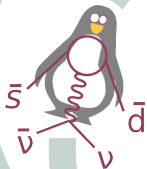NA62

$\bar{s}$

$\bar{d}$

$\bar{\nu}$ ν

The NA62 Experiment
Seminar at LAPP, Annecy, France

Mathieu Perrin-Terrin

CERN, Geneva, Switzerland.

January 15, 2016

Outline

1 Physics Case (10min)

2 The NA62 Experiment (25min)

3 First look at Data (10min)

4 Conclusions and Prospects

A broad physics program

The main target: $K^+ \to \pi^+ \nu \bar{\nu}$ but many more channels:

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	$5.9 \times 10^{-11} \, m_{X^0} = 0$	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	$(2.488 \pm 0.010) \times 10^{-5}$	$> \times 2$ 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	-	$O(10^5)$

keeping growing: axion search

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$: a rare and clean decay

▶ Flavour Changing Neutral Current: no tree diagrams, hard GIM suppression
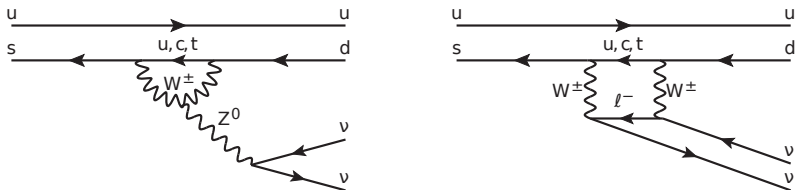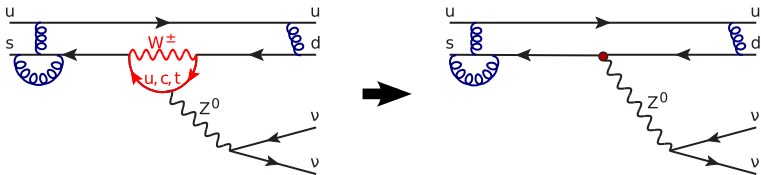

▶ Very rare SM process [Buras, 1503.02693]

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

▶ And very clean, we will see why...

Anatomy of the Decay: Short and Long Ranges

▶ Virtual particles (VP) in loops are off-shell

▶ VPs propagate over $\Delta t = 1/\Delta E$ (uncertainty principle)

▶ QCD energy scale $<<$ EW energy scale hence:

▶ Short and long ranges scale separate naturally [Buras 9806471]:

$$\mathcal{A}(M \to F) = \frac{G_F}{2} \sum_i V_{CKM}^i C_i(\mu) \langle F|Q_i(\mu)|M\rangle$$

$\langle F|Q_i(\mu)|M\rangle$ long range, matrix elements, **large uncertainties**

$C_i(\mu)$ short range, Wilson coefficients

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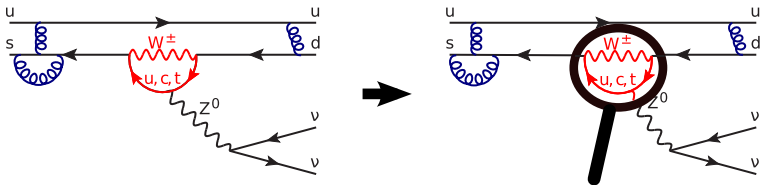
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Theoretical Uncertainties

$$\mathcal{A}(M \to F) = \frac{G_F}{2} \sum_i V_{CKM}^i C_i(\mu) \langle F|Q_i(\mu)|M \rangle$$

Matrix Elements (normally large uncertainties)

► Derived from $K^+ \to \pi^0 e^+ \nu$ using isospin symmetry:
$$\langle \pi^+|(\bar{s}d)_{V-A}|K^+ \rangle = \sqrt{2}\langle \pi^0|(\bar{s}u)_{V-A}|K^+ \rangle$$

Wilson Coefficients

► NLO QCD correction for top, NNLO for charm

► NLO EW correction for top & charm

SM Predictions [Buras 1503.02693]

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 0.3 \pm 1.0_{ext}) \times 10^{-11}$$

► Second error from external CKM inputs (V_{cb}, γ)

Testing the Standard Model

- ▶ $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ with 10% uncertainties allows to determine $|V_{td}|$ at 9% [Buras 0405132]

- ▶ With $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$, $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ [1] the CKM unitarity triangle can be built independently from B observables:

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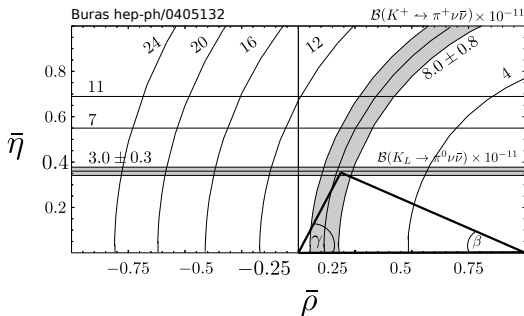
[1] KOTO: SM single event sensitivity by 2020

Going Beyond the Standard Model

- ▶ Any 10% deviation from $\mathcal{B}_{SM}$ would signal new particles (e.g. vector boson) contributions

- ▶ Even more sensitive to NP when using correlations with $\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})$, $\mathcal{B}(B_s^0 \to \mu\mu)$, γ, $B \to K(K^\star)\mu\mu$, ϵ'/ϵ

- ▶ A key observable for the LHC era
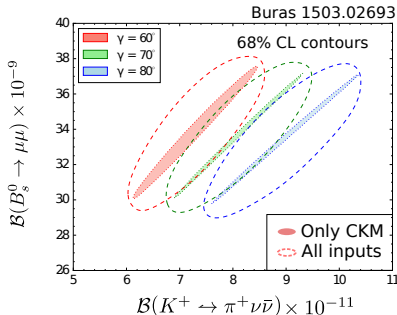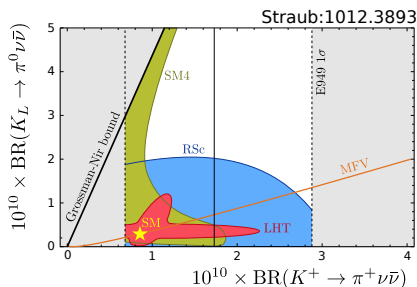
State of the Searches
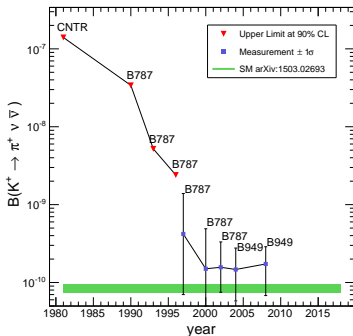
E949 Measurements – 2008

► Stopping kaon technique

$$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

Phys. Rev. D 77, 052003 (2008)

Phys. Rev. D 79, 092004 (2009)

► KOTO at JPARC aims to reach by 2020 the SM single event sensitivity for $K_L \to \pi^0 \nu \bar{\nu}$[2]

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State of the Searches
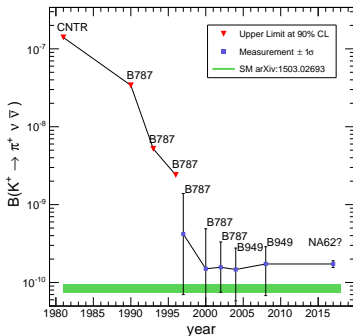
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---

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NA62 Goal

- ▶ Measuring $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ with 10% uncertainty in 2 years

  - ▶ $O(100)$ signal events and Sig/Bkg $O(10)$

- ▶ With a signal efficiency of $\sim 10\%$, it implies:

  - ▶ 10^{13} kaons in 2 years

  - ▶ background rejection of 10^{12}

- ▶ Use SPS: perfect for decay in flight technique

Outline

NA62 Collaboration
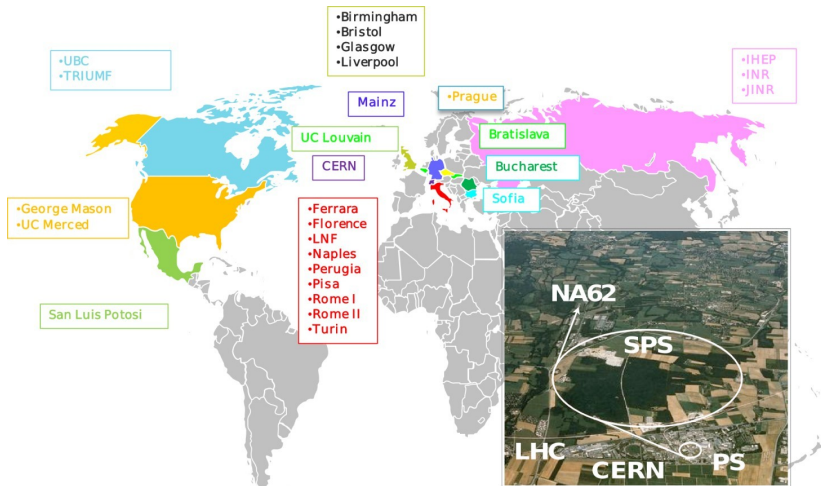
28 Institutes, ~200 Collaborators

NA62 Time Line
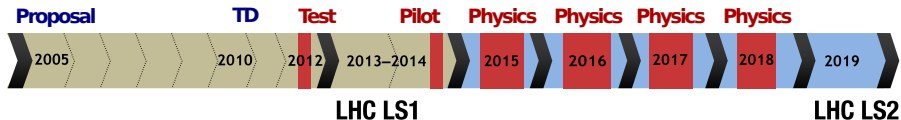
Reference Documents

2005 Proposal

[CERN-SPSC-2005-013]

2010 Technical Design

[NA62-10-07]

2014 Pilot Run

[G. Ruggiero, CERN Seminar]
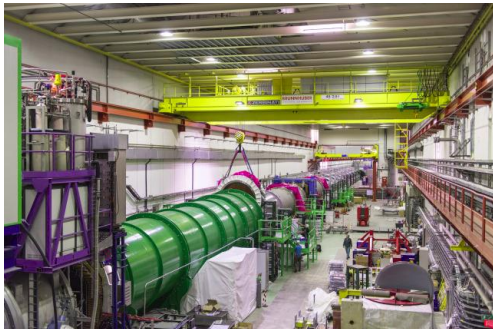
NA62 Apparatus
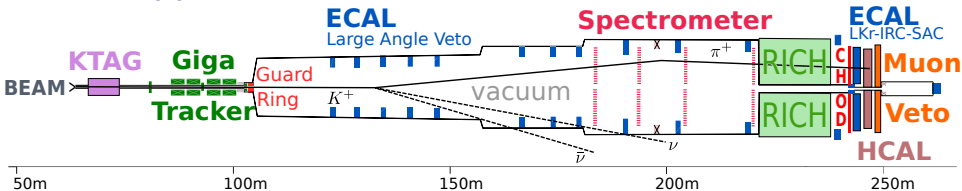
With HCAL and GTK completion in 2015 all detectors are installed

NA62 Apparatus
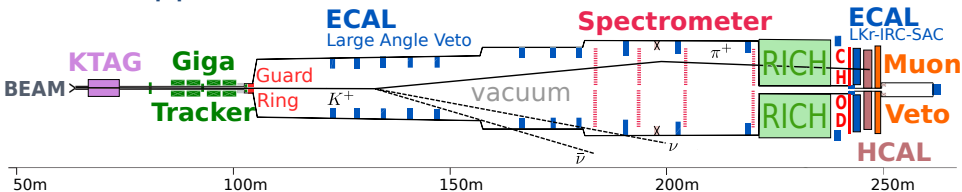
Secondary Beam from SPS

▶ 5s spill at 750 MHz

▶ Composition:

p	π^+	K^+
70	24	6%

▶ 75 GeV/c with $\delta p/p = 1\%$

Mon 03 Aug 2015 18:35:35
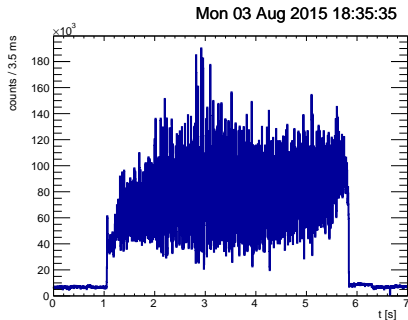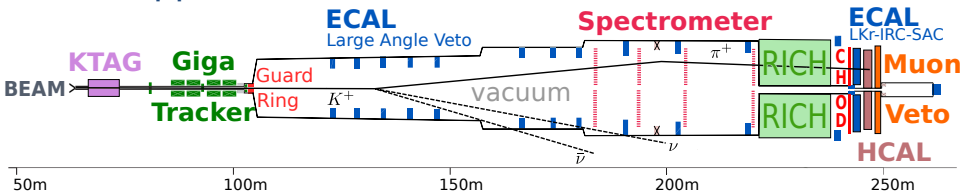
NA62 Apparatus

Beam Instrumentation

- ▸ Kaon Tagging (KTAG, Differential Cerenkov N_2 or H_2)

- ▸ Kinematics (GigaTracker- GTK, Silicon hybrid pixels)

- ▸ Beam particle scattering detection (Guard Ring)

- ▸ Arrival time measurement

NA62 Apparatus
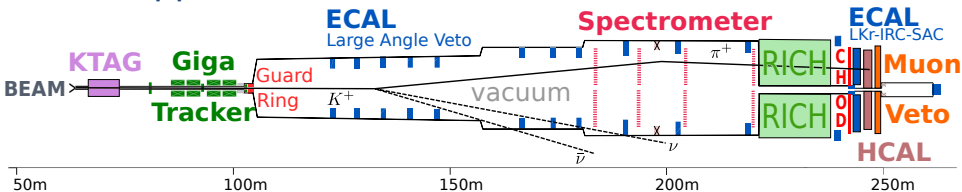
Decay Region

- 120m long, in vacuum (500 m^3 at 10^{-6} mbar)

- 10% of K^+ decay in the first 65m:

  5MHz of K$^+$ decay, 4.5×10^{12}/year

NA62 Apparatus
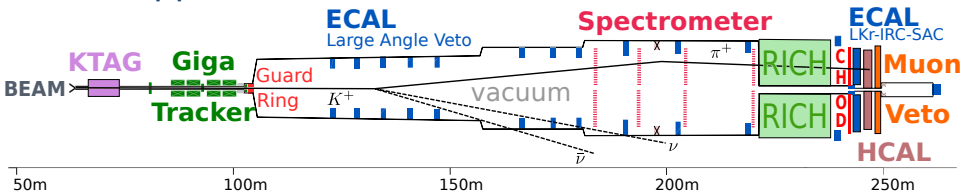
Decay Products Instrumentation

- ► Kinematics (Spectrometer)

- ► Photon Detection (ECAL)

- ► π and μ identification (RICH, HCAL and, Muon Veto)

- ► Arrival time measurement (all + CHOD for charged particles)

$K^+ \to \pi^+ \nu \bar{\nu}$ Analysis Strategy

Background Sources

- K^+ decay incorrectly reconstructed

- Particle accidentally in time with a K^+

Analysis

- Main variable $m^2_{miss} = |p_K - p_\pi|^2$

- Look for signal in regions I and II

- $p_\pi \in [15, 35]$ GeV/c (RICH, kinematics, γ rejection, accidental from $\pi^+ \to \mu^+ \nu$)

- Background suppression needed:

Kinematics	10^{-4}	Charged PID	10^{-7}
π^0's γ Rejection	10^{-8}	Timing	10^{-2}
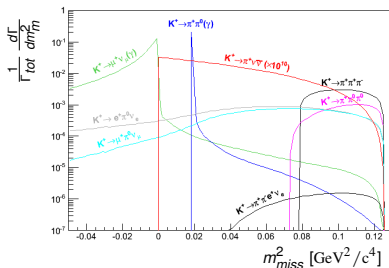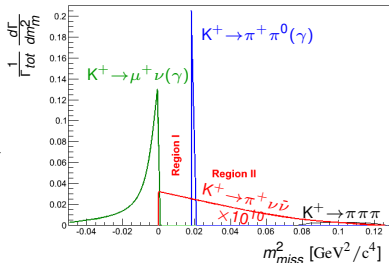
Analysis Sensitivity (MC)

Decay	event/year
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$(SM)	45
Total Background	10
$K^+ \rightarrow \pi^+ \pi^0$	5
$K^+ \rightarrow \mu^+ \nu$	1
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	< 1
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ + other 3 track decays	< 1
$K^+ \rightarrow \pi^+ \pi^0 \gamma^{\text{IB}}$	1.5
$K^+ \rightarrow \mu^+ \nu \gamma^{\text{IB}}$	0.5
$K^+ \rightarrow \pi^0 e^+ (\mu^+) \nu$ + others	negligible

KTAG - Kaon Identification and Timing
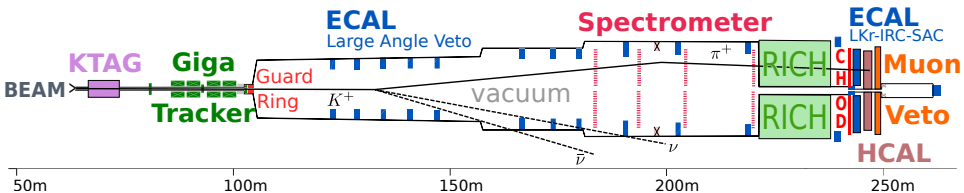
Differential Cerenkov Detector
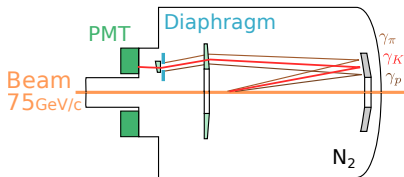
KTAG - Performance
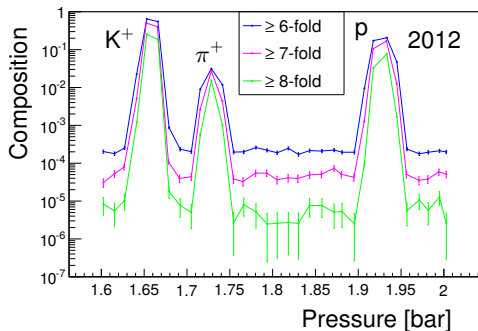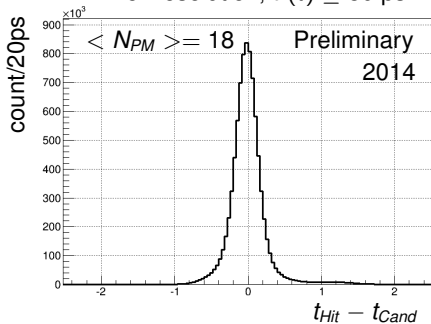
- K^+ Identification $> 95\%$

- π^+, p Rejection $> 99.9\%$

GTK - Beam Particle Kinematics and Timing
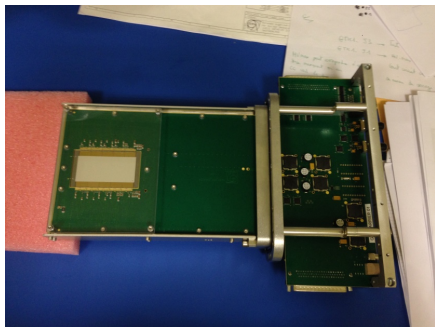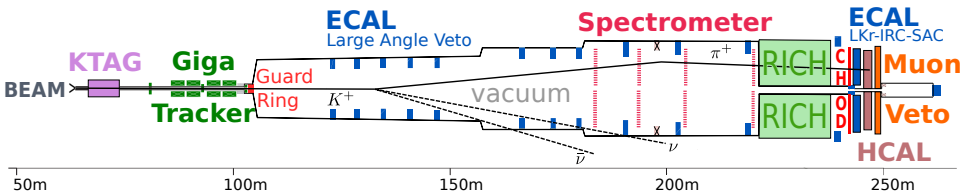
GTK3 in lab

Three Stations of Silicon Hybrid Pixel
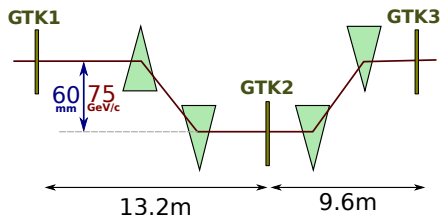
GTK - Beam Particle Kinematics and Timing
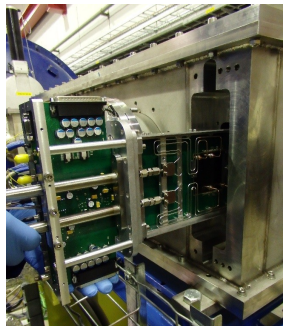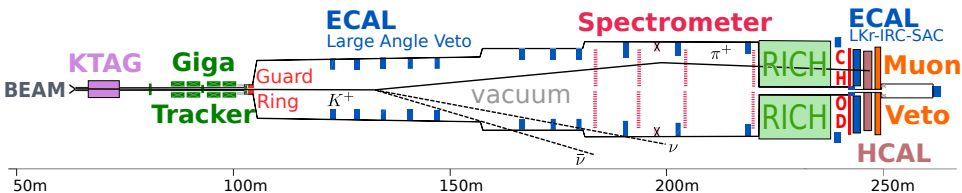
Three Stations of Silicon Hybrid Pixel

GTK3 being installed
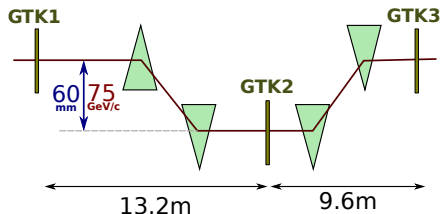
A very innovative detector

Specifications	
Beam Rate	800 MHz - 1GHz
	1.3 MHz/mm^2
Radiation	10^{14} 1MeV eq. n cm^2/y
Momentum Reso	0.2%
Angular Reso	16 μrad
Hit Time Reso	200 ps RMS
Material	$3 \times 0.5\% X_0$
Size	60mm $\times$ 27mm
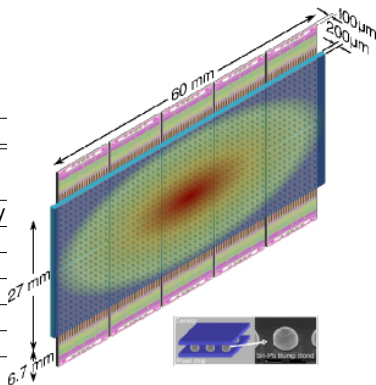
- ▶ Hybrid silicon pixels detector, changed every 100 run days

- ▶ 18k time-resolved pixels / station ($300 \times 300 \mu m^2$)

- ▶ ASIC thinned to 100μm operated in vacuum and cooled with micro-channels: world first HEP implementation!

GTK - Time Measurement Principle
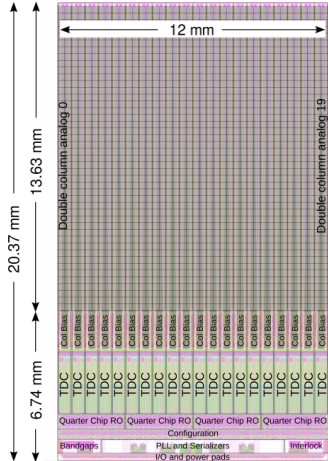
GTK - Time Measurement Principle

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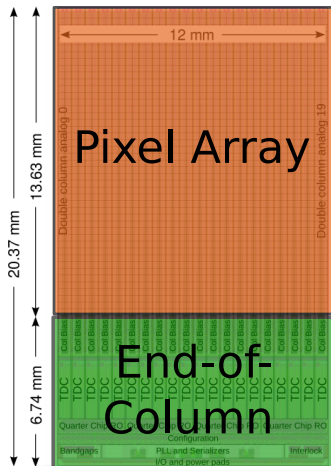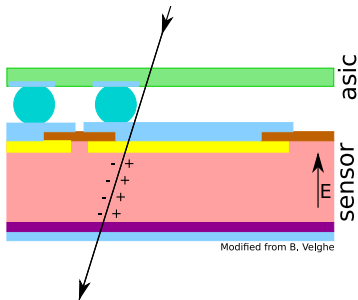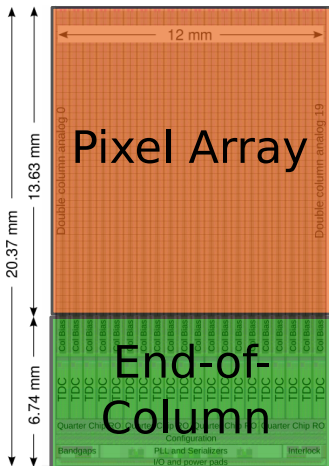
GTK - Time Measurement Principle

GTK - Time Measurement Principle

Modified from B. Velghe
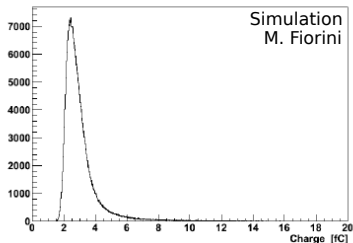
Modified from M. Noy
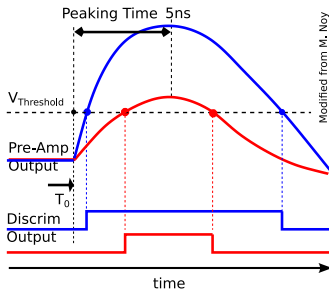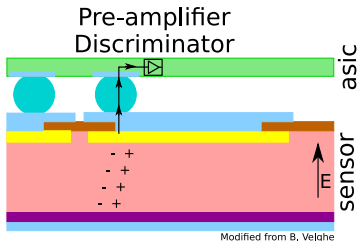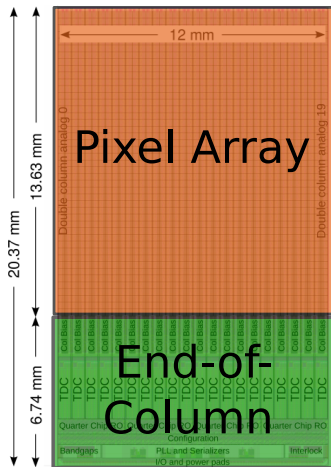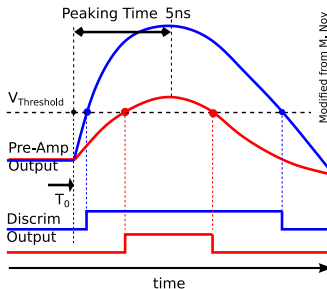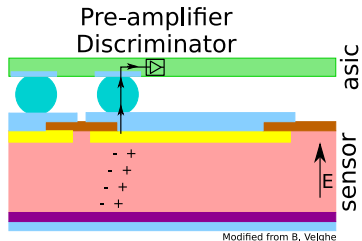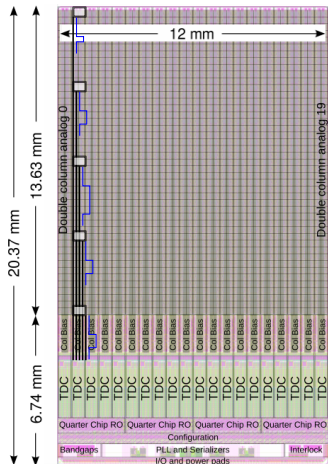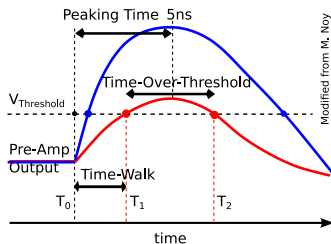
GTK - Time Measurement Principle

- ▶ At EoC, TDCs measure rising and falling edge time

- ▶ The full GTK integrates 21,600 TDCs in <25 cm^2!

- ▶ Use Time-over-Threshold to estimate time walk
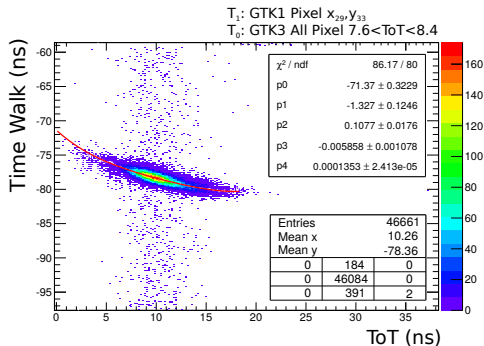
GTK - MicroChannels Cooling

▶ Etch channels in a 130μm thin Si plate glued on the ASICs

▶ Circulate cold C_6F_{14} in micro-channels (3.5 bars, 3 g/s)

▶ Fluid brought with capillaries soldered on cooling plates
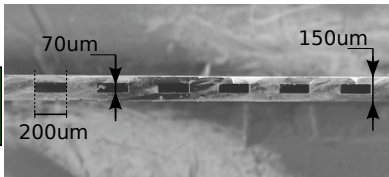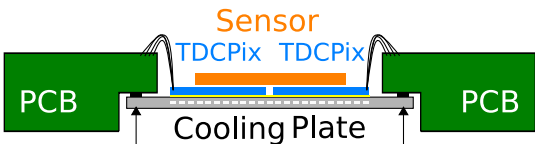
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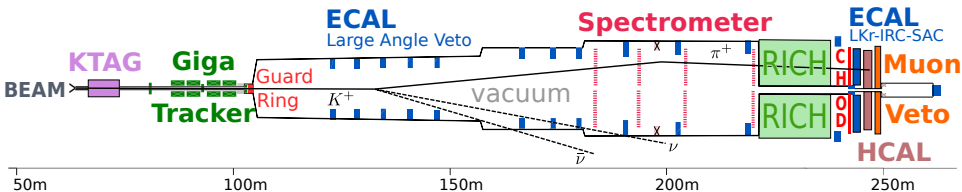- ▶ Fluid brought with capillaries soldered on cooling plates
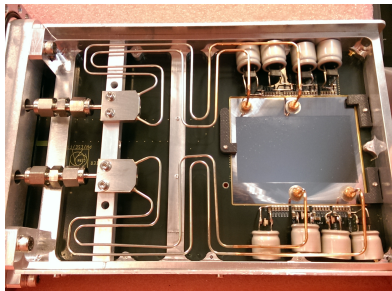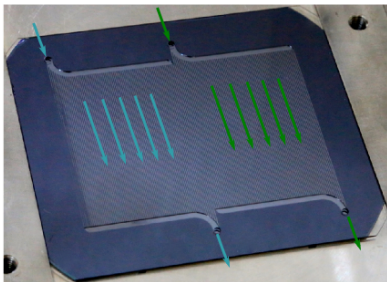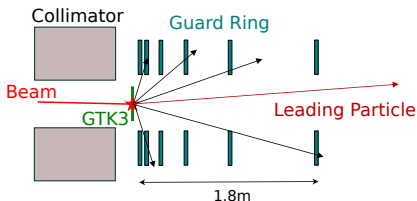
GTK - Status and Performance

- ▶ Three stations installed, (2 thinned at $100\mu m$)

- ▶ 7-8 out of 10 chips per stations were working, fix next run

- ▶ Time resolution 260 ps per hit (at 160V instead of 300V) see First Data for kinematics performance
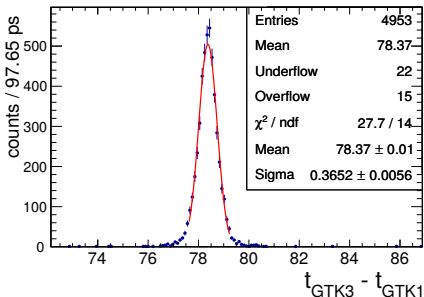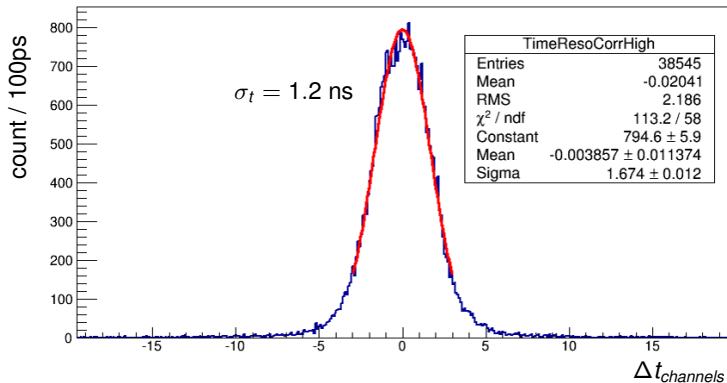
Guard Ring - GTK3 Scattered Particle Detection
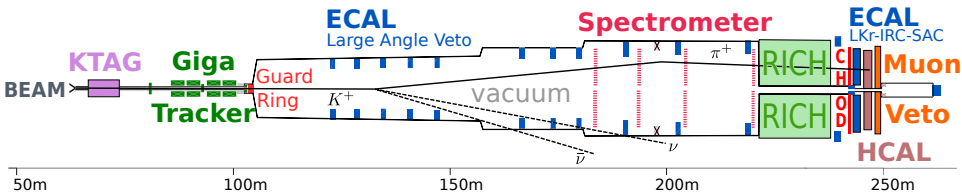

Five first Guard Ring stations during installation

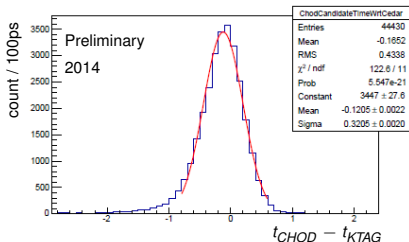| Specifications	
Rate	10-100kHz
Time Reso	1 ns

CHANTI - Design and Performance

- ▶ 6 stations of scintillator+WLS fibres read with SiPMs

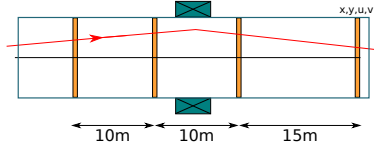- ▶ Signal processed with TDC

CHOD - Charged Decay Product Timing

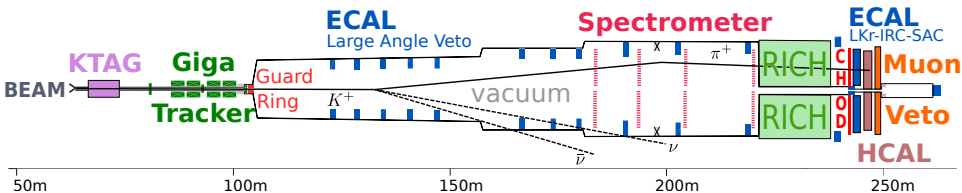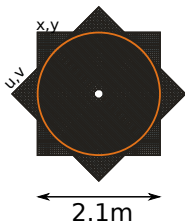Time Resolution, $\sigma(t) \simeq 300$ ps

► 2 layers (X-Y) of scintillator read each by 64 PMT

► Used for time reference

Spectrometer - Decay Products Kinematics

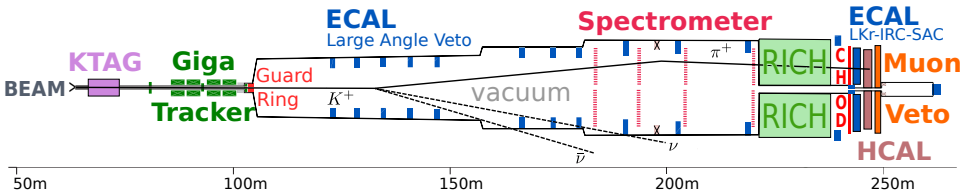# Spectrometer - Design and Status

Specifications	
Rate	15 MHz
Momentum Reso	1%
Angular Reso	20-60 μrad
Material	$4 \times 0.5\% X_0$
Size	2.1 m diameter

2.1m

- ▶ 2.1m long straw filled wilt $Ar+CO_2$ at 1 atm ran in vacuum

- ▶ 7168 straws arranged in 4 chambers of 4 views (x,y,u,v)

- ▶ Readout up to 700kHz per straw with TDCs

- ▶ See performance in First Data

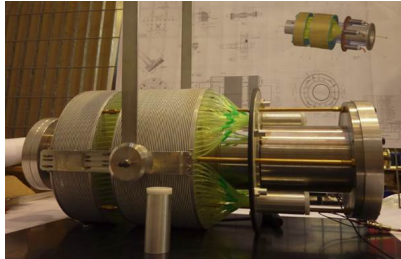# ECAL - Photon Detection ($K^+ \to \pi^+ \pi^0$)

LAV Pb Glass - OPAL

LKr NA48

IRC (+ SAC) Shashlik type

$8.5 \to 50$ mrad

$1 \to 8.5$ mrad

< 1 mrad: angular coverage

LAV: 8.5 → 50 mrad

Specifications	
Eff.	99.8 - 99.99%
Time Reso	< 1 ns
Tot Rate	1MHz

Lead Glass

Vacuum Vessel
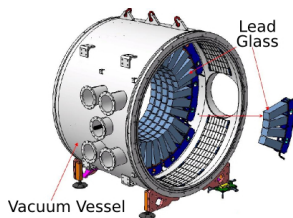
▶ 12 stations of 4-5 rings of staggered lead glass blocks

Preliminary
2014

$\sigma_t < 1ns$

χ^2 / ndf	269.7 / 65
Constant	774.8 ± 6.9
Mean	-0.006916 ± 0.007069
Sigma	0.9567 ± 0.0048

$t_{Hit} - t_{KTAG}$
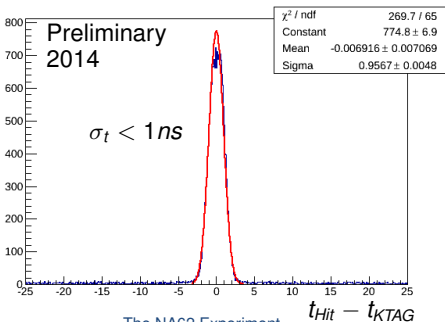
LKr: $1 \to 8.5$ mrad
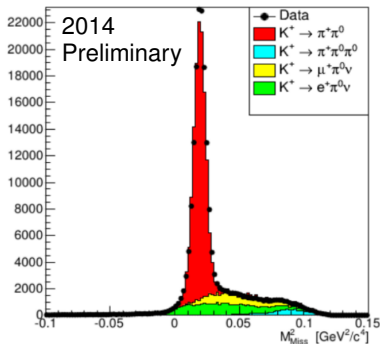

- Quasi homogenous liquid Kripton calorimeter from NA48

- Inefficiency measured in 2004 at 10^{-5} for $E > 10$ GeV

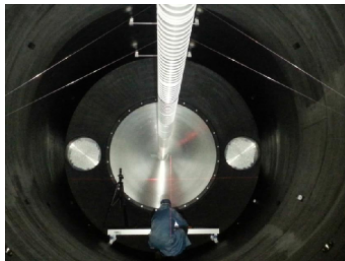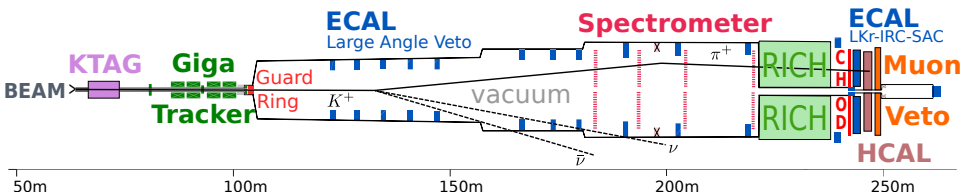- Major RO upgrade: full LKr sampled at 40MHz with 14bits FADC
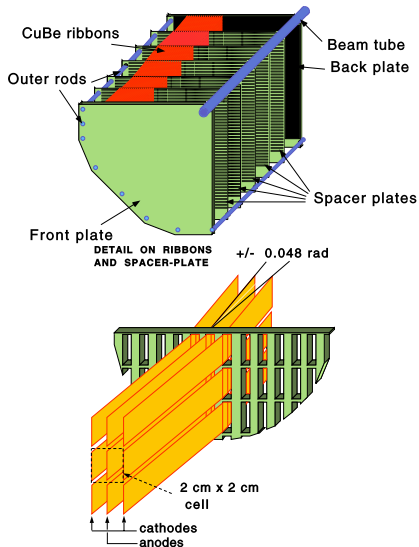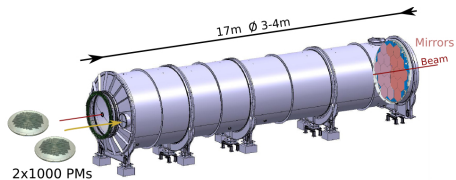
LKr - Performance
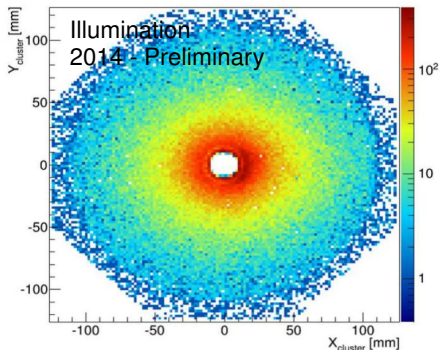
$$|p_K - p_{\pi^0}|^2$$

- ▶ $K^+ \to \pi^+\pi^0$ event reconstructed with LKr only

- ▶ p_K set to it nominal value

- ▶ π^0 reconstructed from two EM clusters, constrained to m_{π^0}
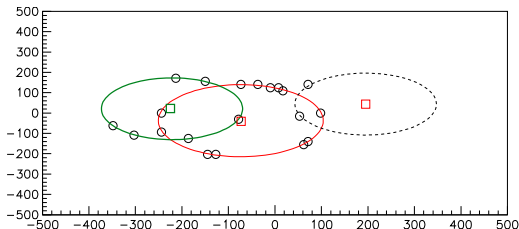
RICH - π, μ Identification

RICH - Design

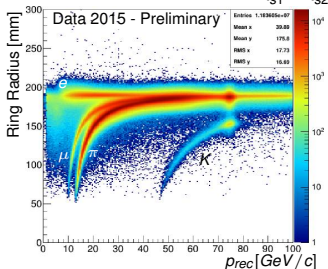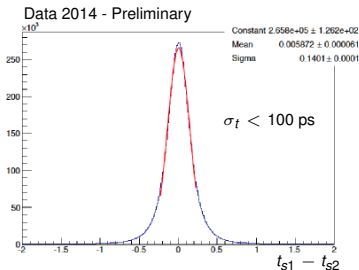| Specifications	
$\pi \to \mu$	< 1% for $p \in [15, 35]$ GeV
Angular Reso	< 100µrad
Time Reso	< 100 ps RMS
Rate	10 MHz

- ► Neon at 1 atm:
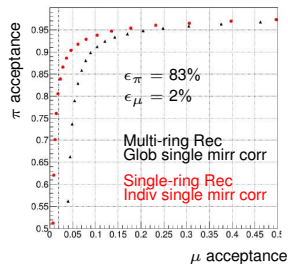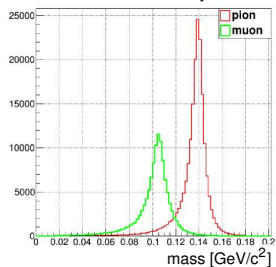 $p_{Th}^{\pi} = 13 GeV/c$

- ► 17m long vessel:
  ~20 hits per ring

- ► Light reflected on
  two 1000 PM arrays
  read with TDC
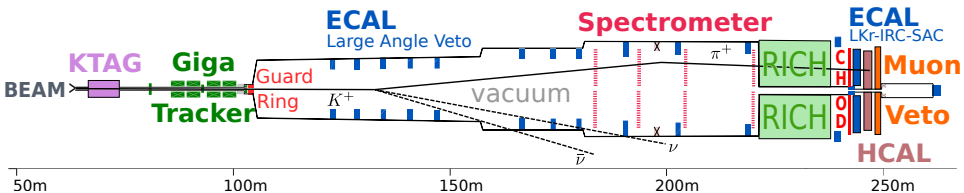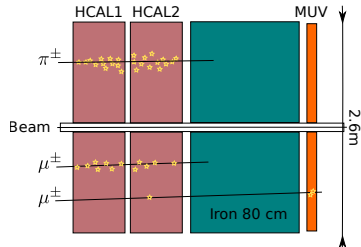
RICH - Performance

Data 2014 - Preliminary

$\sigma_t < 100$ ps

$t_{S1} - t_{S2}$

Data 2015 - Preliminary

mass $[GeV/c^2]$

Data 2015 - Preliminary

Ring Radius [mm]

μ π K

$p_{rec}[GeV/c]$

π acceptance

$\epsilon_\pi = 83\%$
$\epsilon_\mu = 2\%$

Multi-ring Rec
Glob single mirr corr

Single-ring Rec
Indiv single mirr corr

μ acceptance
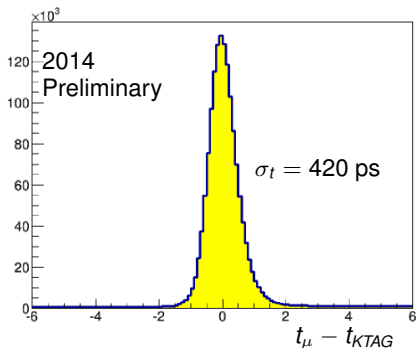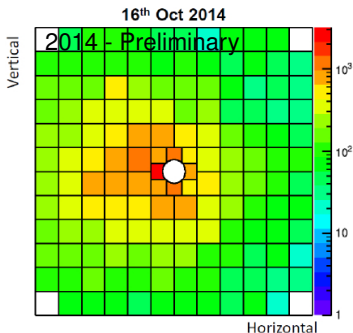
HCAL and MUV - π, μ Identification

HCAL 1 and 2

MUV - back

MUV - Design and Performance

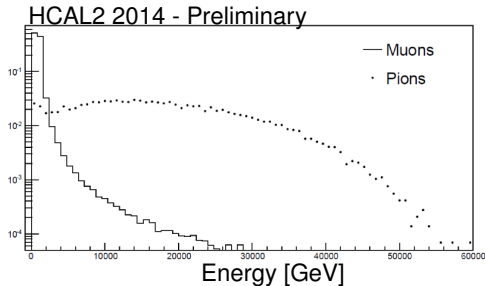▶ MUV made of scintillator 22x22 cm^2 tiles read with 2 PMs and CFDs

Specifications	
$\pi \to \mu$	$< 10^{-2}$
Time Reso	$< 1 ns$ RMS
Rate	10 MHz

HCAL 1 and 2 - Design and Performance

▶ HCAL1 (HCAL2) made of alternating layers of iron and 6 (12) cm scintillator strip read with PMs and TDCs

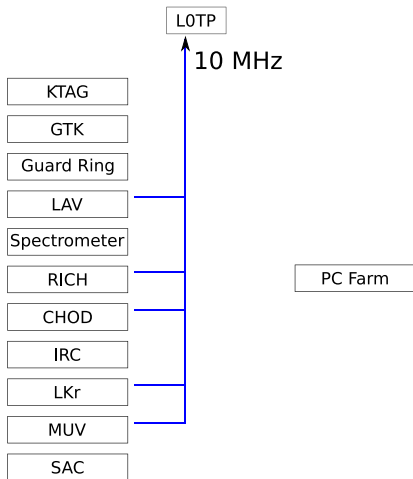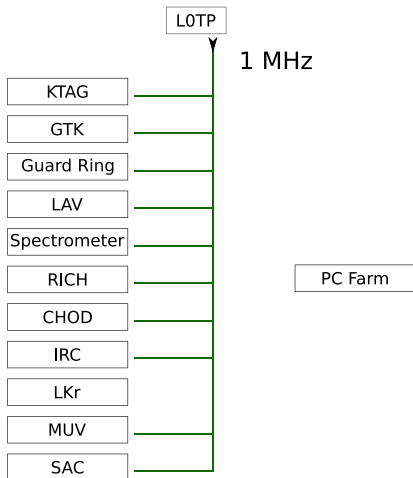| Specifications	
$\pi \to \mu$	$< 10^{-3}$
Time Reso	$< 1 ns$ RMS
Rate	10 MHz

Digital Trigger System

System Feature

- As beam is not bunched triggers arrive asynchronously

- Digital inputs to L0TP

2015 Run

- System tested up to full intensity

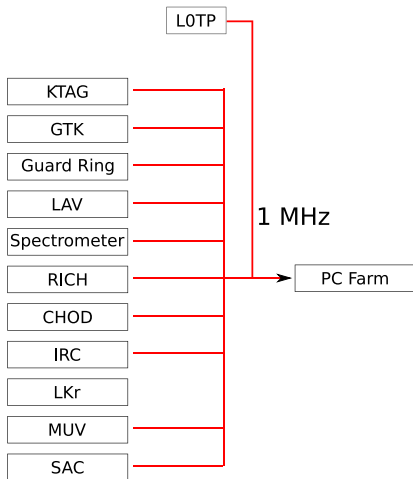- Digital calorimetric trigger implemented

Digital Trigger System

System Feature

- ▶ As beam is not bunched triggers arrive asynchronously

- ▶ Digital inputs to L0TP

2015 Run

- ▶ System tested up to full intensity
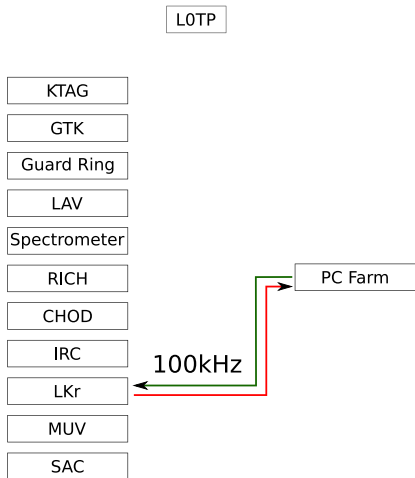
- ▶ Digital calorimetric trigger implemented

Digital Trigger System

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2015 Run

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L0TP

KTAG

GTK

Guard Ring

LAV

Spectrometer

RICH

CHOD

IRC

LKr

MUV

SAC

L2

PC Farm

20kHz
on disk

Calorimetric Trigger

- ▶ Full LKr sampled at 40 MHz with 14bits FADC

- ▶ Energies in one 25ns sampling of 16 (4x4) adjacent cells summed and pipe-lined in trigger boards

- ▶ With 5 consecutive 16-cell sum, trigger boards look for peaks in time and fit to get maximum (i.e. energy)

- ▶ Peak time extracted by constant fraction discrimination

- ▶ Energy filled in a 6.25ns lsb histo
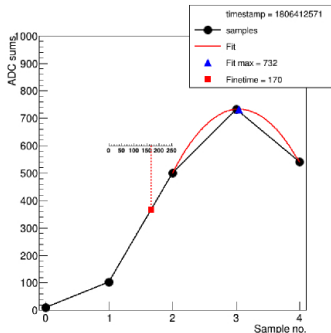
Calorimetric Trigger Status and Prospects

2015 Run

- ▶ Machinery operated synchronously on LKr and HCAL

- ▶ Trigger based on total energy in LKr and HCAL1:

$$E_{HCAL1}^{tot} > 6 \text{ GeV} \quad \& \quad E_{LKr}^{tot} < 4 \text{ GeV}$$

Prospects for Next Run

- ▶ LKr clustering in space (X and Y) at trigger level

- ▶ Trigger on individual LKr cluster instead of total energy

Outline

A look at min-bias 2014 and 2015 data

- ▶ One track candidates:
  Good χ^2 and 4(3)-chambers (in 2014)

- ▶ K^+ kinematics:
  Beam mean values in 2014, GTK in 2015

- ▶ Results preliminary:

  - ▶ B field constant

  - ▶ Drift-Time to Radius relation from MC (Garfield)

  - ▶ Rough detector alignment

  - ▶ Rough t0 (refined in 2015)
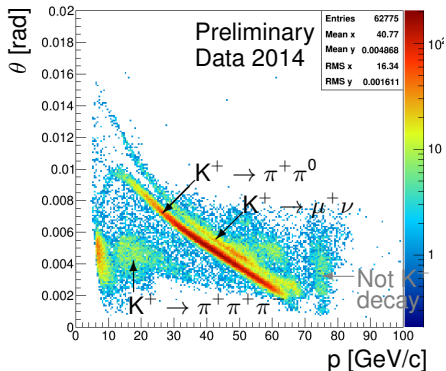
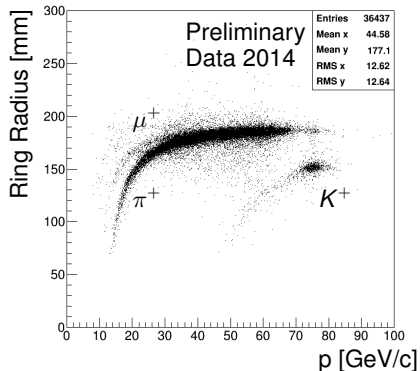# Angle Track-Beam versus Track Momentum
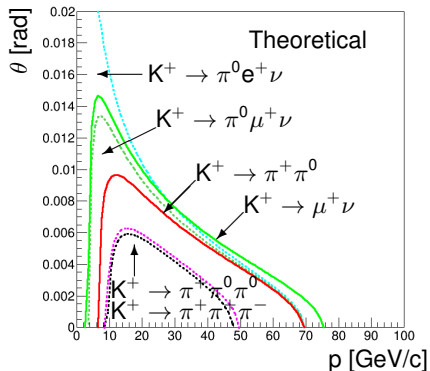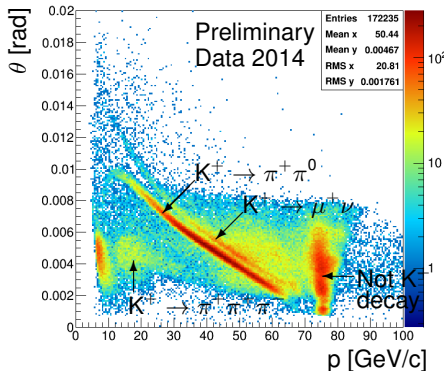
Requesting in Time Kaon with KTAG

K^+ in time with Track
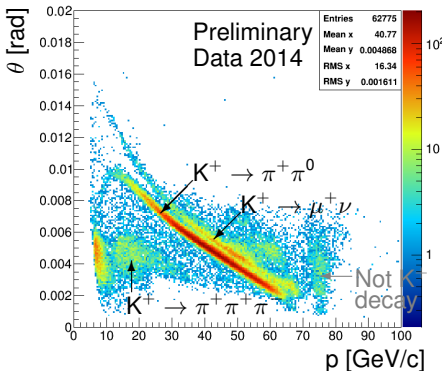
No K^+ in time with Track
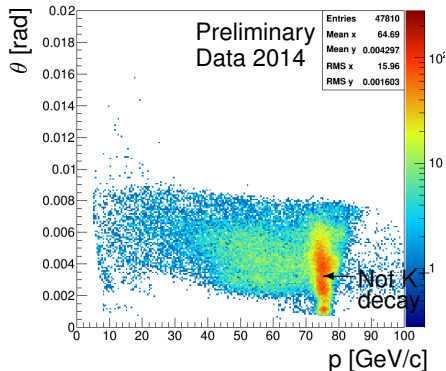
Checking Track Id using RICH

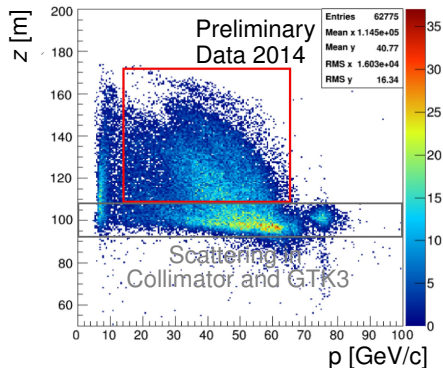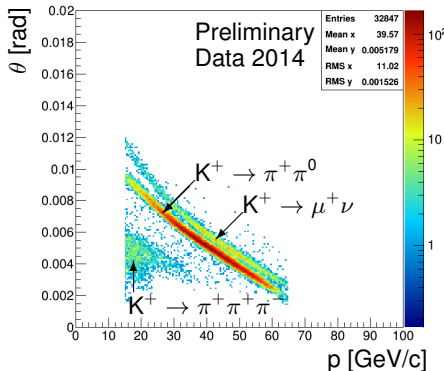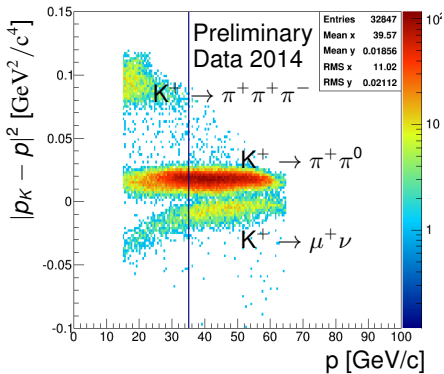# Removing Scattered Beam Particle Component
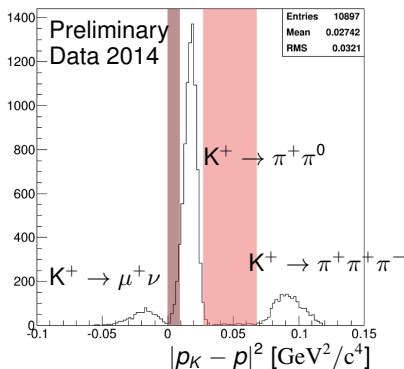

K^+ in time with Track not scattered

Squared Missing Mass

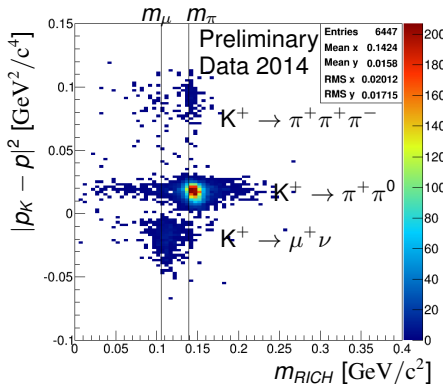# Squared Missing Mass

K^+ in time with Track
not scattered

Preliminary
Data 2014

Entries	32847
Mean x	39.57
Mean y	0.01856
RMS x	11.02
RMS y	0.02112

$K^+ \rightarrow \pi^+ \pi^+ \pi^-$

$K^+ \rightarrow \pi^+ \pi^0$

$K^+ \rightarrow \mu^+ \nu$
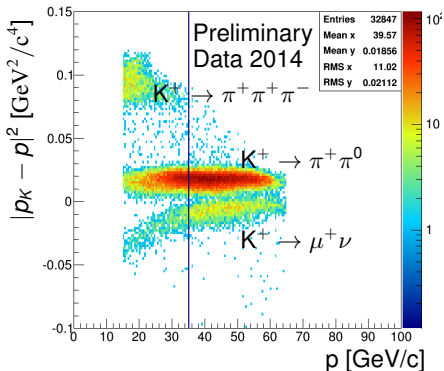
Reminder: No GTK
$p_\pi < 35 \text{GeV/c}$

Preliminary
Data 2014

Entries	10897
Mean	0.02742
RMS	0.0321

$K^+ \rightarrow \pi^+ \pi^0$

$K^+ \rightarrow \mu^+ \nu$

$K^+ \rightarrow \pi^+ \pi^+ \pi^-$

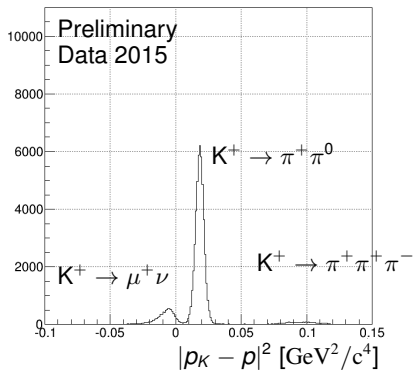# More Discriminating Power using RICH mass
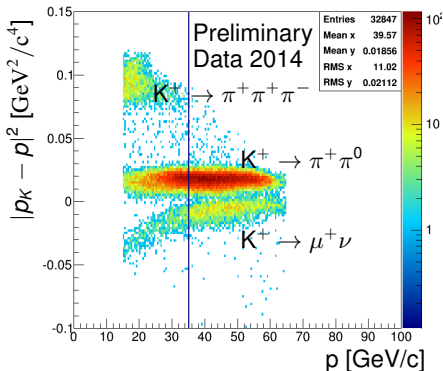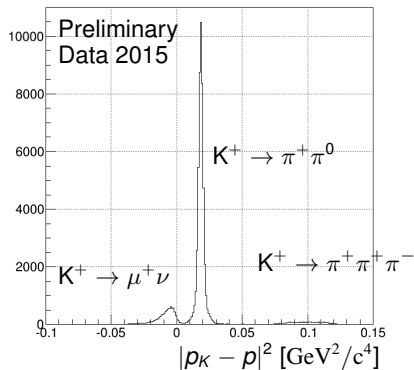
Improving kinematics with GTK - 2015
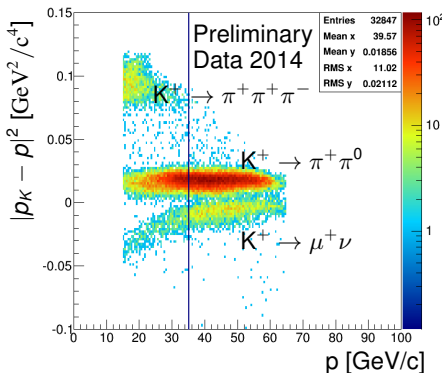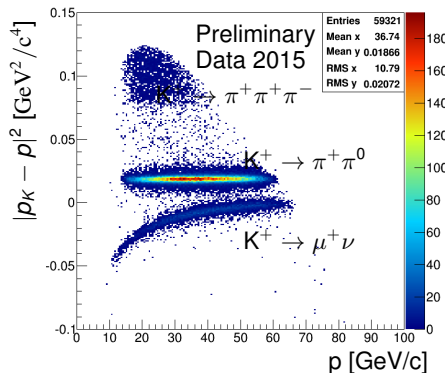
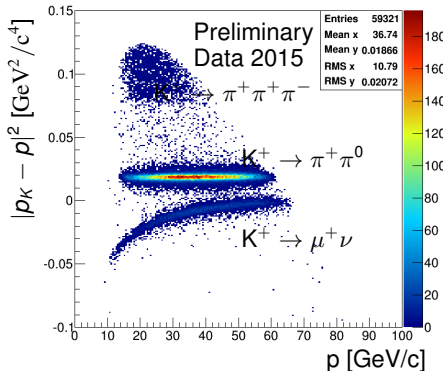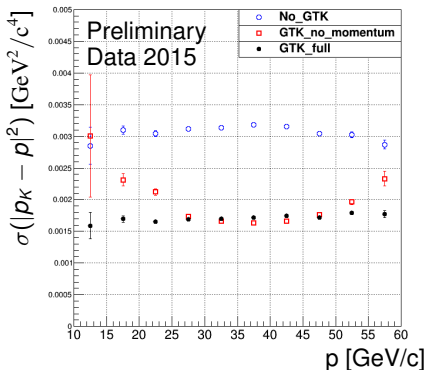# Improving kinematics with GTK - 2015

Without GTK
Full *p* range

With GTK
Full *p* range

Improving kinematics with GTK - 2015

Missing Mass Resolution

Outline

1. Physics Case (10min)

2. The NA62 Experiment (25min)

3. First look at Data (10min)

4. Conclusions and Prospects

Conclusion and Prospects

- $\mathcal{B}(\text{K}^+ \to \pi^+ \nu \bar{\nu})$ an important observable in LHC era

- NA62 apparatus installed and first data taken

- New technologies developed (time resolved pixel, micro-channel cooling) now considered for LHC upgrades

- Data quality shows good performance

- Ready for 2-3 years of physics data taking

Thanks you for your attention.

SPARES

Uncertainty budget
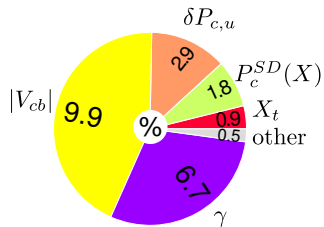
- ▶ $\delta P_{c,u}$ long range contribution to charm

- ▶ P_c^{SD} short range contribution to charm

Unitarity Triangles