



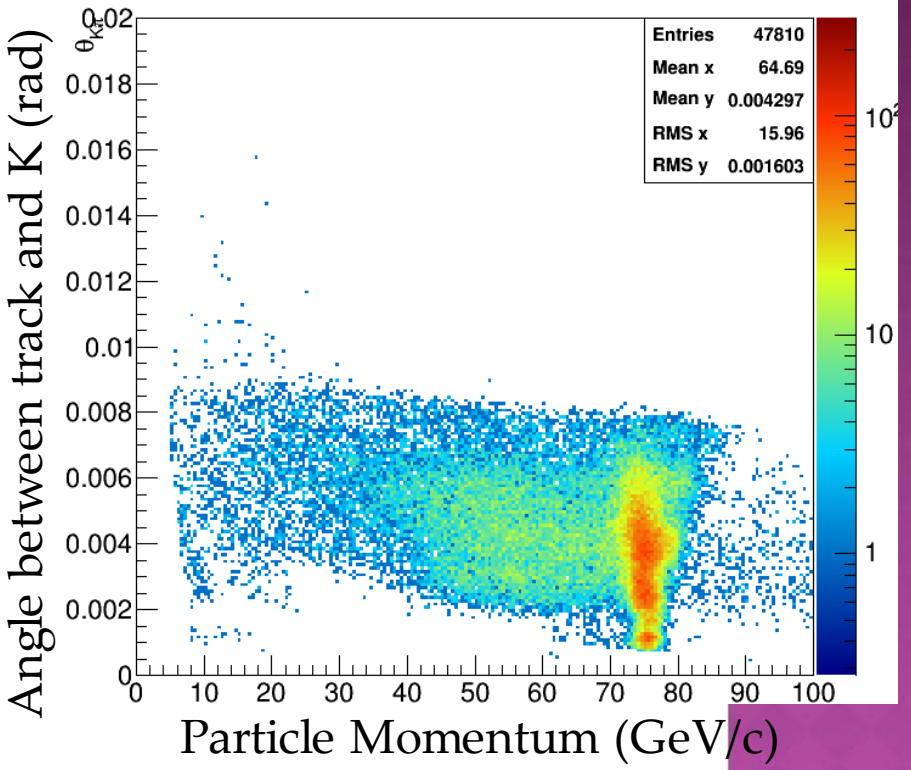
2014 DATA QUALITY

- Apply KTAG for kaon identification

KTAG candidate

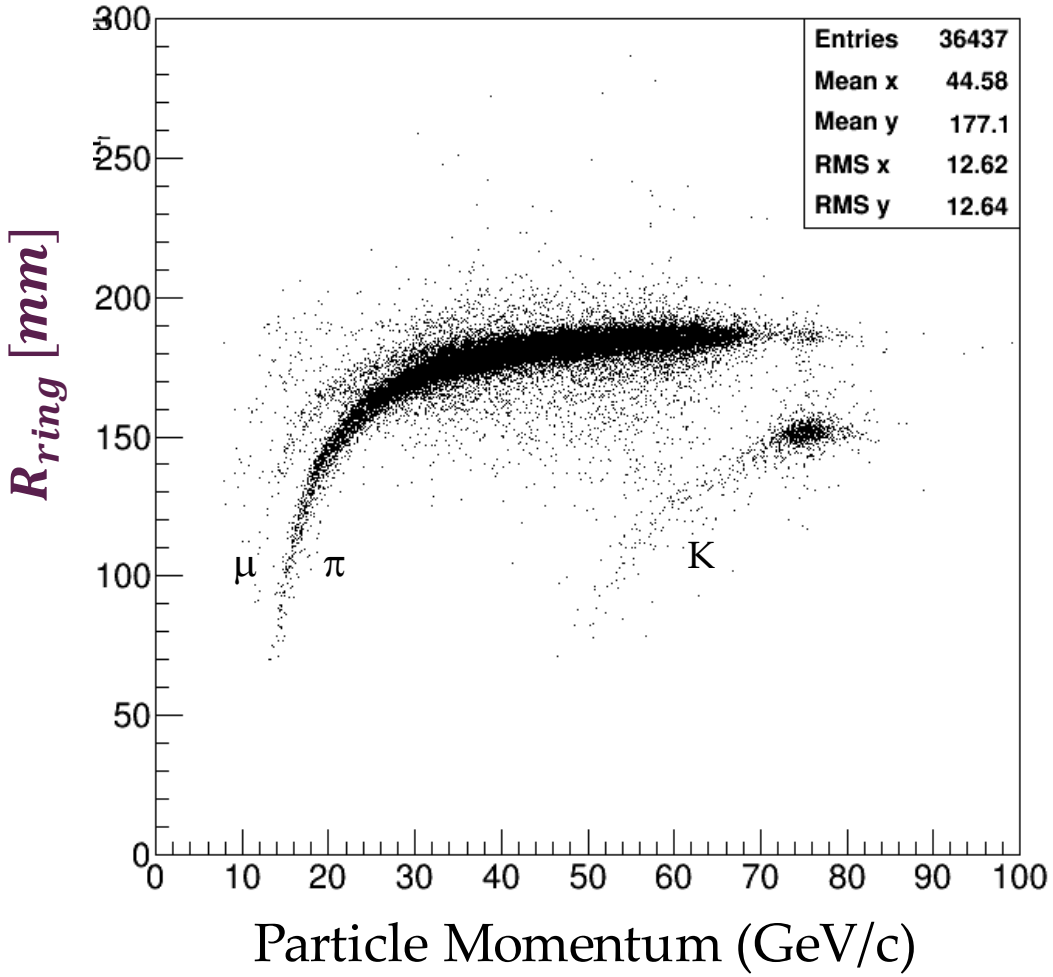


No KTAG candidate



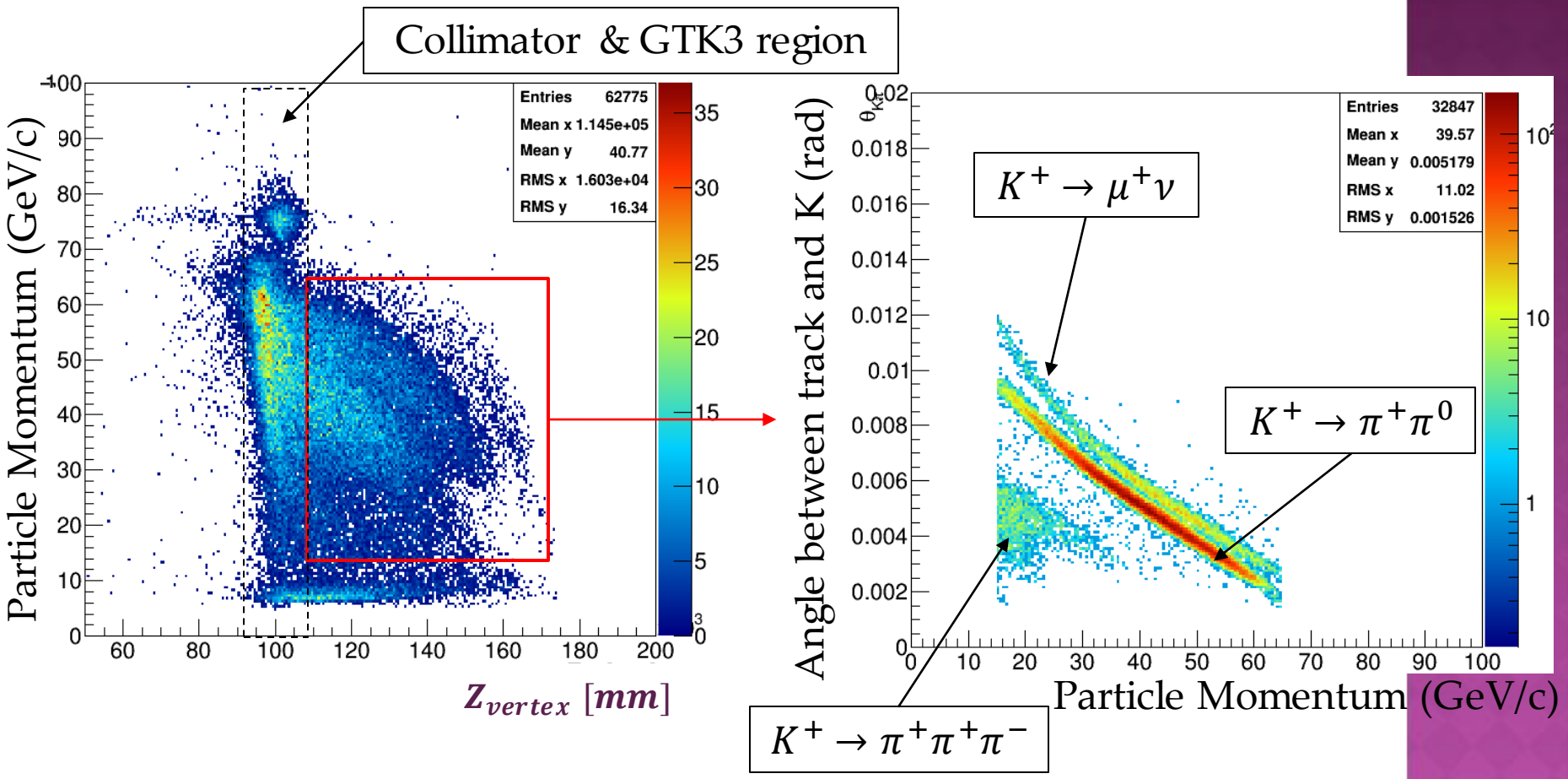
2014 DATA QUALITY

- Matching between track and RICH ring to study the particle content
- Positrons suppressed by the trigger



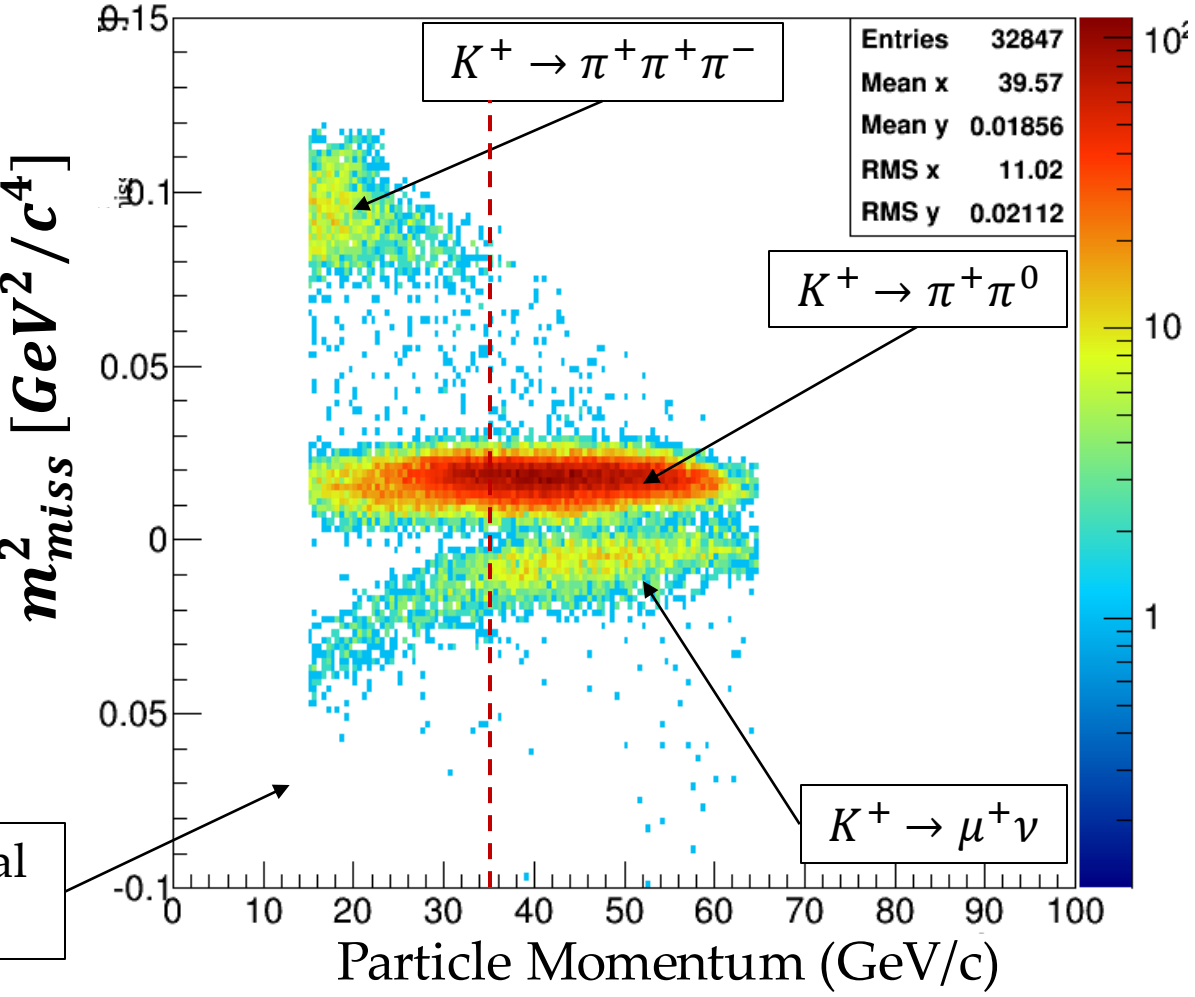
2014 DATA QUALITY

- Use track origin to suppress the background from kaon interactions
- Decay vertex from the intersection between the track and the nominal K direction



2014 DATA QUALITY

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

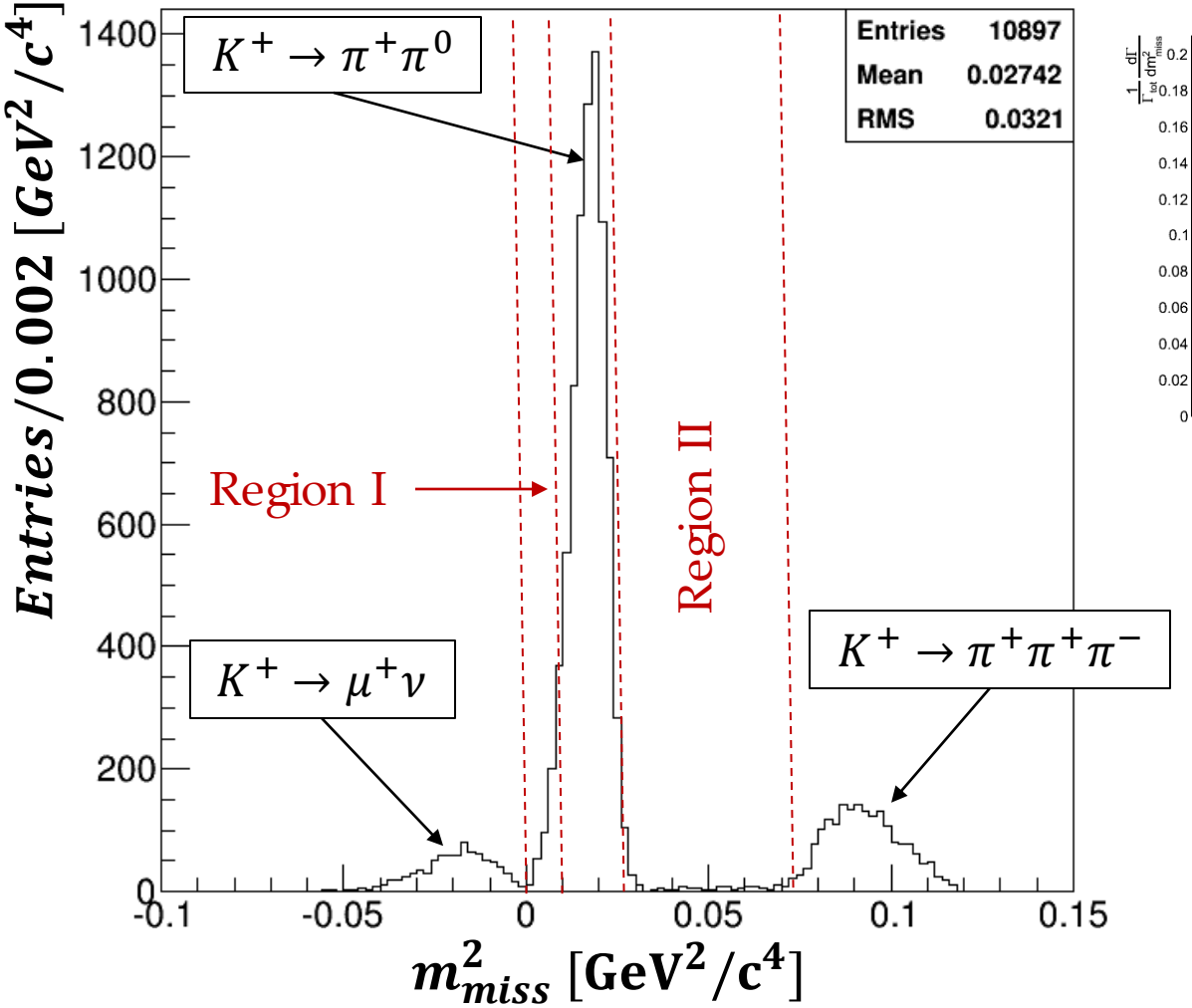


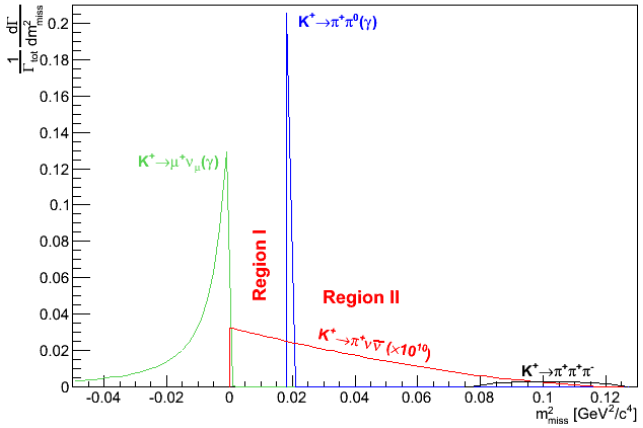
Momentum Signal Region

2014 DATA QUALITY

$P < 35\ GeV/c$

theoretical shapes



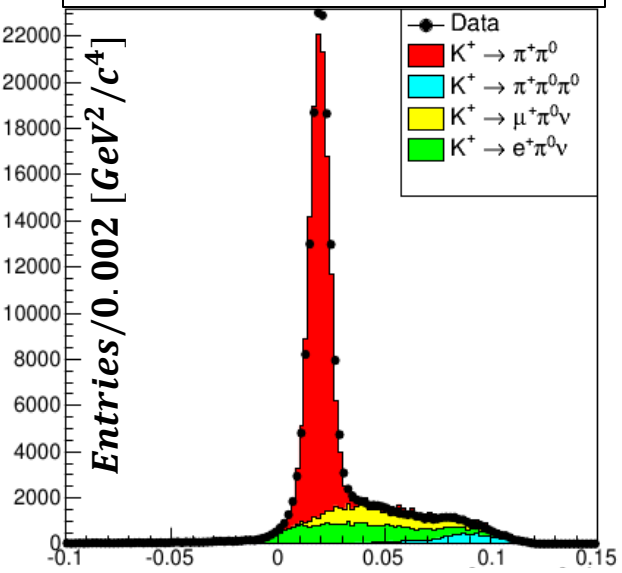


CONTROL SAMPLES

- Kaon decay modes reconstructed with the liquid Krypton calorimeter only (from minimum bias data)
- Useful to measure the kinematic suppression factor, particle ID efficiency …

π^0 mass assumed

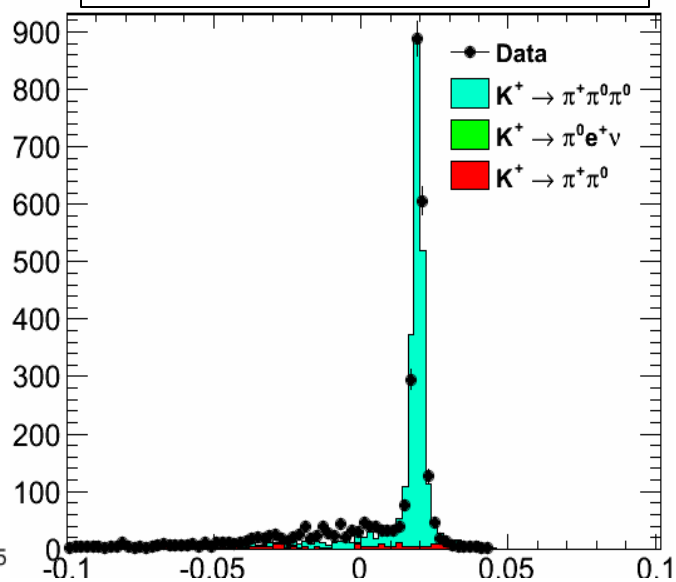
$K^+ \to \pi^+\pi^0$



$(P_K - P_{\pi^0})^2$ GeV^2/c^4

π^0 mass assumed

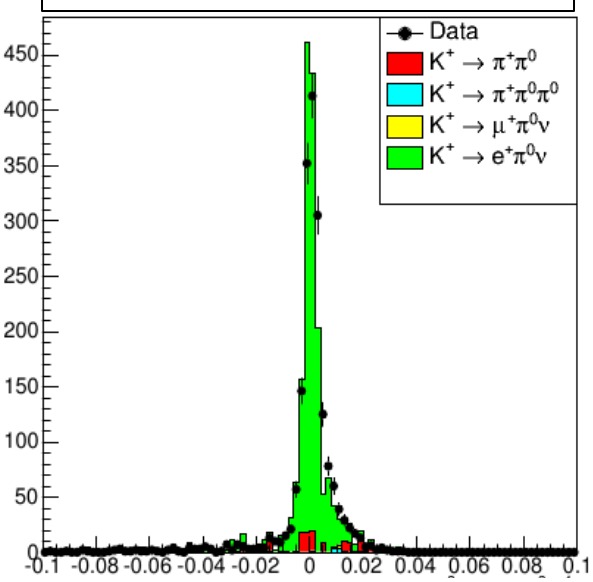
$K^+ \to \pi^+\pi^0\pi^0$



$\left(P_K - P_{\pi_1^0} - P_{\pi_2^0}\right)^2$ GeV^2/c^4

π^0 mass assumed and e^+ energy

$K^+ \to \pi^0 e^+\nu$



$(P_K - P_{\pi^0} - P_{e^+})^2$ GeV^2/c^4

Further NA62 K Physics Program

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}
$\mu^+\nu_h,\nu_h\rightarrow\nu\gamma$	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)

STATUS OF NA62: SUMMARY

- 2014 has been a great year:
  - Performance in line with expectation
  - All major detectors have been commissioned
- Run 2015 just started
  - Tuning of triggers and analysis programs
- Accumulate and analyze O(10^{13}) good kaon decays before LS2 (2018)