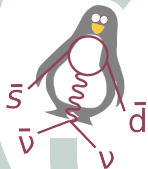


NA62



The NA62 Experiment

Seminar at LPNHE, Paris, France

Mathieu PERRIN-TERRIN

CERN, Geneva, Switzerland.

February 4, 2016

Outline

- 1 Physics Case (10min)
- 2 The NA62 Experiment (25min)
- 3 Outlook of the First Data (10min)
- 4 Conclusions and Prospects

A broad physics program

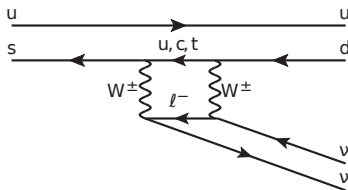
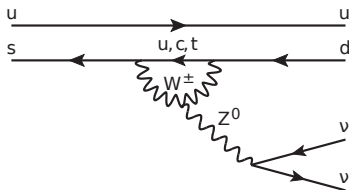
The main target: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ but many more channels:

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}
$\pi^+ X^0$	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}
$\mu^+ \nu_h, \nu_h \rightarrow \nu \gamma$	Heavy neutrino	Limits up to $m_{\nu_h} = 350 \text{ MeV}$	
R_K	LU	$(2.488 \pm 0.010) \times 10^{-5}$	$> \times 2$ better
$\pi^+ \gamma \gamma$	χ^2 PT	< 500 events	10^5 events
$\pi^0 \pi^0 e^+ \nu$	χ^2 PT	66000 events	$O(10^6)$
$\pi^0 \pi^0 \mu^+ \nu$	χ^2 PT	—	$O(10^5)$

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



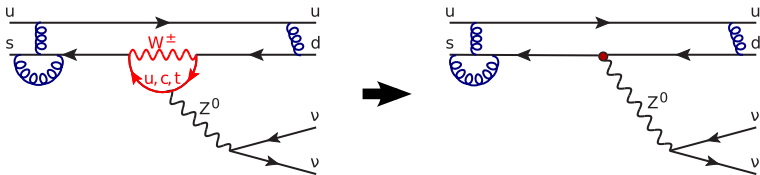
- Very **rare** SM process [Buras, 1503.02693]

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

- 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 $\ll$ EW energy scale hence:



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

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

$$\langle F | Q_i(\mu) | M \rangle$$

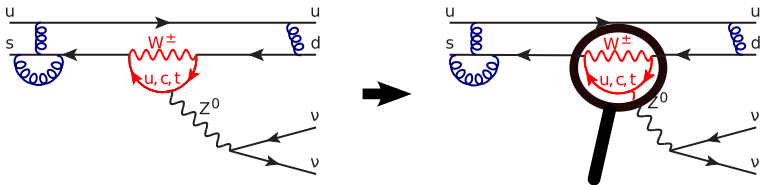
long range, matrix elements, **large uncertainties**

$$C_i(\mu)$$

short range, Wilson coefficients

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$\langle F | Q_i(\mu) | M \rangle$

long range, matrix elements, **large uncertainties**

$C_i(\mu)$

short range, Wilson coefficients

Theoretical Uncertainties

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

Matrix Elements (normally large uncertainties)

- Derived from $K^+ \rightarrow \pi^0 e^+ \nu$ 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]

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

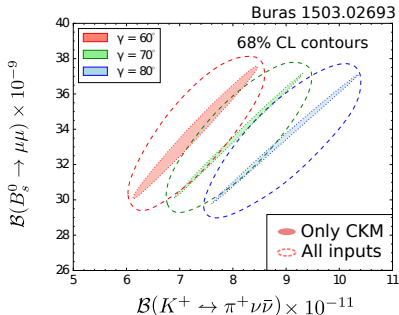
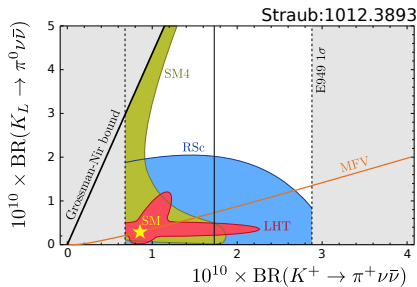
- Second error from **external CKM inputs** (V_{cb} , γ)

- $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ with 10% uncertainties allows to determine $|V_{td}|$ at 9% [Buras 0405132]
- With $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$, $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ the CKM unitarity triangle can be built independently from B observables:

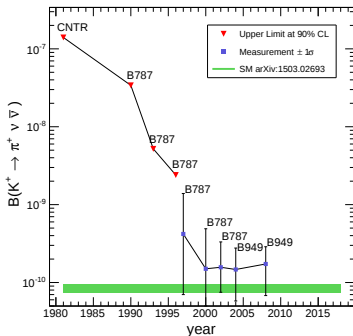


Going Beyond the Standard Model

- 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 $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$, $\mathcal{B}(B_s^0 \rightarrow \mu \mu)$, γ , $B \rightarrow K(K^*) \mu \mu$, ϵ'/ϵ
- A key observable for the LHC era



State of the Searches



E949 Measurements – 2008

- Stopping kaon technique

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

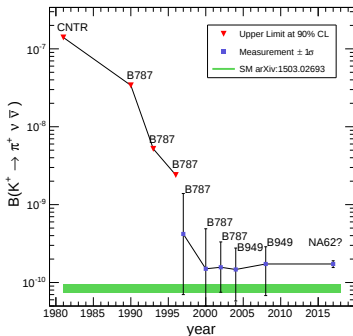
Phys. Rev. D 77, 052003 (2008)

Phys. Rev. D 79, 092004 (2009)

- KOTO at JPARC aims to reach by 2020 the SM **single event sensitivity for $K_L \rightarrow \pi^0 \nu \bar{\nu}$** ¹

¹ $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11}$ Buras 1503.02693

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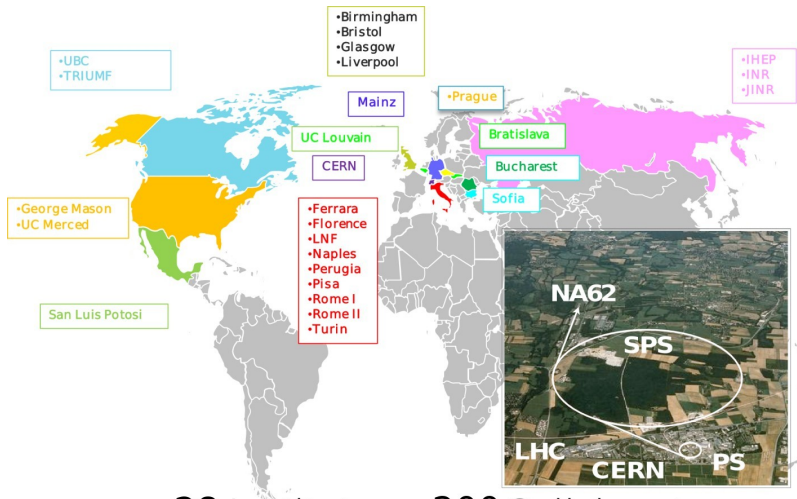
NA62 Goal

- ▶ Measuring $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ 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

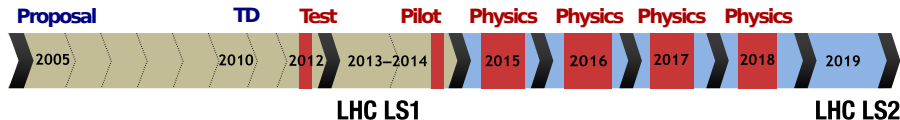
- 1 Physics Case (10min)
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NA62 Collaboration



28 Institutes, ~200 Collaborators

NA62 Time Line



Reference Documents

2005 Proposal

[CERN-SPSC-2005-013]

2010 Technical Design

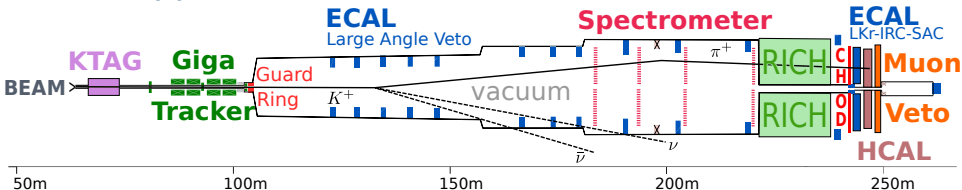
[NA62-10-07]

2014 Pilot Run

[G. Ruggiero, CERN Seminar]

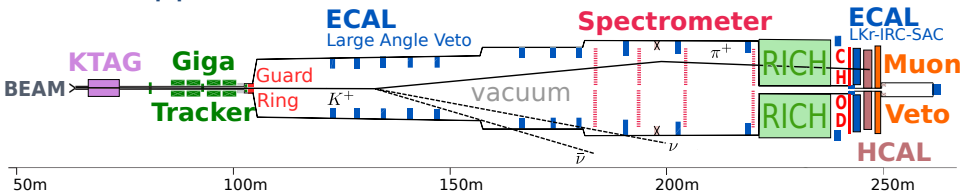


NA62 Apparatus



With HCAL and GTK completion in 2015 all detectors are installed

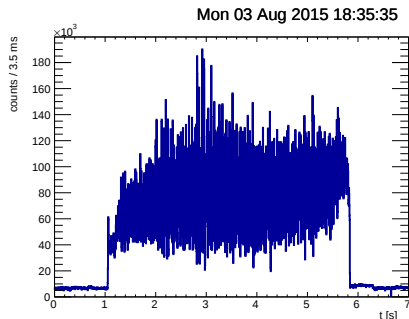
NA62 Apparatus



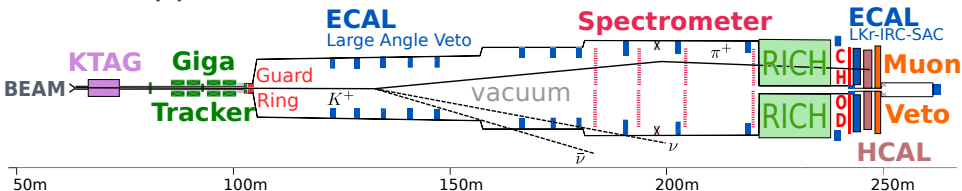
Secondary Beam from SPS

- ▶ 5s spill at 750 MHz
- ▶ Composition:

p	π^+	K^+
70	24	6%
- ▶ 75 GeV/c with $\delta p/p = 1\%$



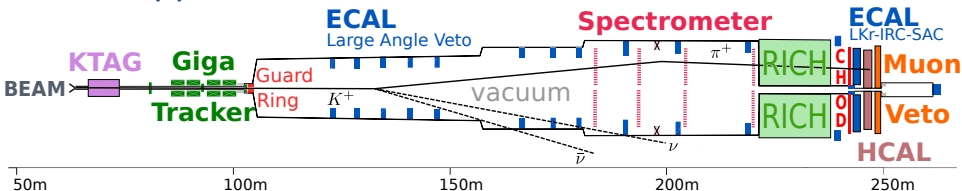
NA62 Apparatus



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

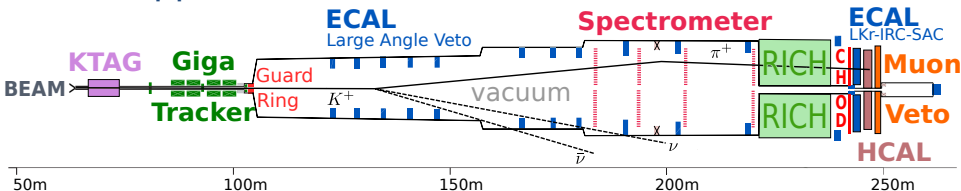


Decay Region

- ▶ 120m long, in **vacuum** (500 m^3 at 10^{-6} mbar)
- ▶ 10% of K^+ decay in the first 65m:

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

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)

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

Background Sources

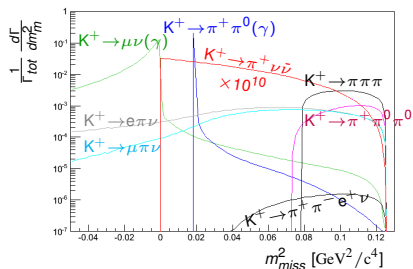
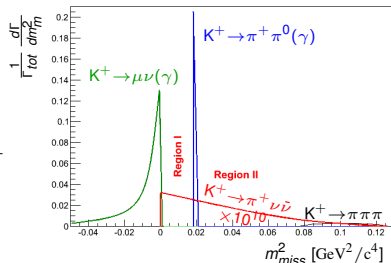
- ▶ K^+ decay incorrectly reconstructed
- ▶ Particle accidentally in time with a K^+

Analysis

- ▶ Main variable $m_{miss}^2 = |p_K - p_\pi|^2$
- ▶ Look for signal in regions I and II
- ▶ $p_\pi \in [15, 35]$ GeV/c (RICH, kinematics, γ rejection, accidental from $\pi^+ \rightarrow \mu^+ \nu$)

- ▶ Background suppression needed:

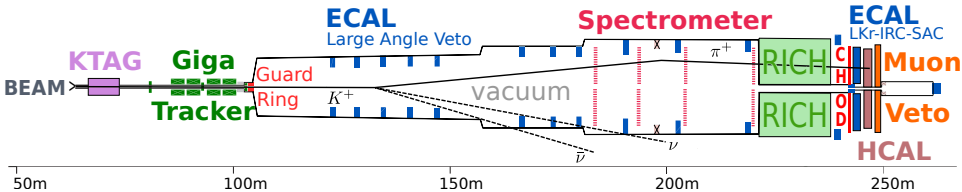
Kinematics	10^{-4}	Charged PID	10^{-7}
π^0 's γ Rejection	10^{-8}	Timing	10^{-2}



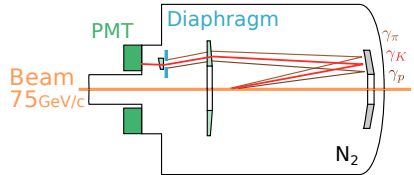
Analysis Sensitivity (MC)

Decay	event/year
$K^+ \rightarrow \pi^+ \nu \bar{\nu}(\text{SM})$	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

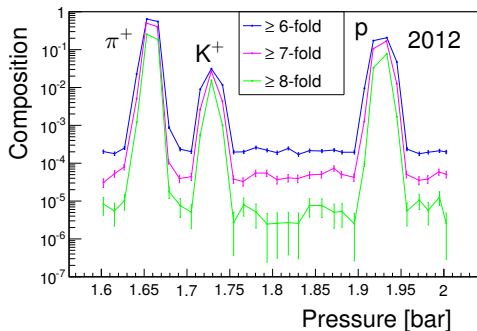
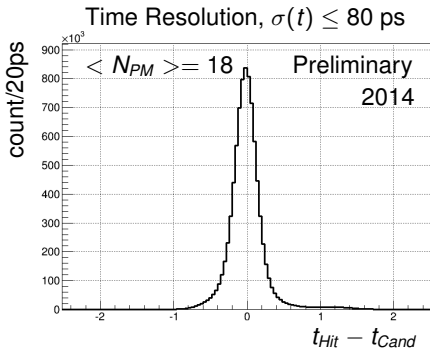
KTAG - Kaon Identification and Timing



Differential Cerenkov Detector

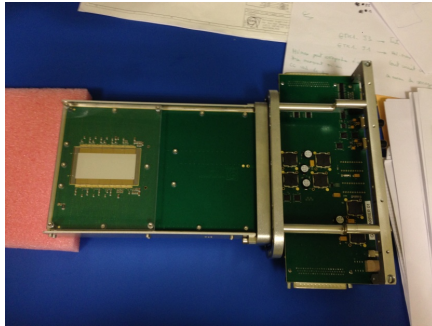
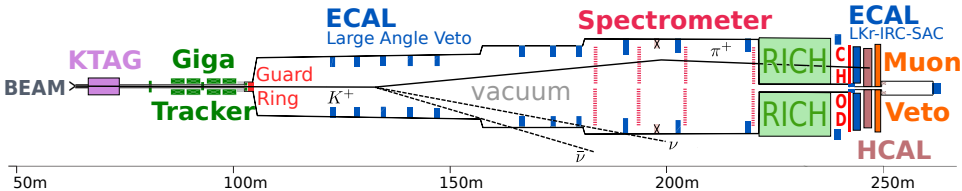


KTAG - Performance



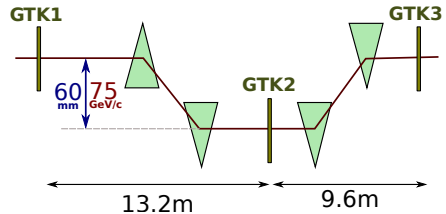
- ▶ K^+ Identification $> 95\%$
- ▶ π^+ , p Rejection $> 99.9\%$

GTK - Beam Particle Kinematics and Timing

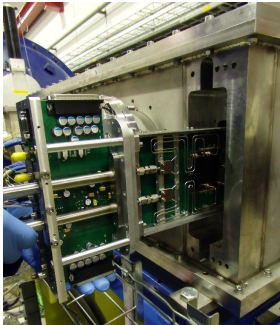
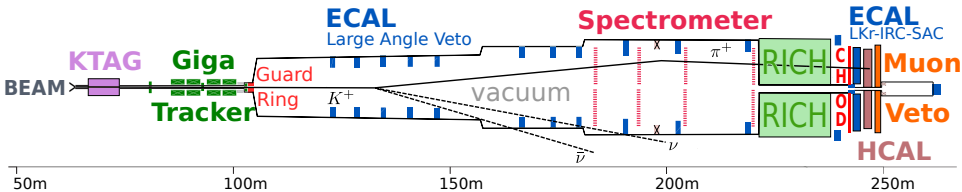


GTK3 in lab

Three Stations of Silicon Hybrid Pixel

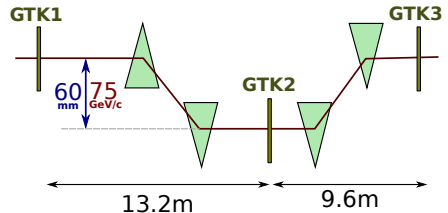


GTK - Beam Particle Kinematics and Timing



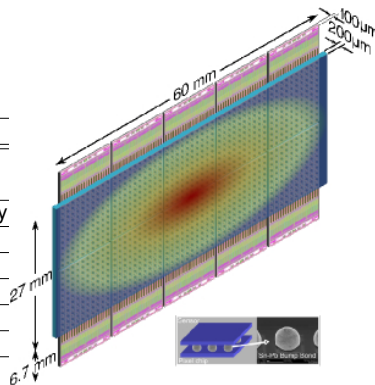
GTK3 being installed

Three Stations of Silicon Hybrid Pixel



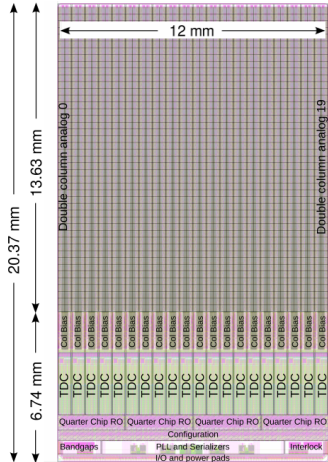
A very innovative detector

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 μ rad
Hit Time Reso	200 ps RMS
Material	$3 \times 0.5\% X_0$
Size	60mm $\times$ 27mm

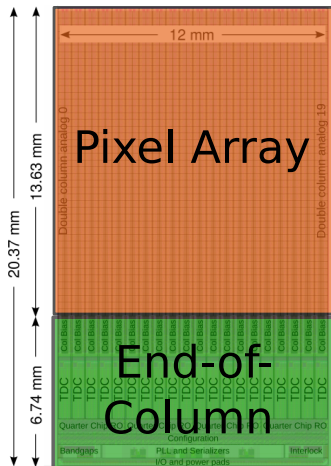


- ▶ Hybrid silicon pixels detector, changed every 100 run days
- ▶ 18k **time-resolved** pixels / station ($300 \times 300 \mu\text{m}^2$)
- ▶ ASIC thinned to $100 \mu\text{m}$ operated in vacuum and cooled with **micro-channels**: **world first HEP implementation!**

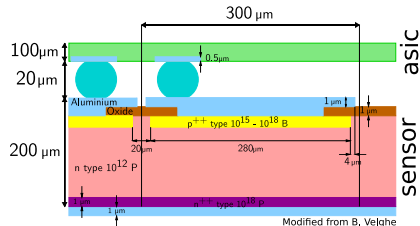
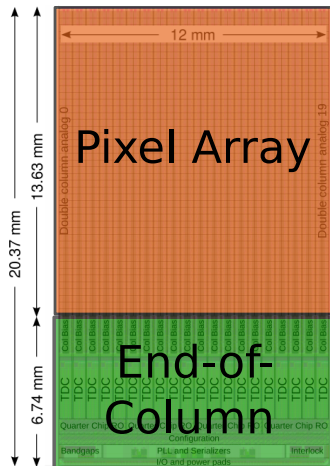
GTK - Time Measurement Principle



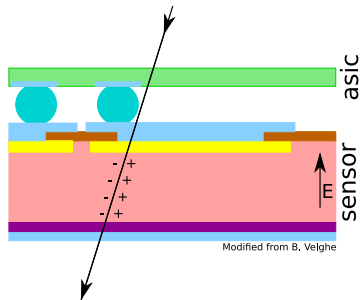
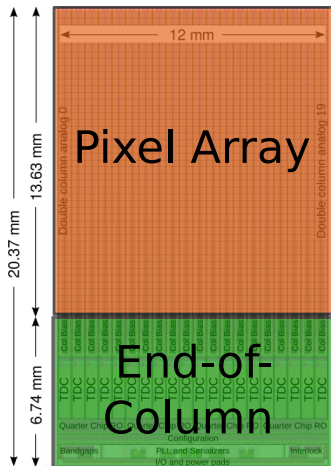
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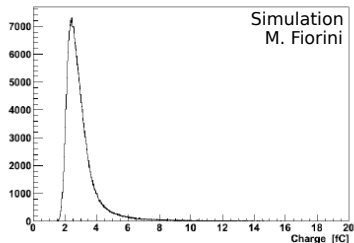
GTK - Time Measurement Principle

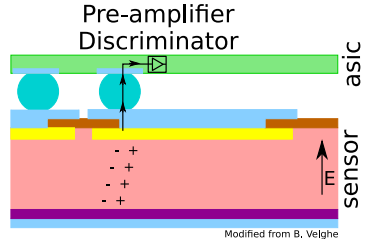


GTK - Time Measurement Principle

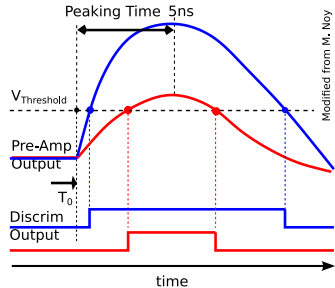
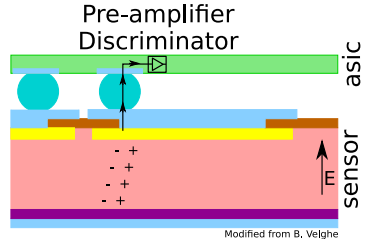
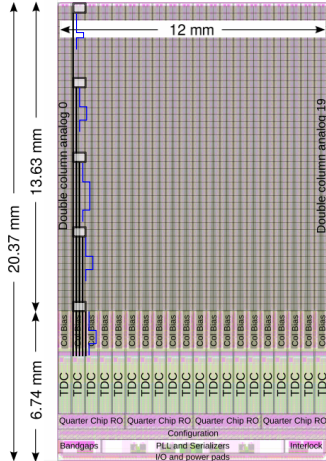


Generated signal in GTK1



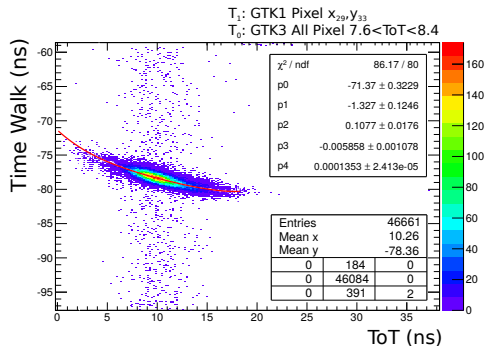
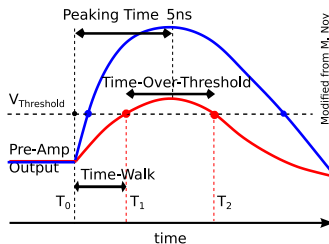


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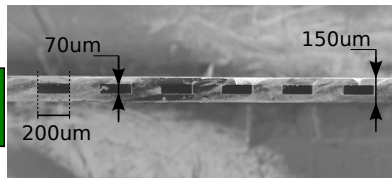
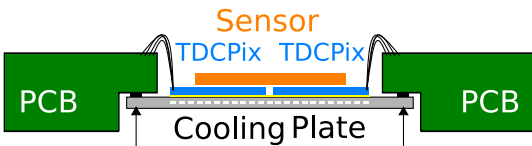
GTK - Time Measurement Principle

- ▶ At EoC, TDCs measure **rising and falling** edge time
- ▶ The full GTK integrates **21,600 TDCs** in $<25 \text{ cm}^2$!
- ▶ Use Time-over-Threshold to estimate **time walk**



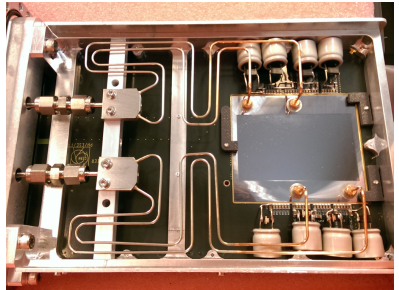
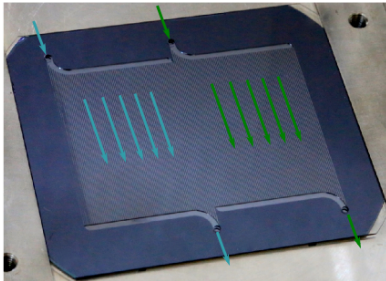
GTK - MicroChannels Cooling

- ▶ Etch channels in a **130 μm 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**



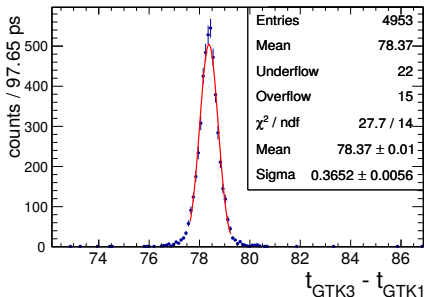
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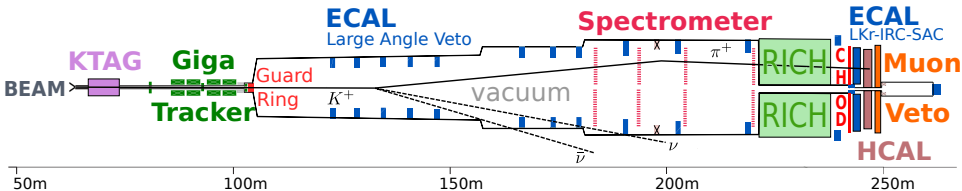


GTK - Status and Performance

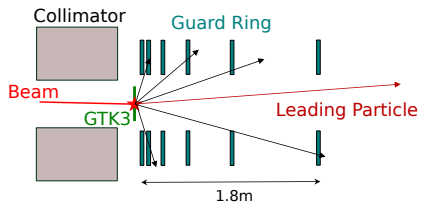
- ▶ Three stations **installed**, (2 thinned at $100\mu\text{m}$)
- ▶ 7-8 out of 10 chips per stations were working, fix next run
- ▶ Time resolution **260 ps per hit** (at 160V instead of 300V)
see First Data for kinematics performance



Guard Ring - GTK3 Scattered Particle Detection



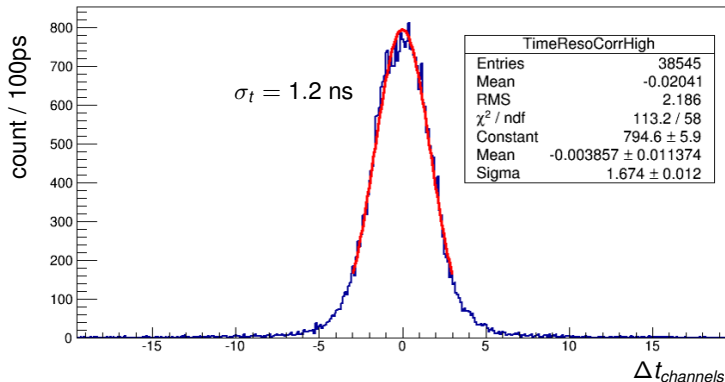
Five first Guard Ring stations during installation



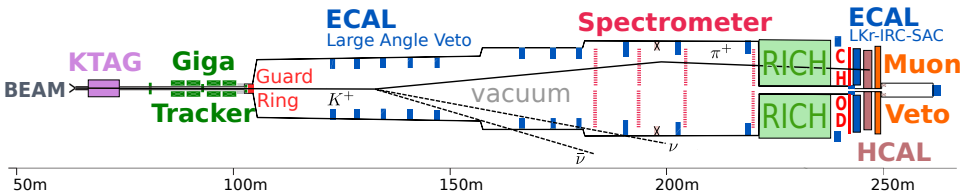
Specifications	
Rate	10-100kHz
Time Reso	1 ns

CHANTI - Design and Performance

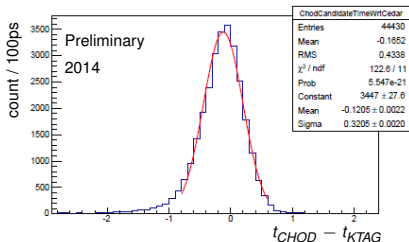
- ▶ 6 stations of **scintillator+WLS** fibres read with SiPMs
- ▶ Signal processed with **TDC**



CHOD - Charged Decay Product Timing

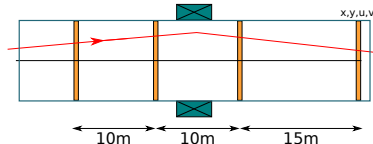
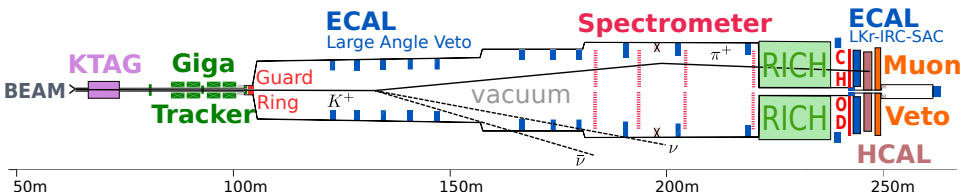


Time Resolution, $\sigma(t) \simeq 300$ ps



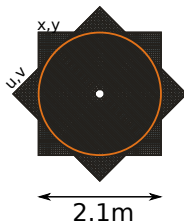
- 2 layers (X-Y) of **scintillator** read each by 64 PMT
- Used for **time reference**

Spectrometer - Decay Products Kinematics



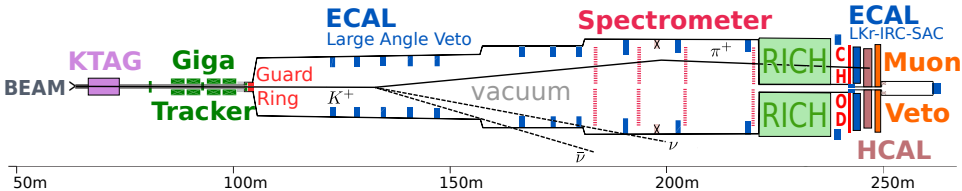
Spectrometer - Design and Status

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 long straw filled with Ar+CO₂ 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 ($K^+ \rightarrow \pi^+ \pi^0$)



LAV Pb Glass - OPAL

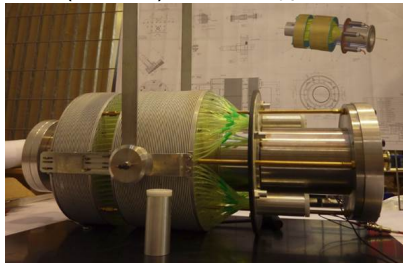


8.5 $\rightarrow$ 50 mrad

LKr NA48

 $1 \rightarrow 8.5 \text{ mrad}$

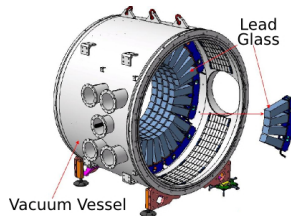
IRC (+ SAC) Shashlik type



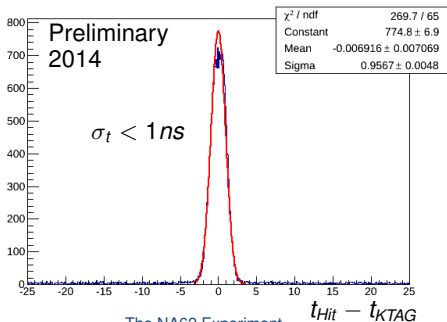
< 1 mrad: angular coverage

LAV: $8.5 \rightarrow 50$ mrad

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

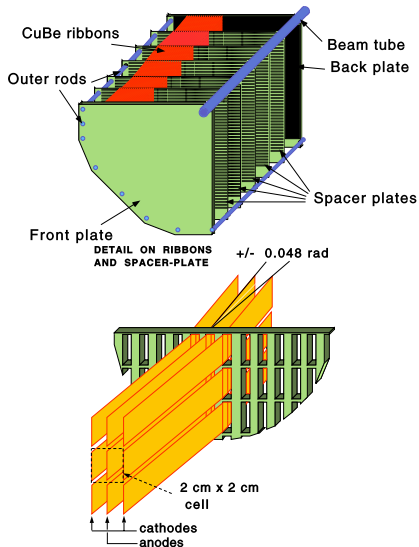


- 12 stations of 4-5 rings of staggered lead glass blocks

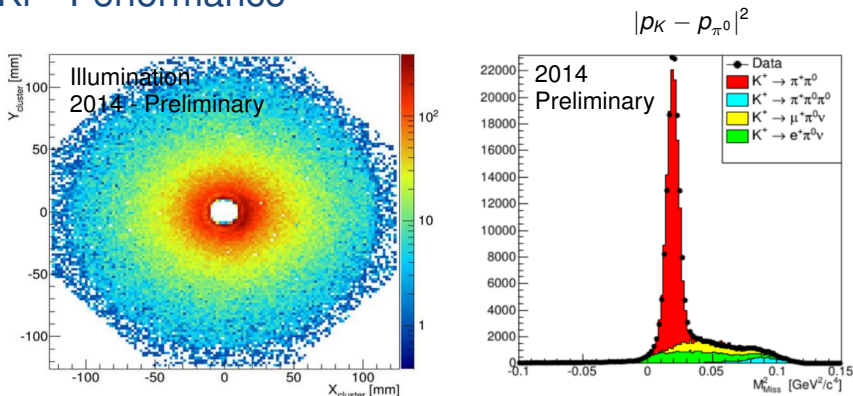


LKr: 1 $\rightarrow$ 8.5 mrad

- ▶ Quasi homogenous liquid Krypton 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

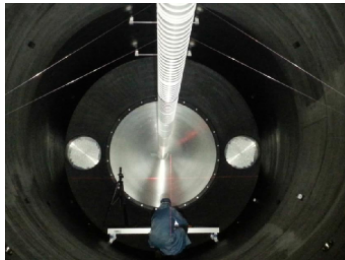
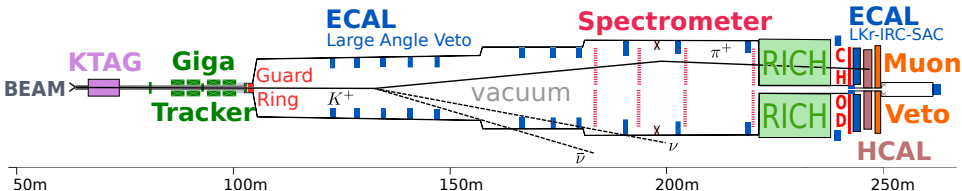


LKr - Performance



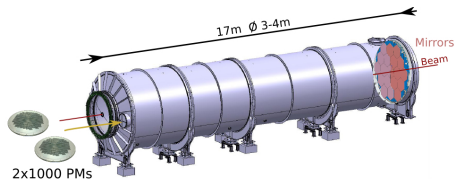
- ▶ $K^+ \rightarrow \pi^+\pi^0$ event reconstructed with **LKr only**
- ▶ p_K set to its nominal value
- ▶ π^0 reconstructed from two EM clusters, constrained to m_{π^0}

RICH - π , μ Identification

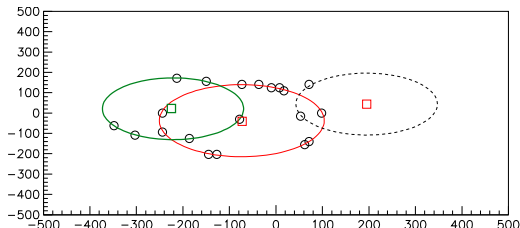


RICH - Design

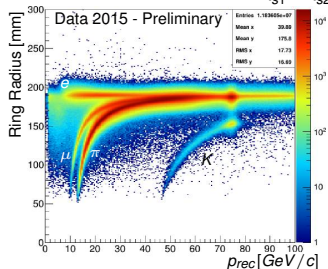
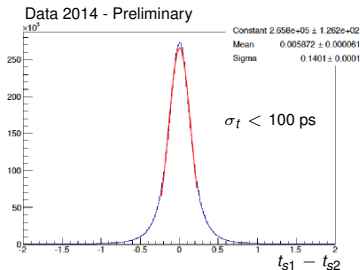
Specifications	
$\pi \rightarrow \mu$	$< 1\%$ for $p \in [15, 35]$ GeV
Angular Reso	$< 100 \mu\text{rad}$
Time Reso	< 100 ps RMS
Rate	10 MHz



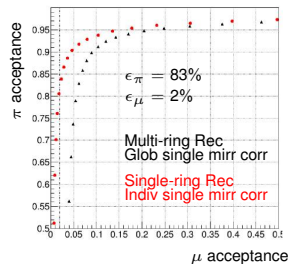
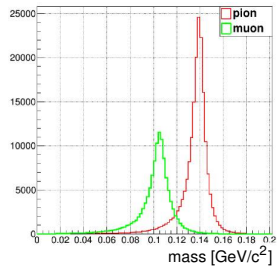
- Neon at 1 atm:
 $p_{Th}^{\pi} = 13 \text{ GeV}/c$
- 17m long vessel:
 ~ 20 hits per ring
- Light reflected on
two 1000 PM arrays
read with TDC



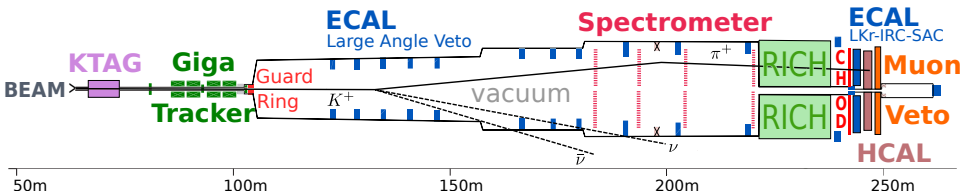
RICH - Performance



Data 2015 - Preliminary



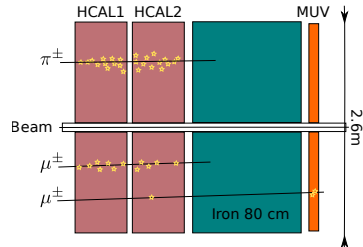
HCAL and MUV - π , μ Identification



HCAL 1 and 2



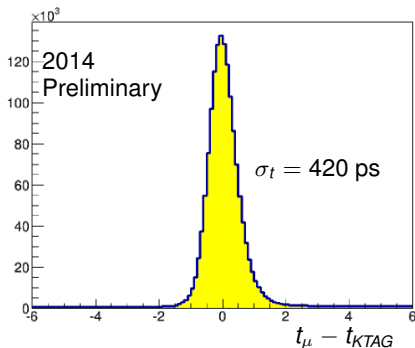
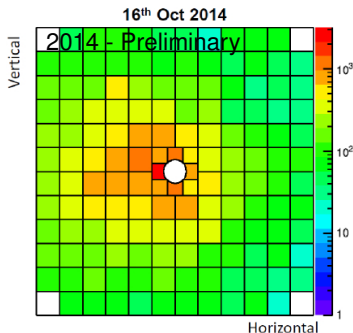
MUV - back



MUV - Design and Performance

- MUV made of **scintillator** 22x22 cm² tiles read with 2 PMs and CFDs

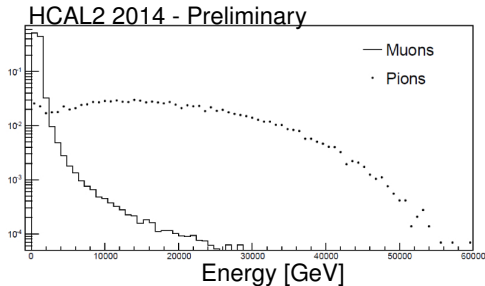
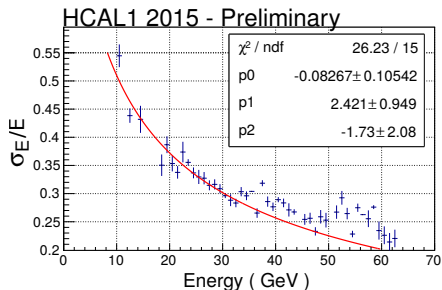
Specifications	
$\pi \rightarrow \mu$	$< 10^{-2}$
Time Reso	$< 1\text{ ns RMS}$
Rate	10 MHz



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	
$\pi \rightarrow \mu$	$< 10^{-3}$
Time Reso	$< 1\text{ ns RMS}$
Rate	10 MHz



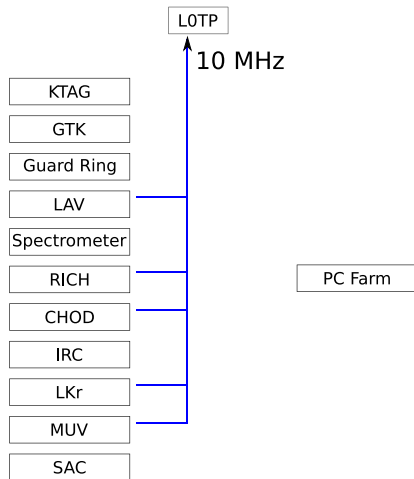
Digital Trigger System

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



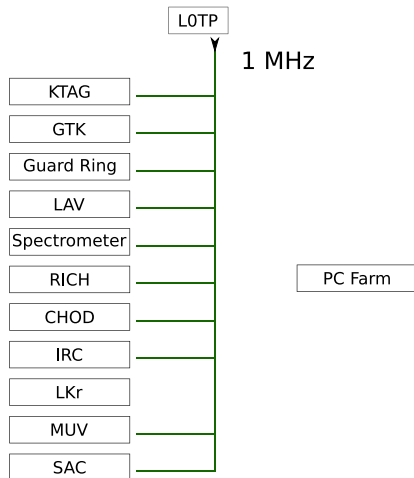
Digital Trigger System

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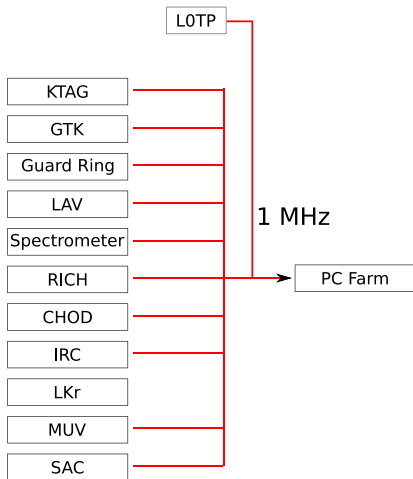
Digital Trigger System

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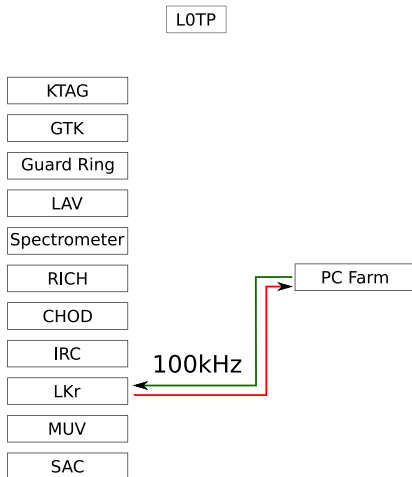
Digital Trigger System

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Digital Trigger System

System Feature

- ▶ As beam is not bunched triggers arrive asynchronously
- ▶ Digital inputs to L0TP

L0TP

2015 Run

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

KTAG

GTK

Guard Ring

LAV

Spectrometer

RICH

CHOD

IRC

LKr

MUV

SAC

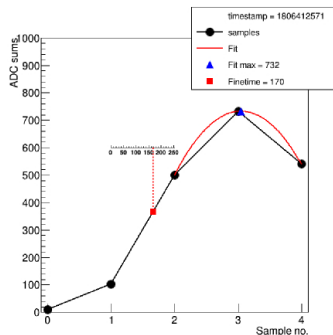
L2

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

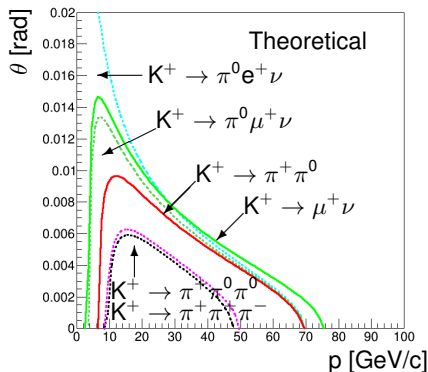
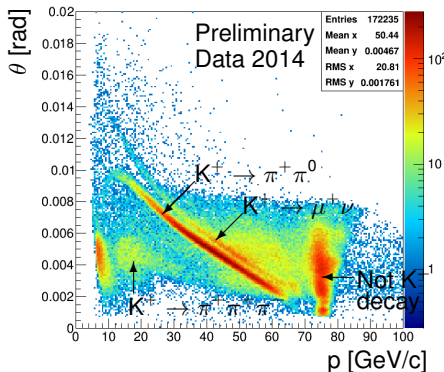
Outline

- 1 Physics Case (10min)
- 2 The NA62 Experiment (25min)
- 3 Outlook of the First Data (10min)**
- 4 Conclusions and Prospects

A look at min-bias 2014 and 2015 data

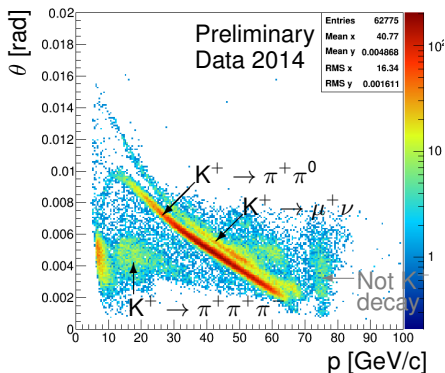
- ▶ **One track candidates:**
Good χ^2 and 4(3)-chambers (in 2014)
- ▶ **K⁺ kinematics:**
Beam mean values in 2014, GTK in 2015
- ▶ Results **preliminary:**
 - ▶ B field constant
 - ▶ Drift-Time to Radius relation from MC (Garfield)
 - ▶ Rough detector alignment
 - ▶ Rough t0 (refined in 2015)

Angle Track-Beam versus Track Momentum

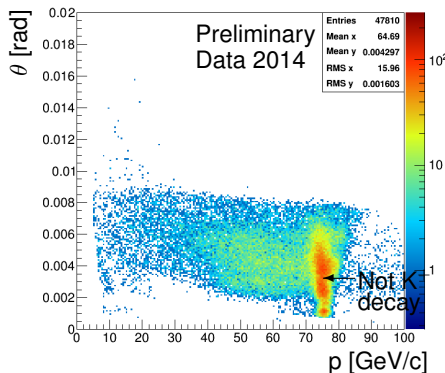


Requesting in Time Kaon with KTAG

K^+ in time with Track

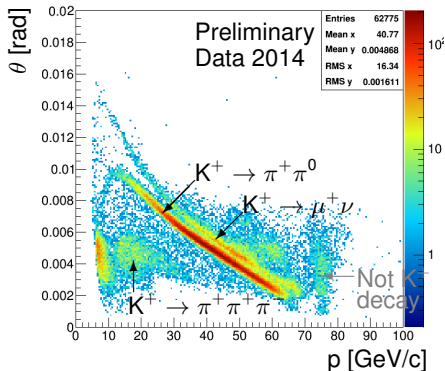


No K^+ in time with Track

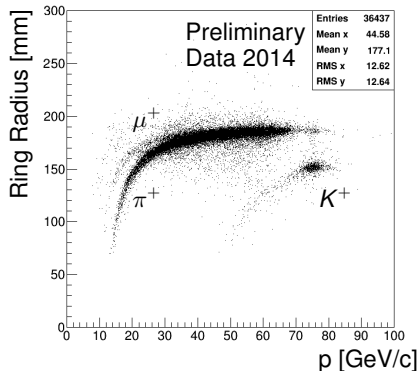


Checking Track Id using RICH

K^+ in time with Track

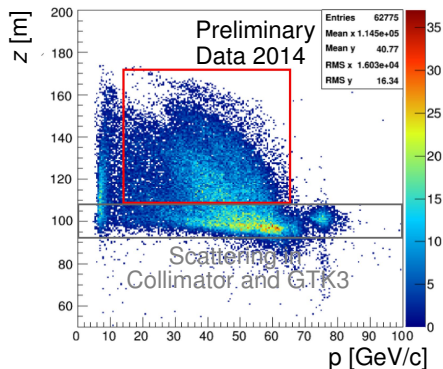
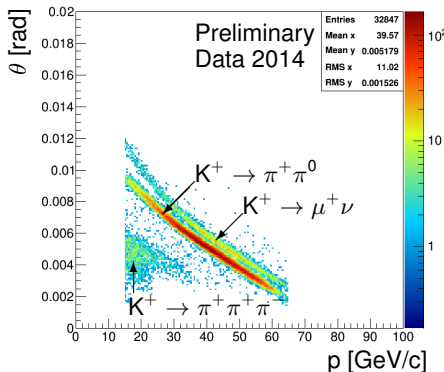


Matched Ring in RICH



Removing Scattered Beam Particle Component

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

$|p_K - p|^2 \text{ [GeV}^2/\text{c}^4]$

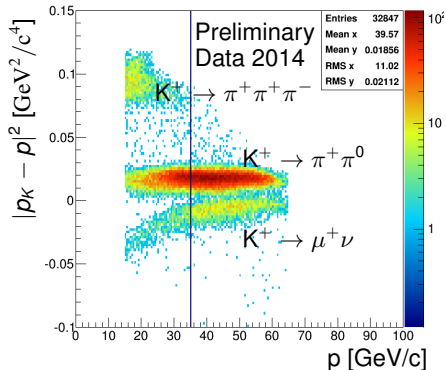
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$
 $K^+ \rightarrow \pi^+ \pi^0$
 $K^+ \rightarrow \mu^+ \nu$

$p \text{ [GeV/c]}$



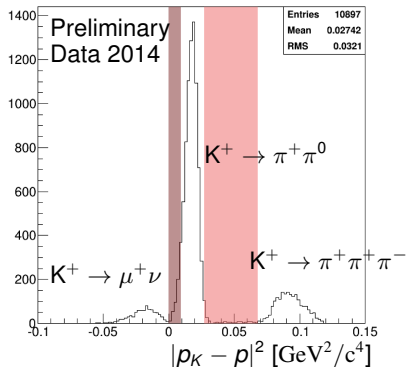
Squared Missing Mass

K^+ in time with Track
not scattered



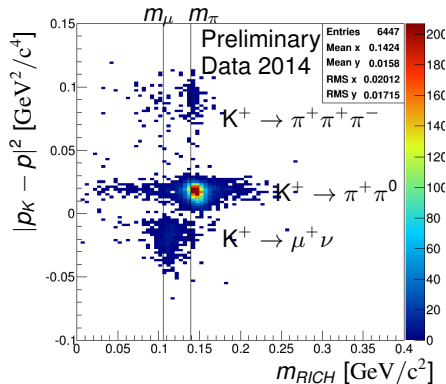
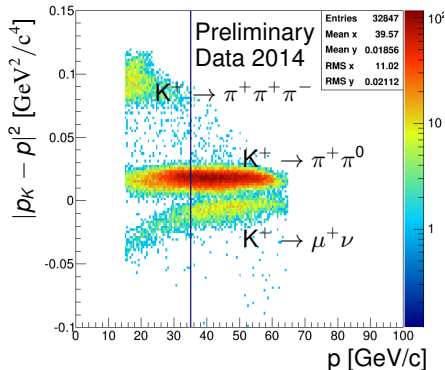
Reminder: No GTK

$p_\pi < 35 \text{ GeV}/c$



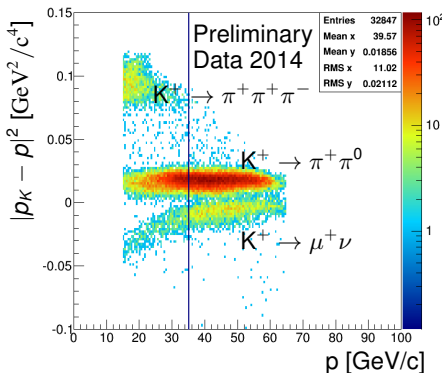
More Discriminating Power using RICH mass

K^+ in time with Track
not scattered

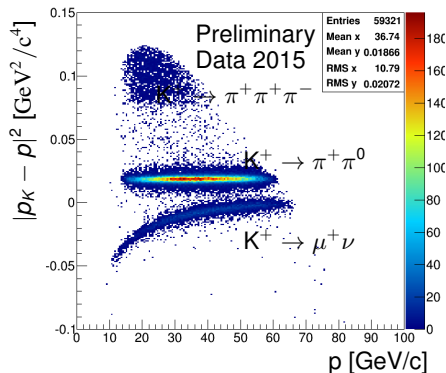


Improving kinematics with GTK - 2015

K^+ in time with Track
not scattered

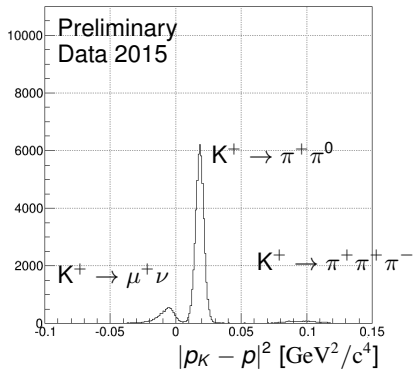


p_{K^+} from GTK

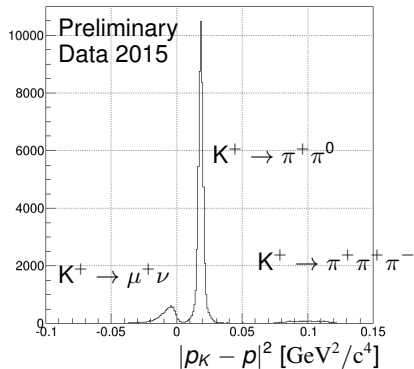


Improving kinematics with GTK - 2015

Without GTK
Full p range

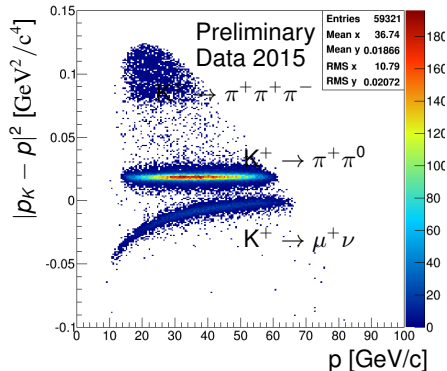
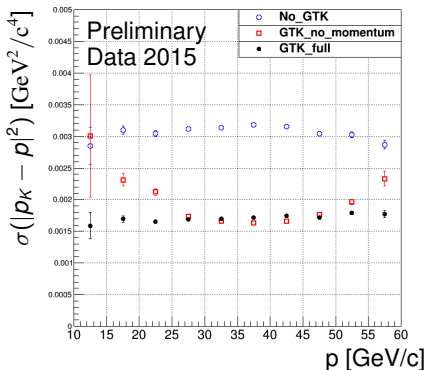


With GTK
Full p range



Improving kinematics with GTK - 2015

Missing Mass Resolution



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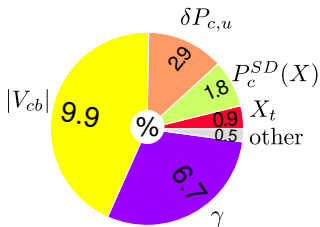
Conclusion and Prospects

- ▶ $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ 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