The NA62 Experiment

Seminar at CPPM, Marseille, France

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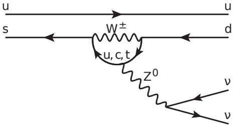
CERN, Geneva, Switzerland.

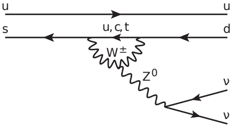
January 11, 2016

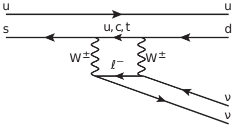
Outline

The physics case of $K^+ \to \pi^+\nu\bar{\nu}$

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







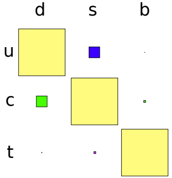
- Amplitudes proportional to $\left(\frac{m_q}{m_W}\right)^2 V^*_{qs}V_{qd}$, with $q = u, c, t$

- Mass and CKM terms compensate: both t and c contribute

- Very rare SM process [Buras, 1503.02693]

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

- And very clean...

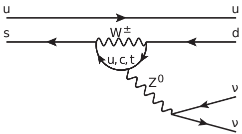


A word on Effective Field Theory

- Flavour observables are computed within EFT [Buras 9806471]
- EFT Virtue: separate short from long range pheno

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

Short Range



- Matrix elements bring normally large hadronic uncertainties
- Remaining uncertainties from Wilson coefficients,
- And external inputs

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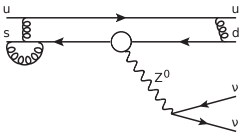
Long Range



- Matrix elements bring normally large hadronic uncertainties
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$K^+ \to \pi^+\nu\bar{\nu}$ in Effective Field Theory

$$\mathcal{H} = \frac{G_F}{2}\sum_i V^i_{CKM} C_i(\mu) Q_i(\mu)$$

Matrix Elements

- 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

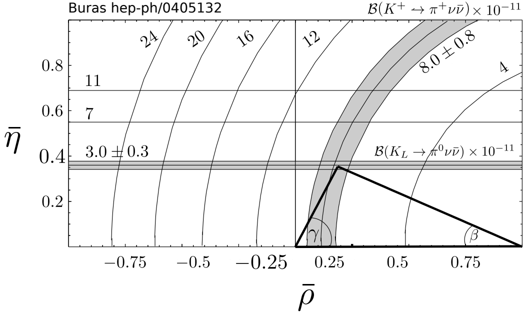
SM Predictions [Buras 1503.02693]

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

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

Testing the Standard Model

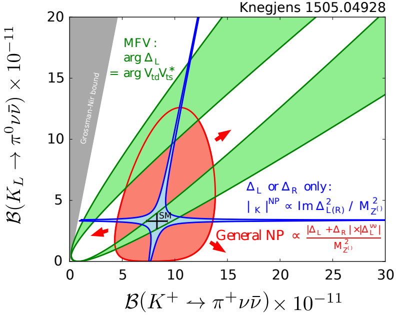
- $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$ with 10% uncertainties allows to determine $|V_{td}|$ at 9% [Buras 0405132]
- With $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$, $\mathcal{B}(\mathrm{K_L} \to \pi^0 \nu\bar{\nu})$ [1] the CKM unitarity triangle can be built independently from B observables:

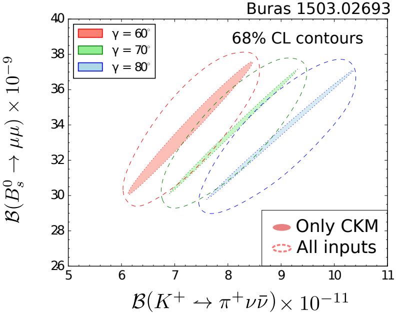


[1] KOTO: SM single event sensitivity by 2020

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





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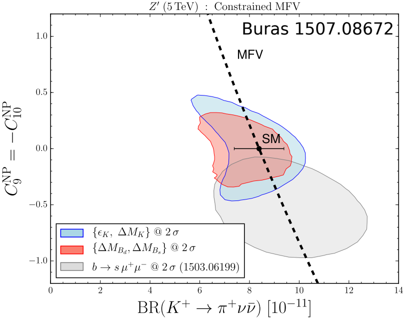
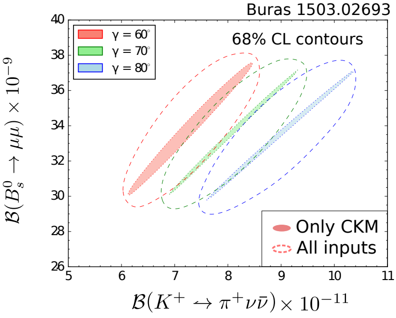
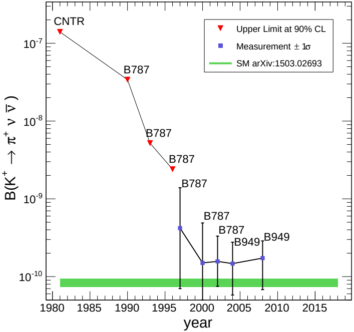




State of the Searches



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)

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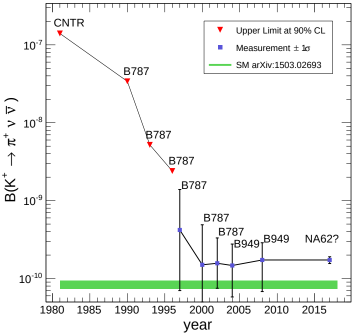
[2] $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11}$ Buras 1503.02693

State of the Searches



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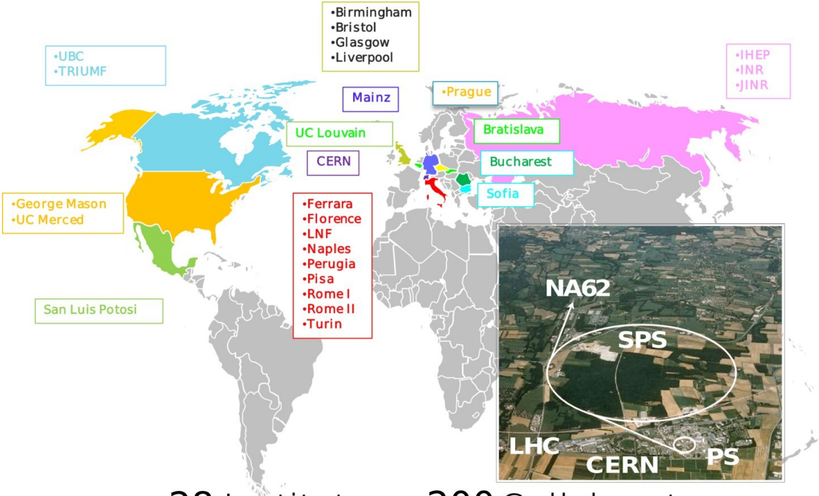
NA62 Goal

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

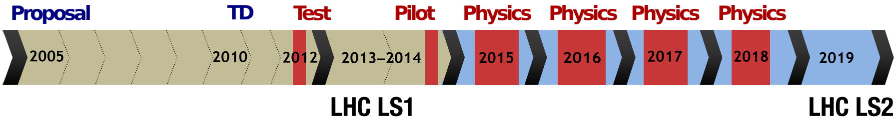
Outline

NA62 Collaboration



28 Institutes, ~200 Collaborators

NA62 Time Line



Reference Documents

2005 Proposal

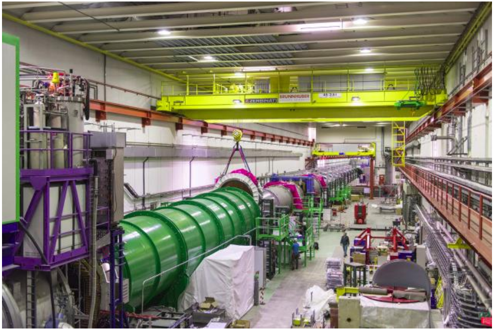
[CERN-SPSC-2005-013]

2010 Technical Design

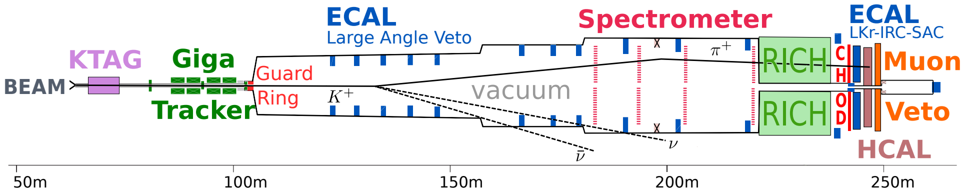
[NA62-10-07]

2014 Pilot Run

[G. Ruggiero, CERN Seminar]

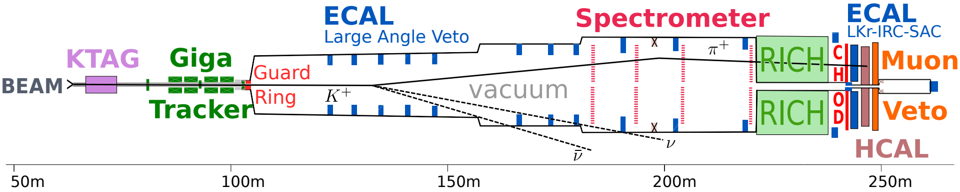


NA62 Apparatus



With HCAL and GTK completion in 2015 all detectors are installed

NA62 Apparatus

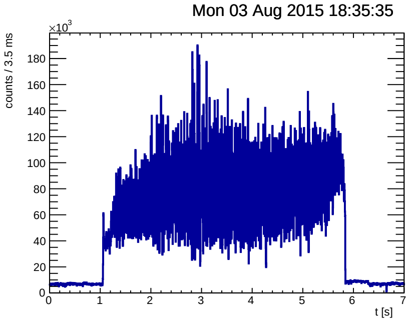


Secondary Beam from SPS

- 5s spill at 750 MHz
- Composition:

p	π^+	K^+
70	24	6%

- 75 GeV/c with $\delta p/p = 1\%$



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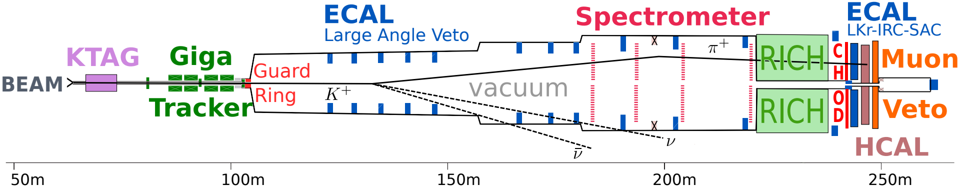
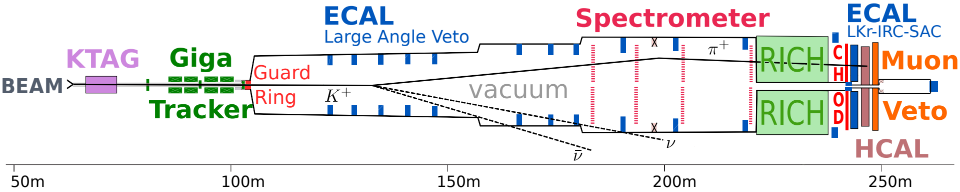


Beam Instrumentation

- 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

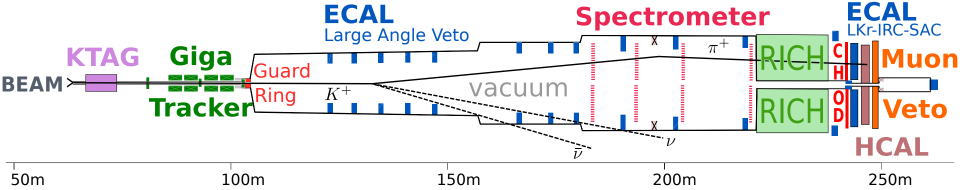


Decay Region

- 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

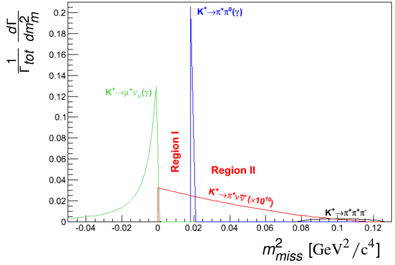
NA62 Apparatus



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



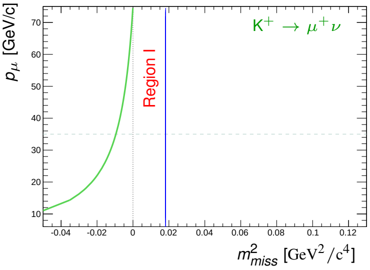
Background Sources

- 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}



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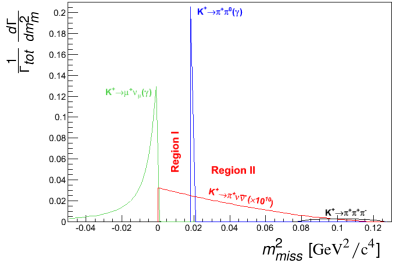
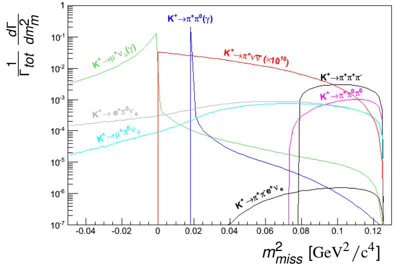
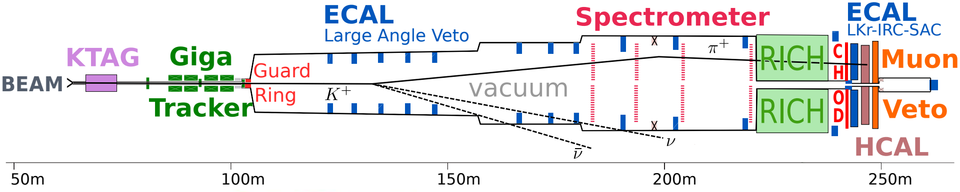




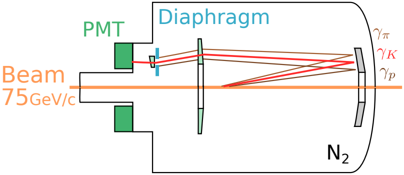
Analysis Sensitivity (MC)

Decay	event/year
$K^+ \to \pi^+\nu\bar{\nu}$(SM)	45
Total Background	10
$K^+ \to \pi^+\pi^0$	5
$K^+ \to \mu^+\nu$	1
$K^+ \to \pi^+\pi^+\pi^-$	< 1
$K^+ \to \pi^+\pi^- e^+\nu$ + other 3 track 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

KTAG - Kaon Identification and Timing

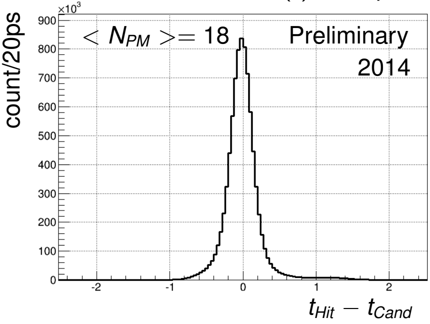


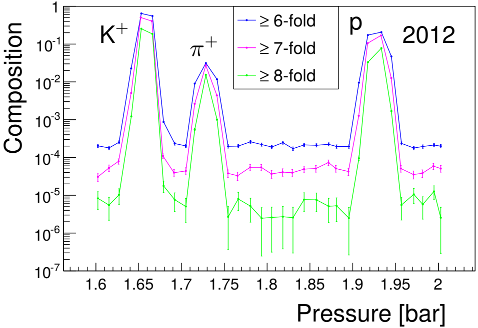
Differential Cerenkov Detector



KTAG - Performance

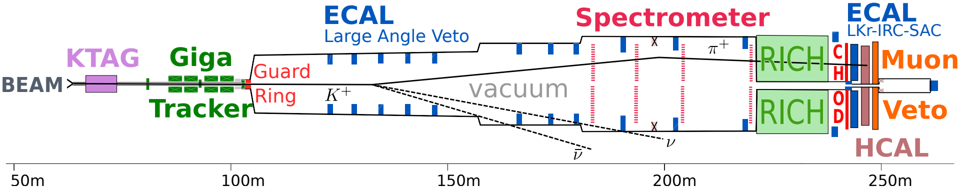
Time Resolution, $\sigma(t) \leq 80$ ps

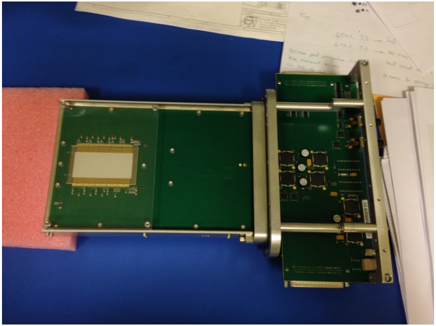




- K^+Identification $> 95\%$
- π^+, p Rejection $> 99.9\%$

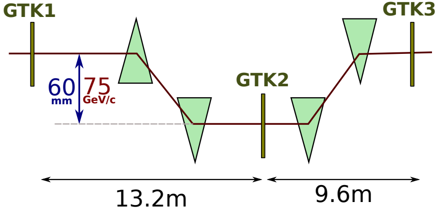
GTK - Beam Particle Kinematics and Timing





GTK3 in lab

Three Stations of Silicon Hybrid Pixel



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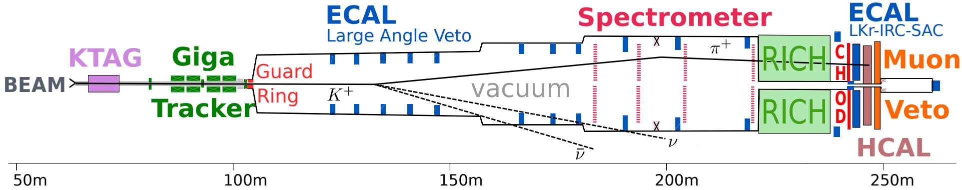

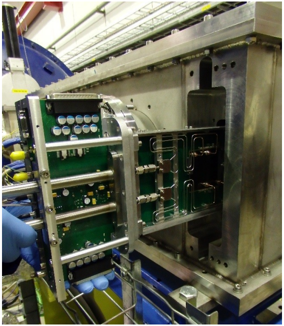

GTK3 being installed

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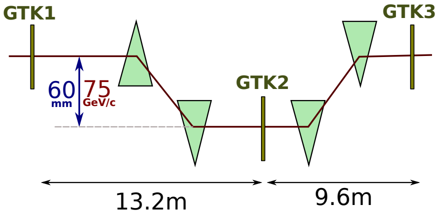
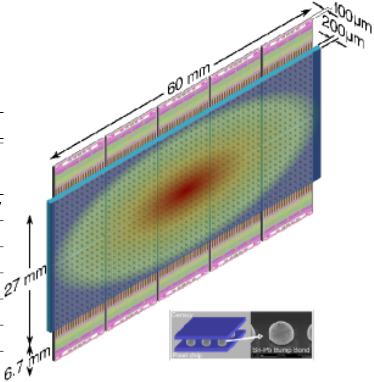


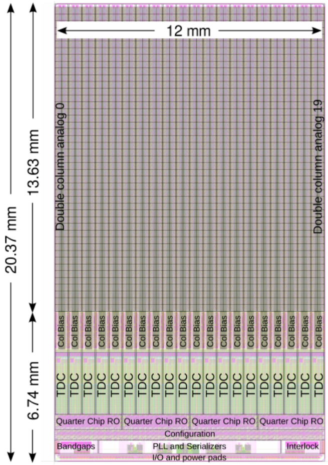
GTK - Design

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	$60\text{mm} \times 27\text{mm}$



- 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



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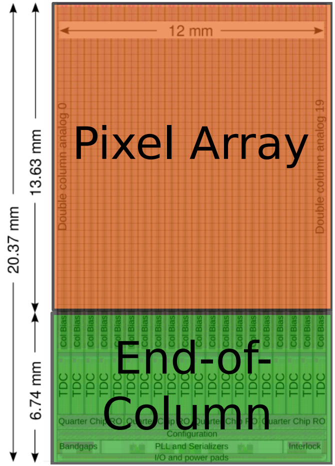

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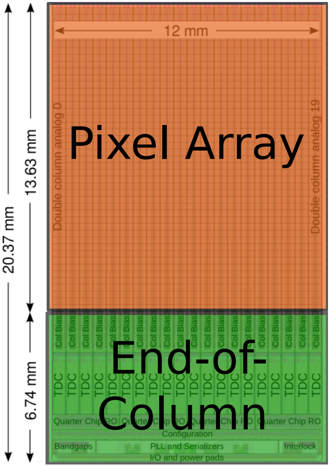

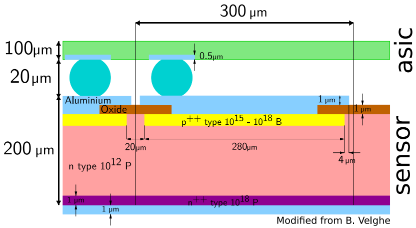

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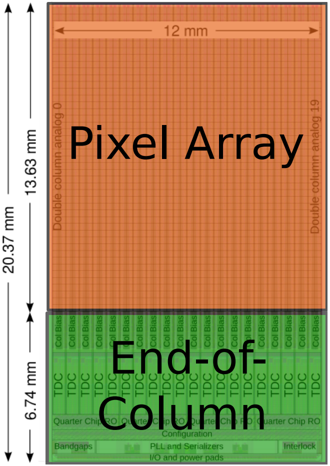

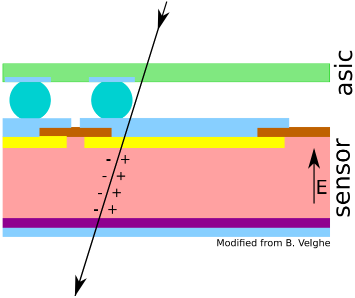

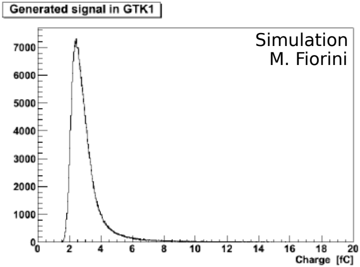

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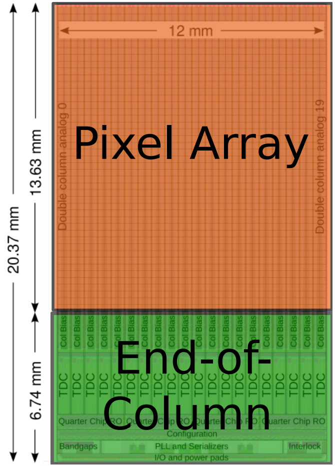

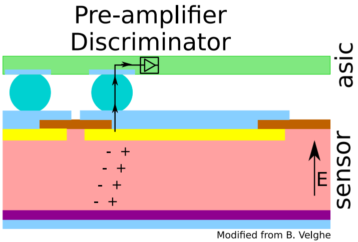

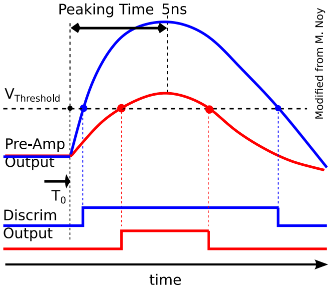

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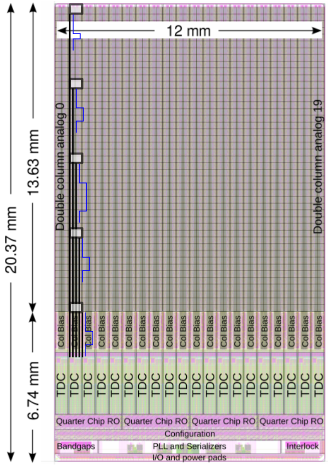
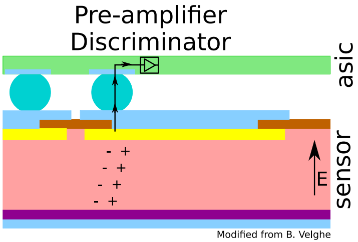
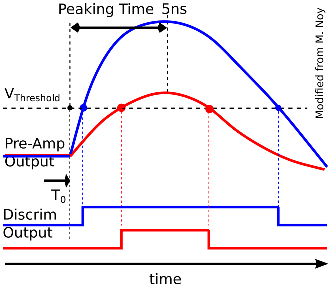
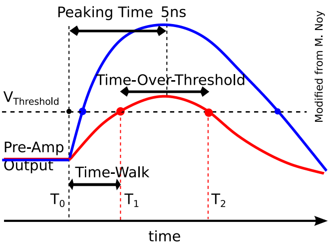


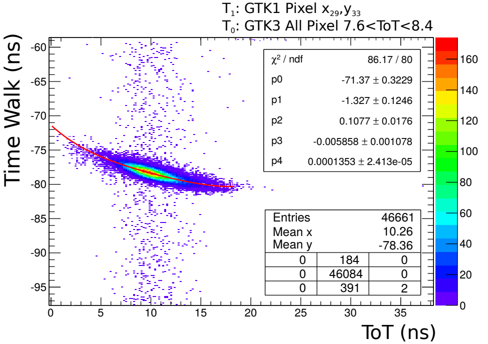




GTK - Time Measurement Principle

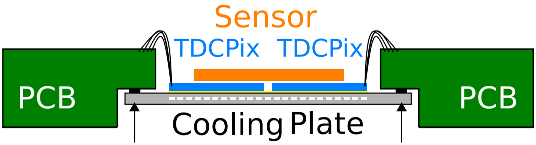
- At EoC, TDCs measure rising and falling edge time
- The full GTK integrates 21,600 TDCs in $<$25 cm^2!
- Use Time-over-Threshold to estimate time walk

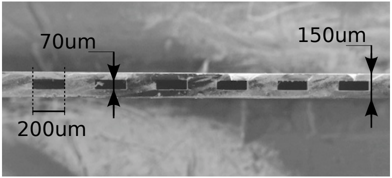




GTK - MicroChannels Cooling

- 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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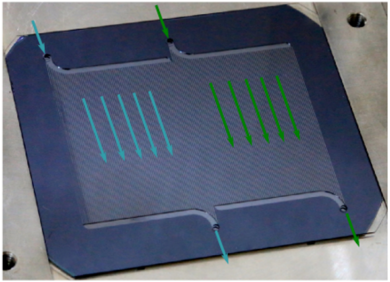
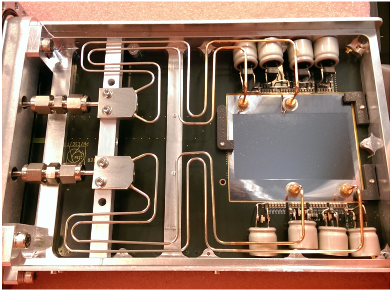
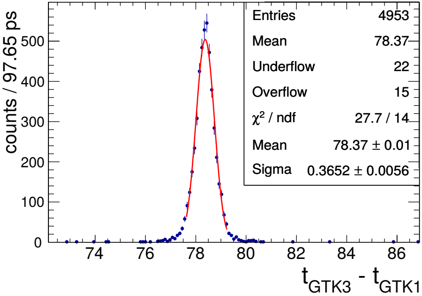


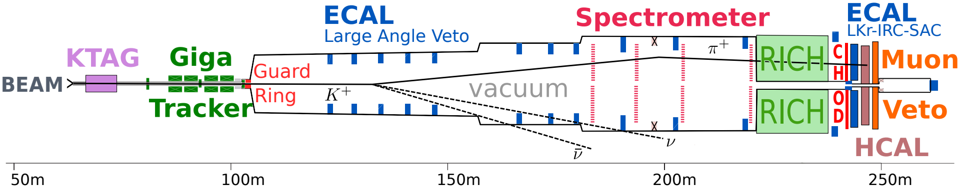


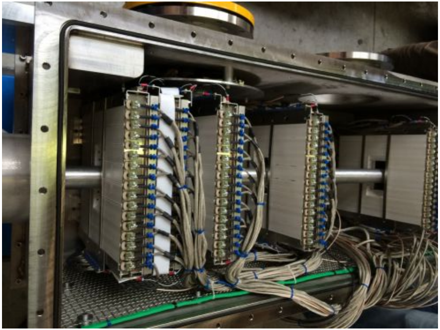
GTK - Status and Performance

- Three stations installed, (2 thinned at 100μm)
- 7-8 out of 10 chips per stations were working, fix next run
- Time resolution 260 ps per hit (at 200V instead of 300V) see First Data for kinematics performance

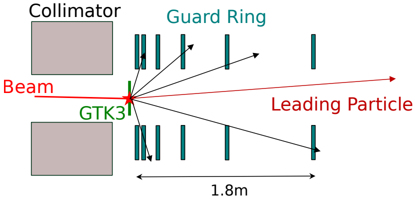


Guard Ring - GTK3 Scattered Particle Detection





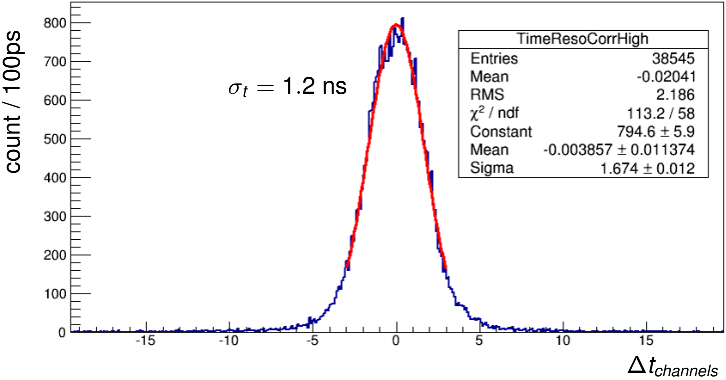
Five first Guard Ring stations during installation



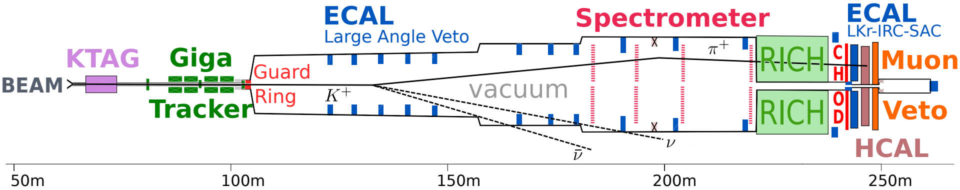
Specifications	
Rate	10-100kHz
Time Reso	1 ns

CHANTI - Design and Performance

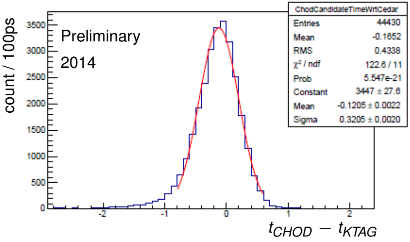
- 6 stations of scintillator+WLS fibres read with SiPMs
- Signal processed with TDC



CHOD - Charged Decay Product Timing

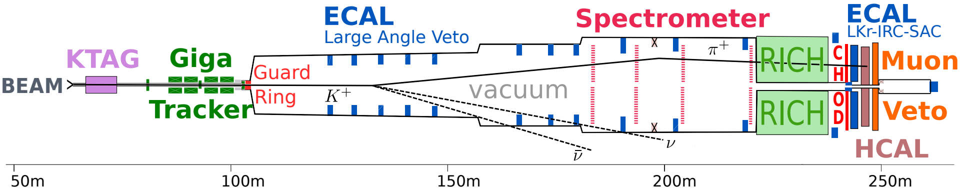


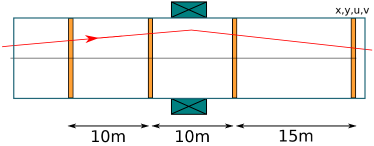
Time Resolution, $\sigma(t) \simeq 300$ ps



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

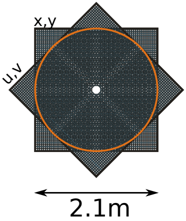
Spectrometer - Decay Products Kinematics





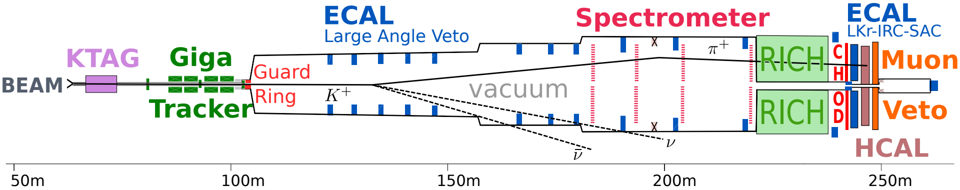
Spectrometer - Design and Status

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



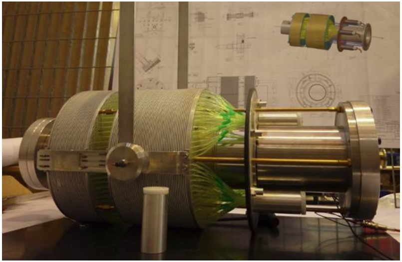
LAV Pb Glass - OPAL

$8.5 \to 50$ mrad

LKr NA48

$1 \to 8.5$ mrad

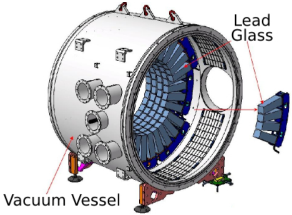
IRC (+ SAC) Shashlik type



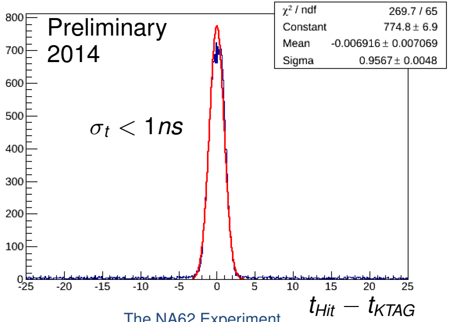
< 1 mrad: angular coverage

LAV: 8.5 $\rightarrow$ 50 mrad

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

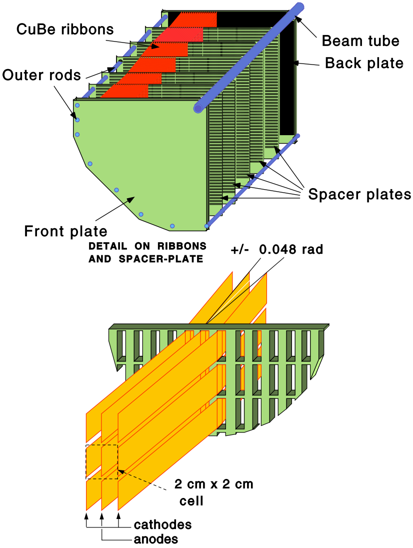


- 12 stations of 4-5 rings of staggered lead glass blocks

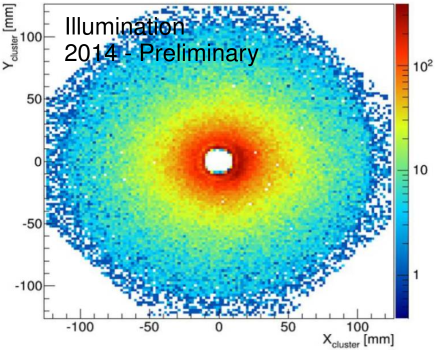


LKr: 1 $\rightarrow$ 8.5 mrad

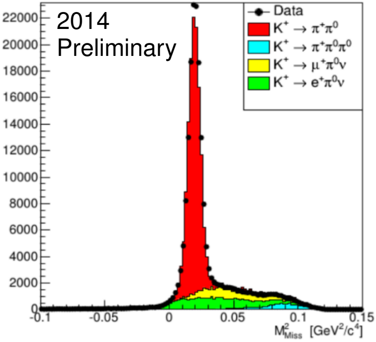
- Quasi homogenous liquid Kripton calorimeter from NA48
- Inefficiency measured in 2004 at 10^{-5} for $E > 10$ GeV
- Major RO upgrade: full LKr sampled at 40MHz with 14bits FADC



LKr - Performance

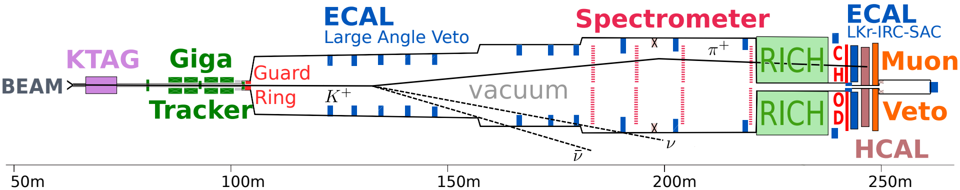


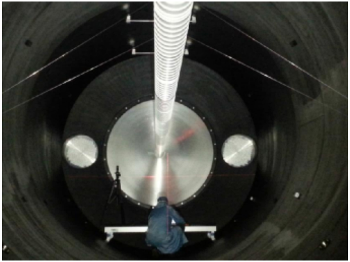
$|p_K - p_{\pi^0}|^2$



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

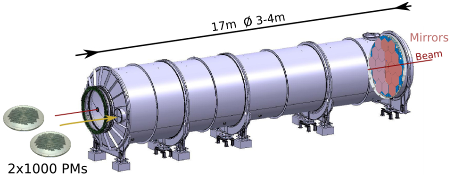
RICH - π, μ Identification



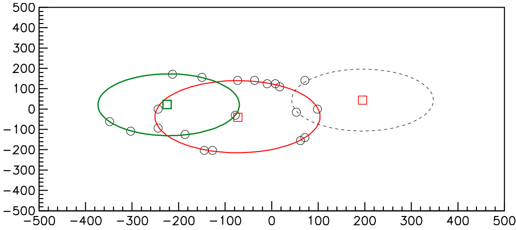


RICH - Design

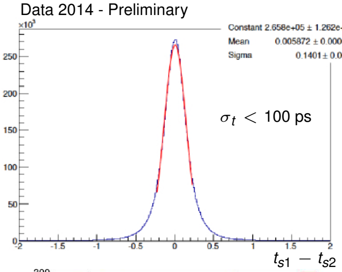
Specifications	
$\pi \to \mu$	$< 1\%$ for $p \in [15, 35]$ GeV
Angular Reso	$< 100\mu\text{rad}$
Time Reso	$<$ 100 ps RMS
Rate	10 MHz

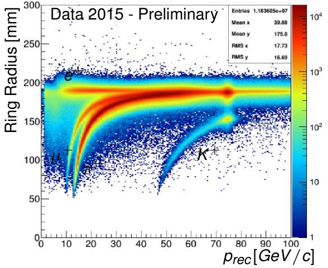


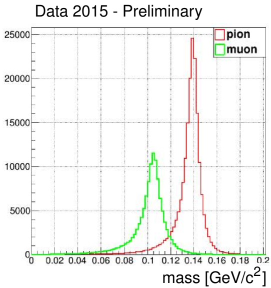
- Neon at 1 atm: $p^{\pi}_{Th} = 13GeV/c$
- 17m long vessel: ∼20 hits per ring
- Light reflected on two 1000 PM arrays read with TDC

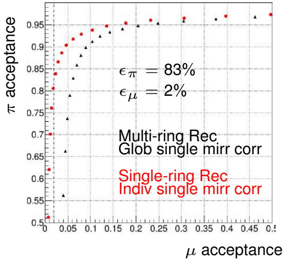


RICH - Performance

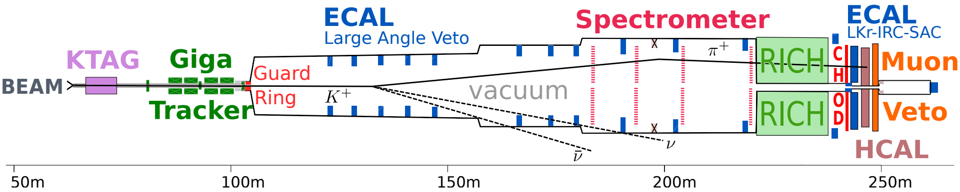






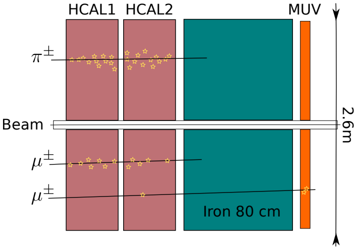


HCAL and MUV - π, μ Identification



HCAL 1 and 2

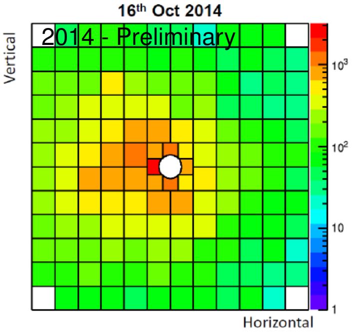
MUV - back

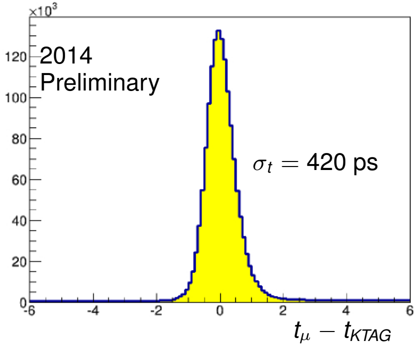


MUV - Design and Performance

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

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

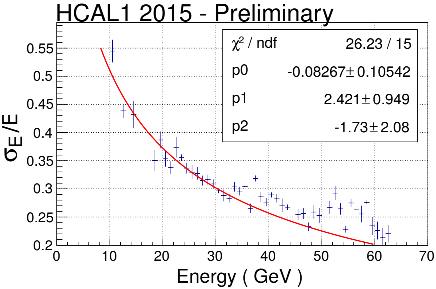


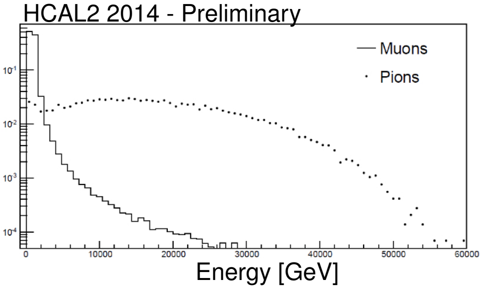


HCAL 1 and 2 - Design and Performance

- 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	$< 1ns$ RMS
Rate	10 MHz





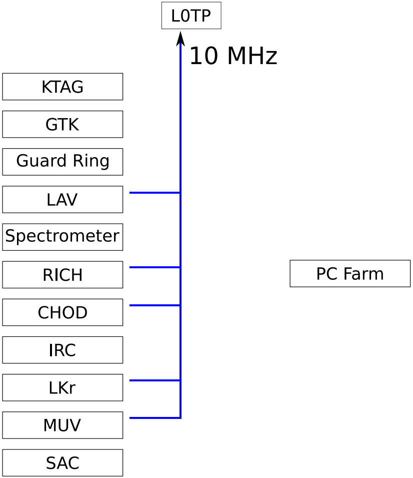
Digital Trigger System

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



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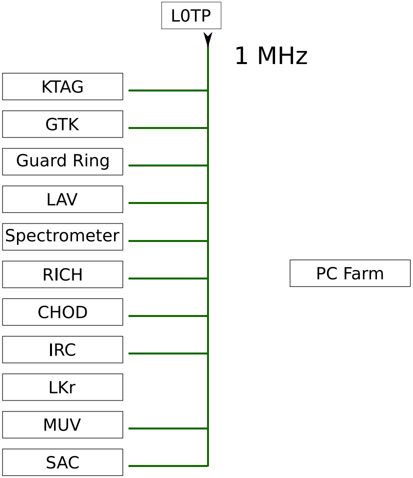

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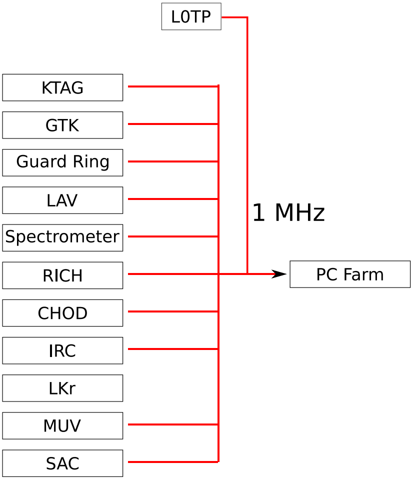

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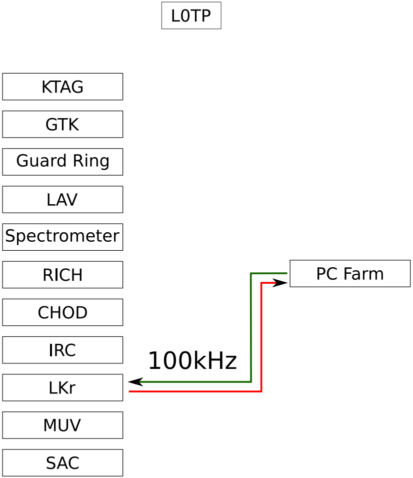

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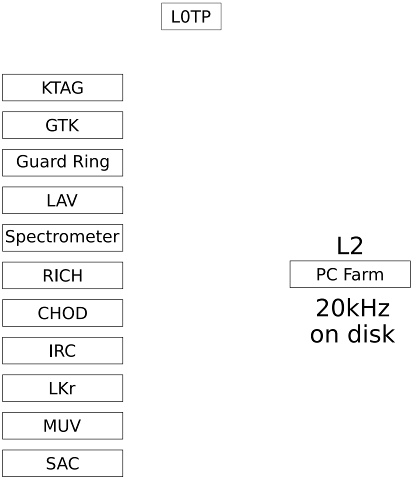
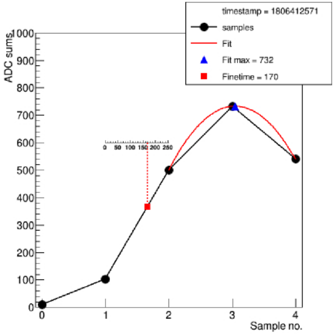


Calorimetric Trigger

- 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:

$$E^{tot}_{HCAL1} > 6\ \mathrm{GeV} \quad \& \quad E^{tot}_{LKr} < 4\ \mathrm{GeV}$$

Prospects for Next Run

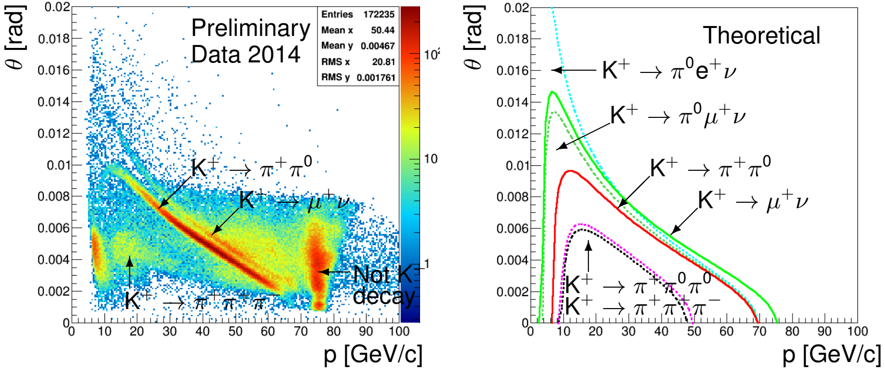
- LKr clustering in space (X and Y) at trigger level
- Trigger on individual LKr cluster instead of total energy

Outline

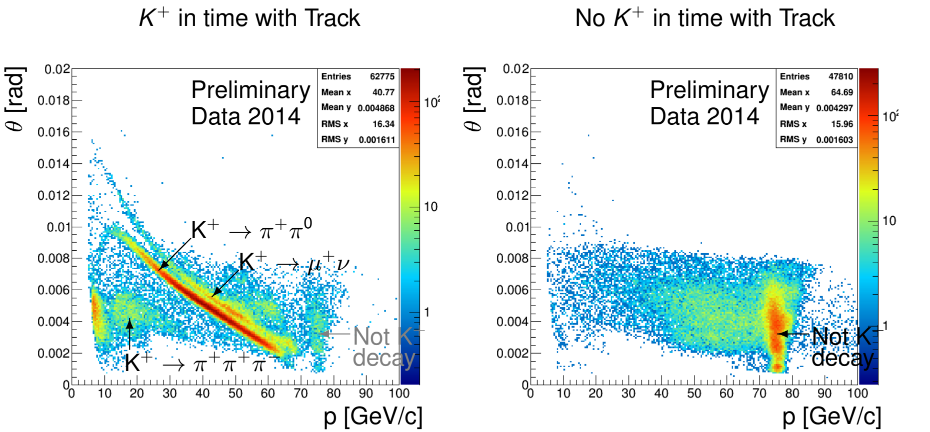
A look at min-bias 2014 and 2015 data

- 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

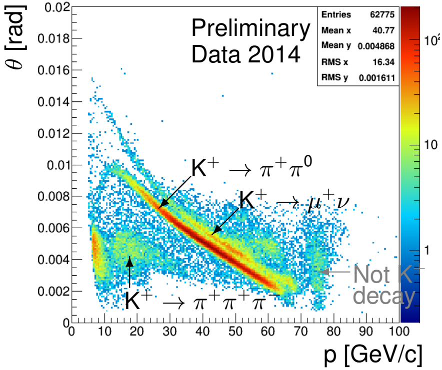


Requesting in Time Kaon with KTAG

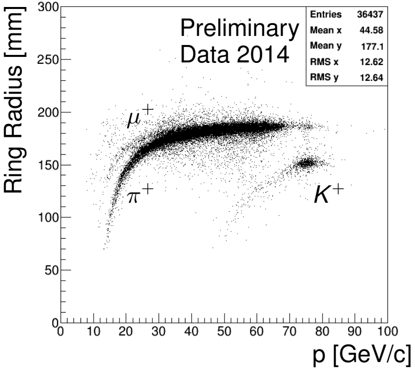


Checking Track Id using RICH

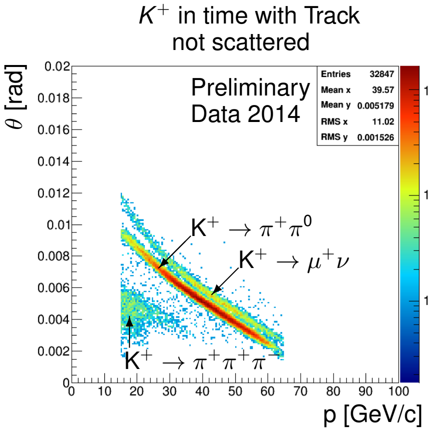
K^+ in time with Track

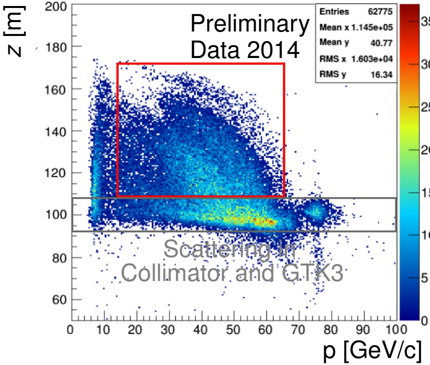


Matched Ring in RICH

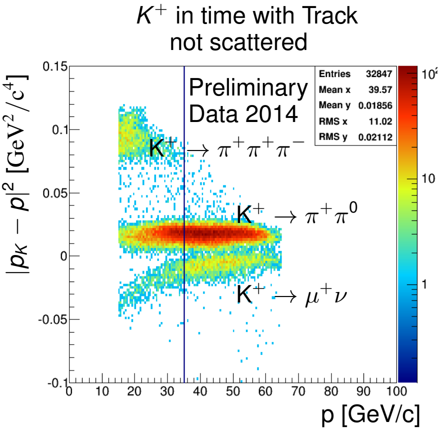


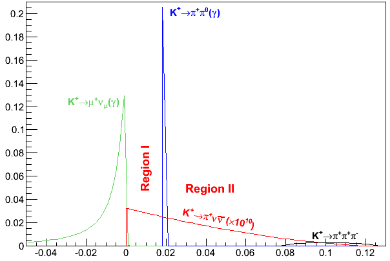
Removing Scattered Beam Particle Component





Squared Missing Mass





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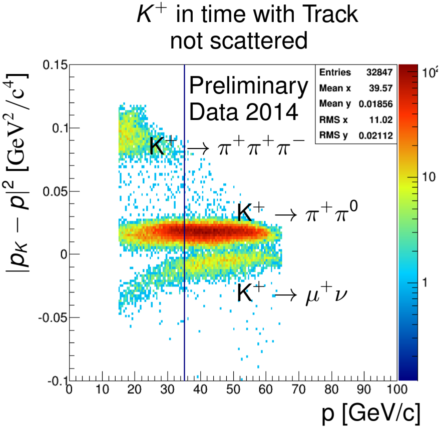
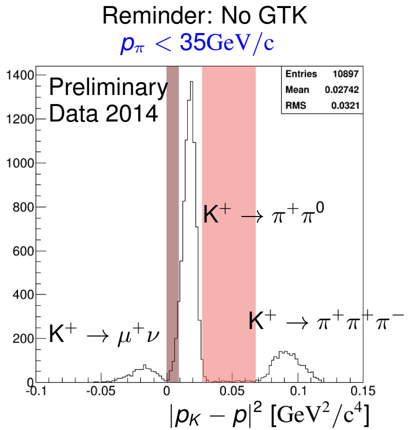
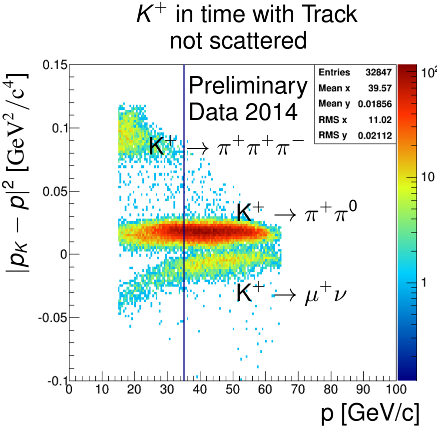
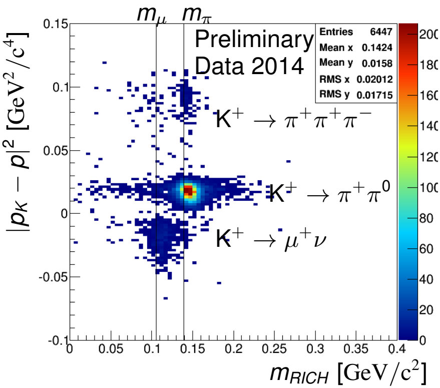




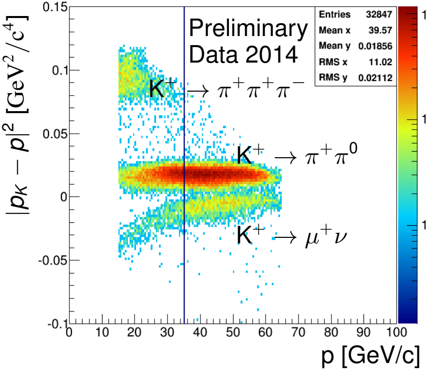
More Discriminating Power using RICH mass



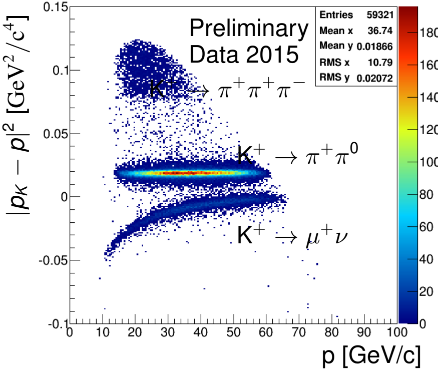


Improving kinematics with GTK - 2015

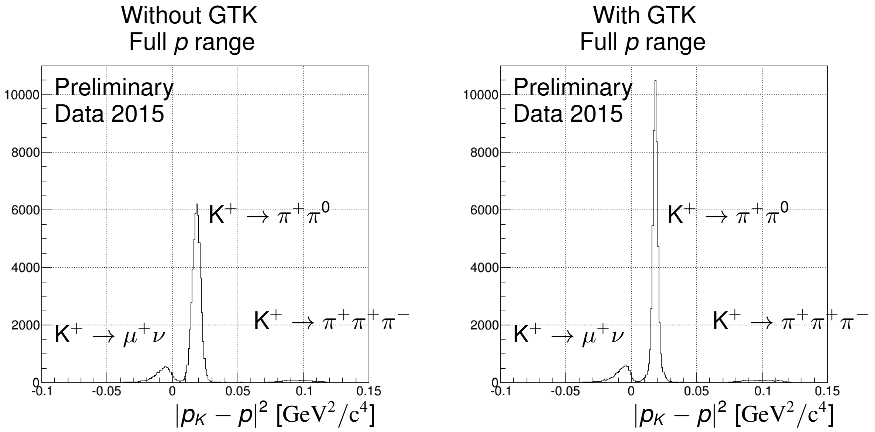
K^+ in time with Track
not scattered



p_{K^+} from GTK

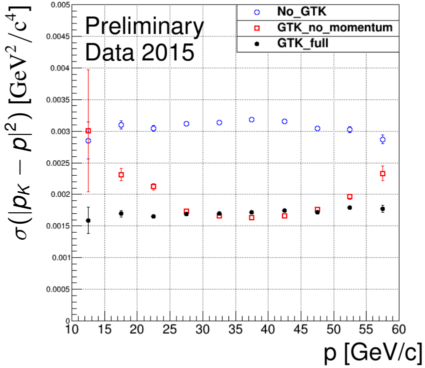


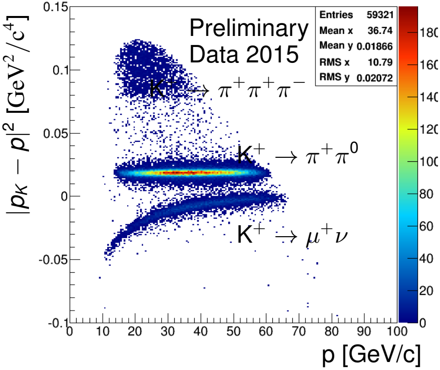
Improving kinematics with GTK - 2015



Improving kinematics with GTK - 2015

Missing Mass Resolution





Outline

A much broader 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	-	$O(10^5)$

keeping growing: axion search

Conclusion and Prospects

- $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ an important observable in LHC era
- NA62 apparatus installed and first data taken
- Data quality shows good performance
- Ready for 2-3 years of physics data taking

Thanks you for your attention.