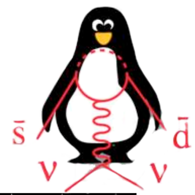
“International Workshop on the CKM Unitarity Triangle - CKM 2014”

Faculty of Electrical Engineering and Information Technology of the Vienna University of Technology

(September 8th – 12th)

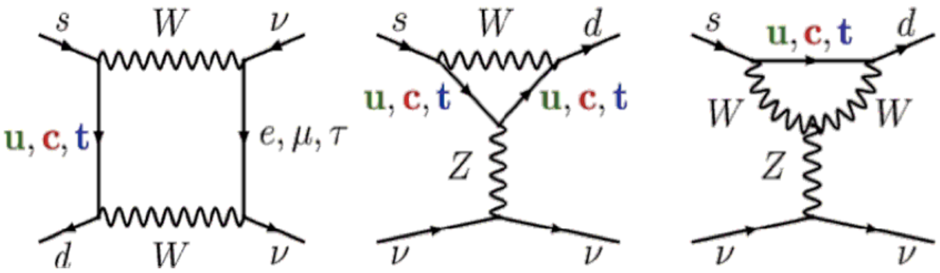
The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay in the NA62 experiment at CERN

Angela Romano, on behalf of the NA62 collaboration



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

Box & Penguin (one-loop) diagrams



✓High sensitivity to New Physics

✓FCNC process forbidden at tree level

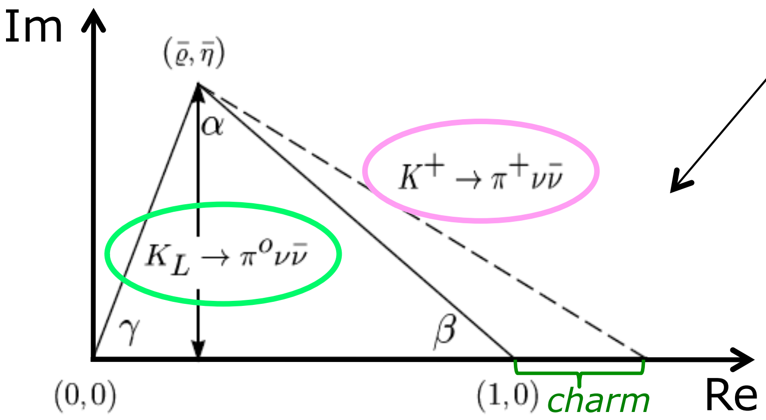
✓ Highly CKM suppressed (BR ~ $|V_{ts}{}^*V_{td}|^2$)

✓Extraction of V_{td} with minimal (few %) non-parametric uncertainty

Extremely precise theoretical predictions:

- (dominant) short-distance t quark part: NLO QCD and 2-loop EW corrections
- (small) c quark part: NNLO QCD and NLO EW corrections
- correction for long-distance contributions
- hadronic matrix element extracted from precisely measured BR($K^+ \rightarrow \pi^0 e^+ \nu$)

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



$BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$

[Brod, Gorbahn, Stamou: PRD 83 (2011) 034030]

1st error: CKM parametric, dominated by V_{cb}

2nd error: theoretical, mostly LD corrections

	Short distance	Irreducible error	BR_{SM}
$K_L \rightarrow \pi^0\nu\bar{\nu}$	>99%	2%	$2.4 \cdot 10^{-11}$
$K^+ \rightarrow \pi^+\nu\bar{\nu}$	90%	4%	$7.8 \cdot 10^{-11}$

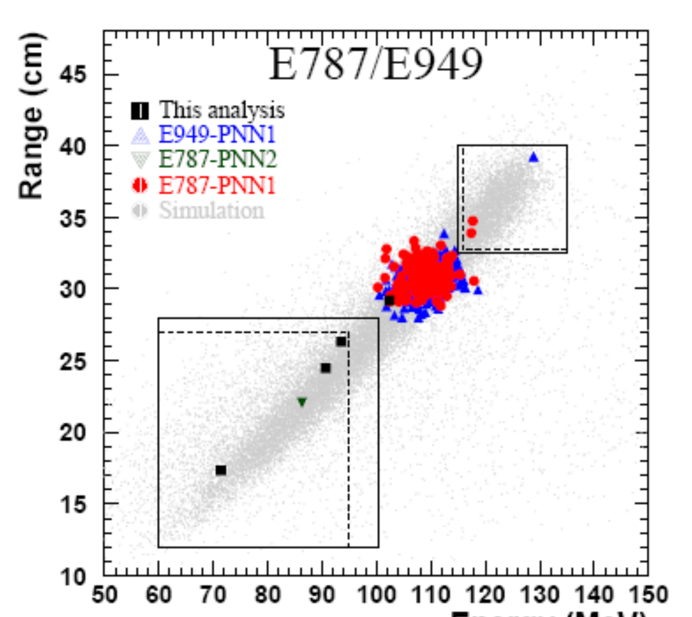
Experimental Status & NP Sensitivity

$BR(K^+ \to \pi^+ \nu\bar{\nu})_{THEORY} = (0.78 \pm 0.07) \times 10^{-10}$

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

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

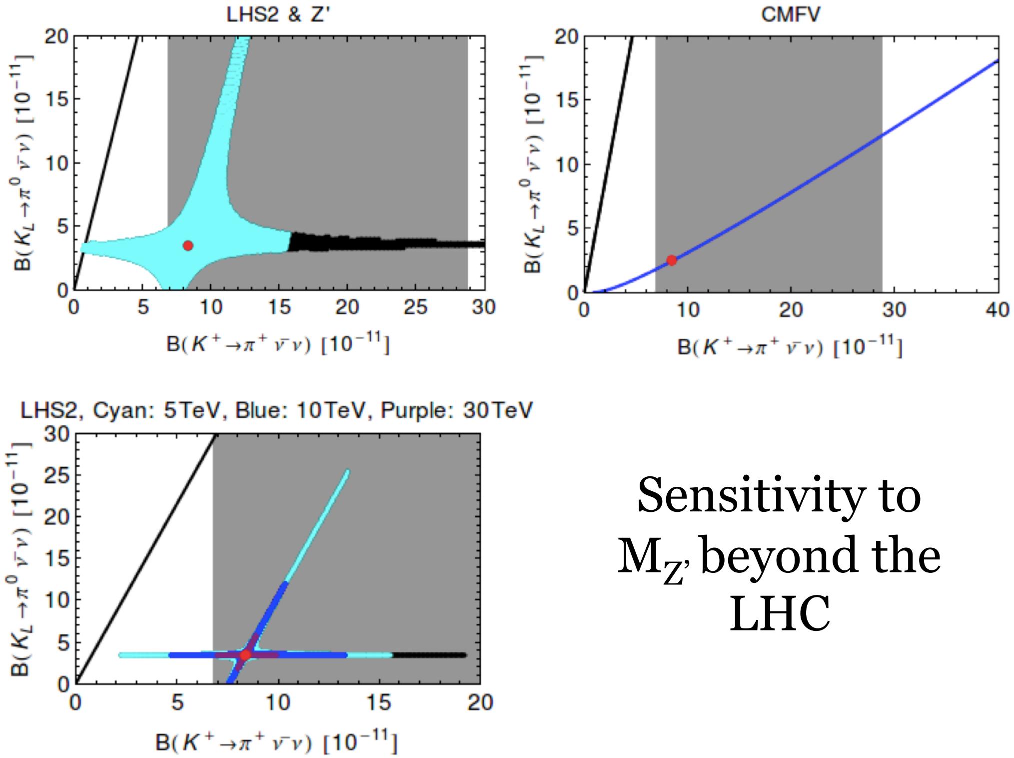
- based on 7 events
- stopped Kaon technique



(7 candidates E787+E949)

Discrimination among NP scenarios

[Buras et al., JHEP 1302 (2013) 116]



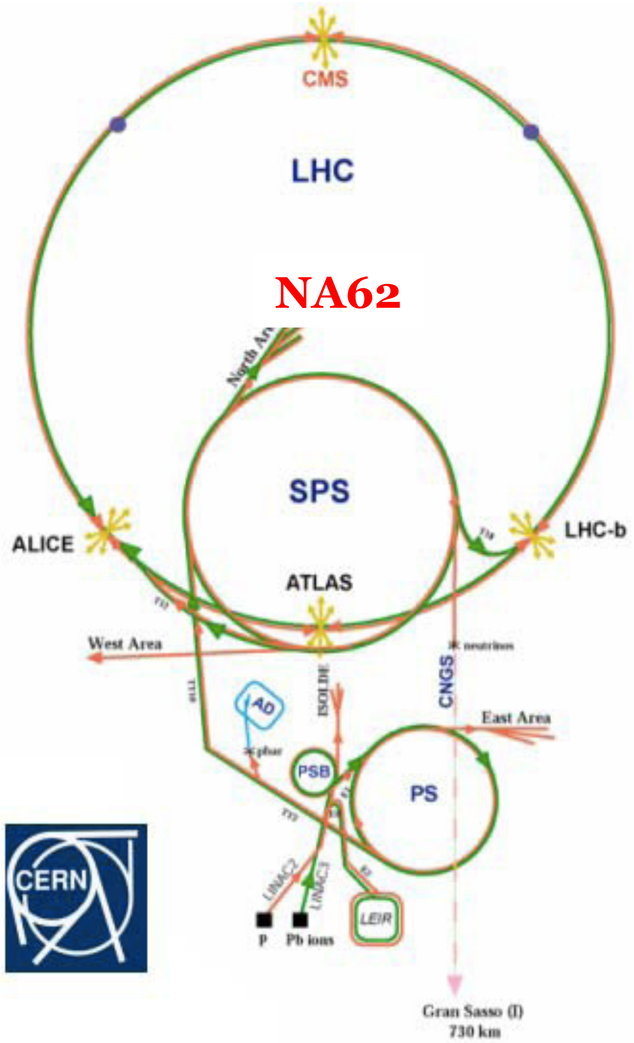
Sensitivity to $M_{Z'}$ beyond the LHC

$K \to \pi\nu\bar{\nu}$ probes of unique sensitivity for NP models among B and K decays

(NP searches complementary/alternative to LHC)

The NA62 experiment

Present-day **CERN** Kaon physics programme (fixed-target)



NA62 Timeline

Dec 2008 - NA62 Approval

2009 - 2012: detector R&D

Oct 2012 - NA62 Technical Run (partial layout)

2013 - 2014: detector installation

Oct 2014 - NA62 Pilot Run (full layout)

2015 - 2016 - 2017: Physics Runs

NA62 primary goal: Measure BR($K^+ \to \pi^+ \nu \bar{\nu}$) with 10% accuracy – collecting O(100) SM events in 3 years of data taking

The NA62 challenge

SM $BR(K^+ \to \pi^+ \nu\bar{\nu}) \sim 8 \times 10^{-11}$

KAON INTENSITY
- At least 10^{13} K^+ decays

SIGNAL EFFICIENCY
- Detector acceptance ~ 10%

→ Detect O(100) $K^+ \to \pi^+ \nu\bar{\nu}$ events in over 2 years of data taking

SIGNAL PURITY
- Background rejection > 10^{12} (<20% bkg)

DETECTOR REDUNDANCY
- Background known to ~10% precision

→ Signal/Bkg ~ 10
Measure $BR(K^+ \to \pi^+ \nu\bar{\nu})$ with a 10% accuracy

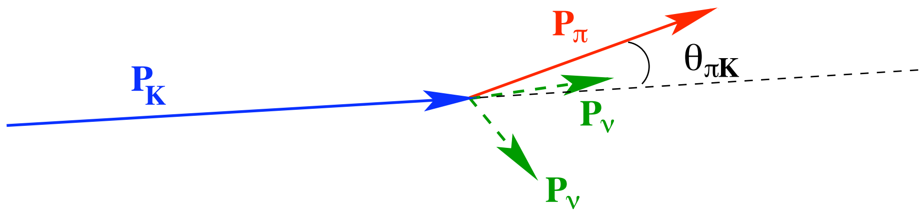
DECAY-IN-FLIGHT TECHNIQUE
- 75 GeV/c momentum beam - K/π/p

→ Help in background rejection (vetoes - PID)

Signal and Backgrounds

Signal $K^+ \rightarrow \pi^+\nu\bar{\nu}$:

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



Backgrounds: Kaon decays & Interactions

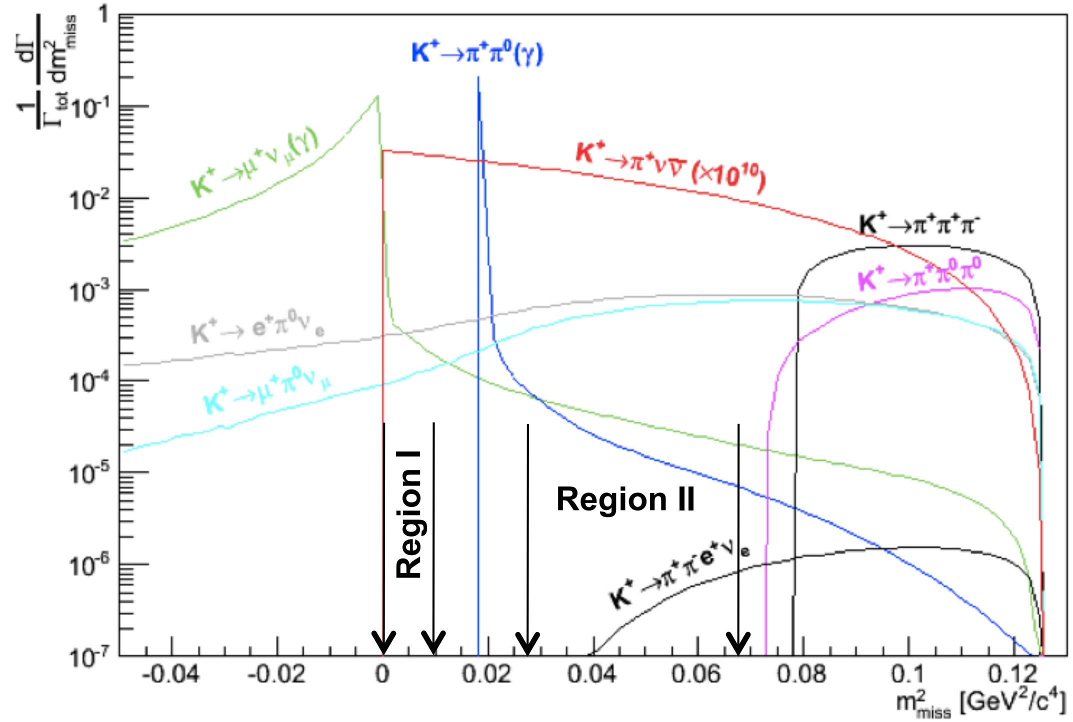
Decay backgrounds

Mode	BR
$\mu^+\nu(\gamma)$	63.5%
$\pi^+\pi^0(\gamma)$	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^0 e^+\nu$	5.1%
$\pi^0\mu^+\nu$	3.3%
$\pi^+\pi^- e^+\nu$	4.1×10^{-5}
$\pi^0\pi^0 e^+\nu$	2.2×10^{-5}
$\pi^+\pi^-\mu^+\nu$	1.4×10^{-5}
$e^+\nu(\gamma)$	1.5×10^{-5}

Other backgrounds

Beam-gas interactions

Upstream interactions



Rejection relies on kinematic reconstruction (m^2_{miss}) used in conjunction with PID and veto systems.

The NA62 Beam line

✓Primary SPS protons on beryllium target

✓P = 400 GeV/c

✓~ 3 x 10^{12} protons/pulse

✓Secondary (unseparated) hadron beam
π / K / p

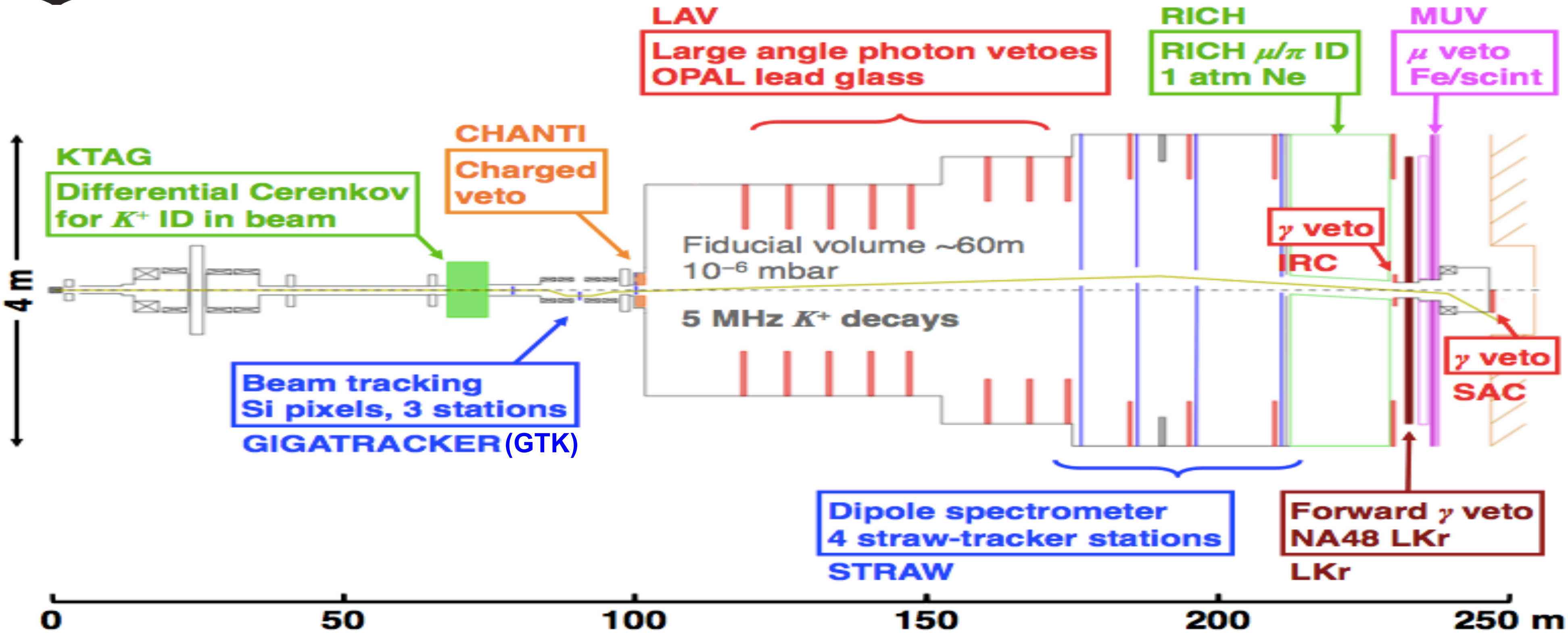
✓p = 75(±1%) GeV/c

✓Total rate ~750MHz (K component ~ 6%)

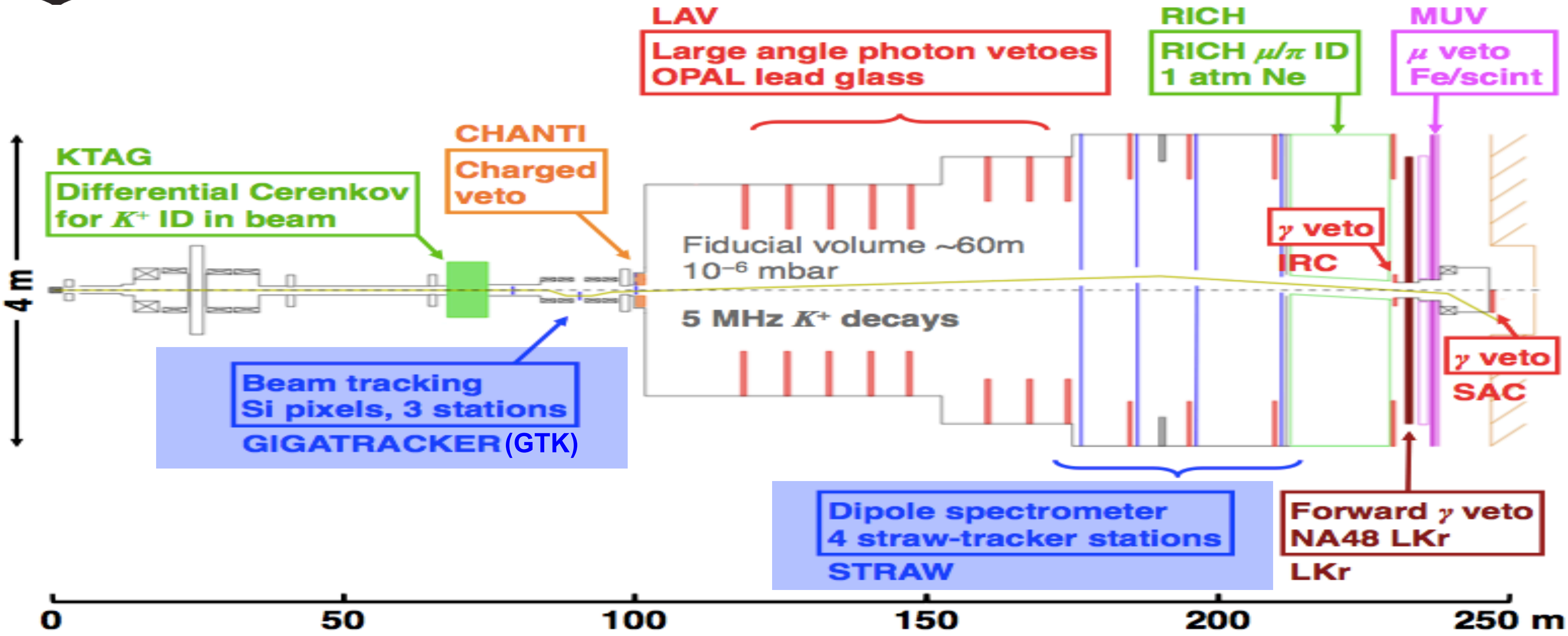
✓10% of K decays in 60m fiducial volume

✓4.5 x 10^{12} K decays/year

The NA62 Detector

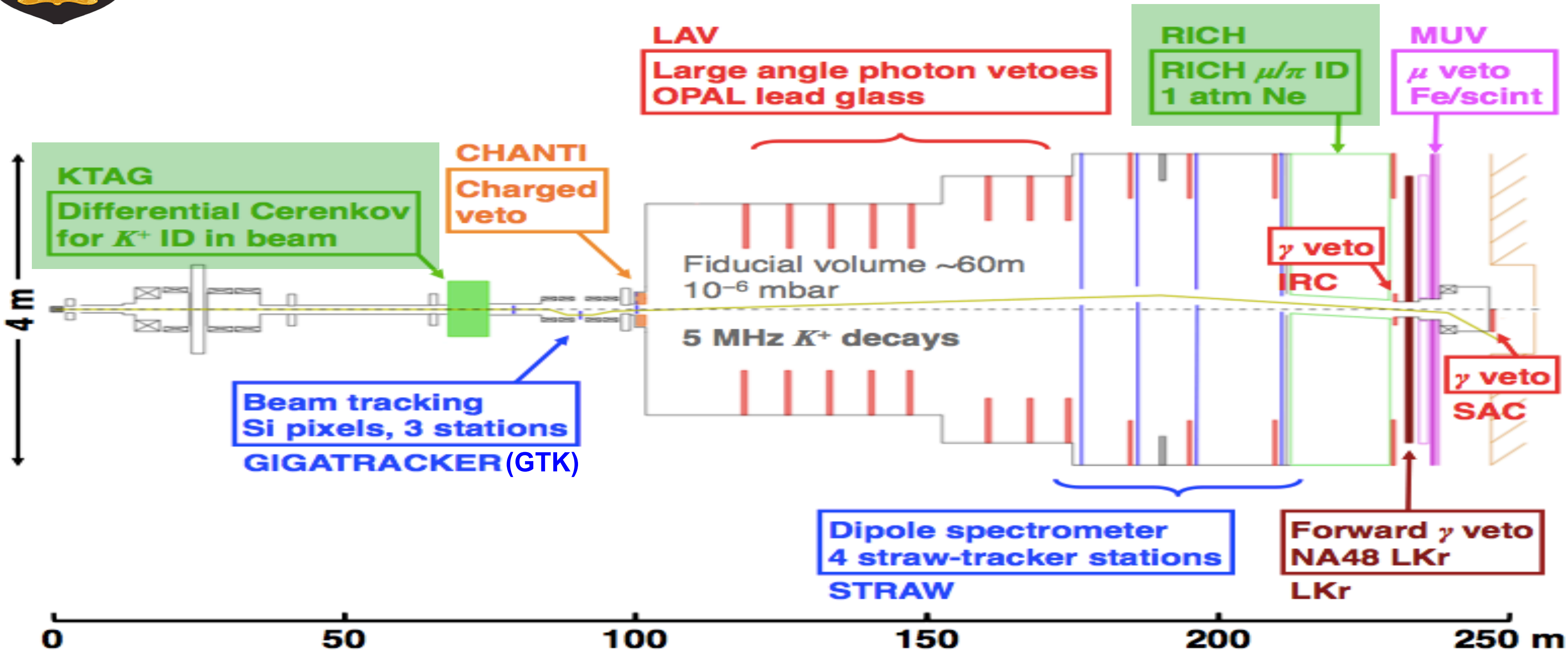


The NA62 Detector



Track reconstruction: P_K (GIGATRACKER, also called **GTK), P_π (STRAW)**

The NA62 Detector

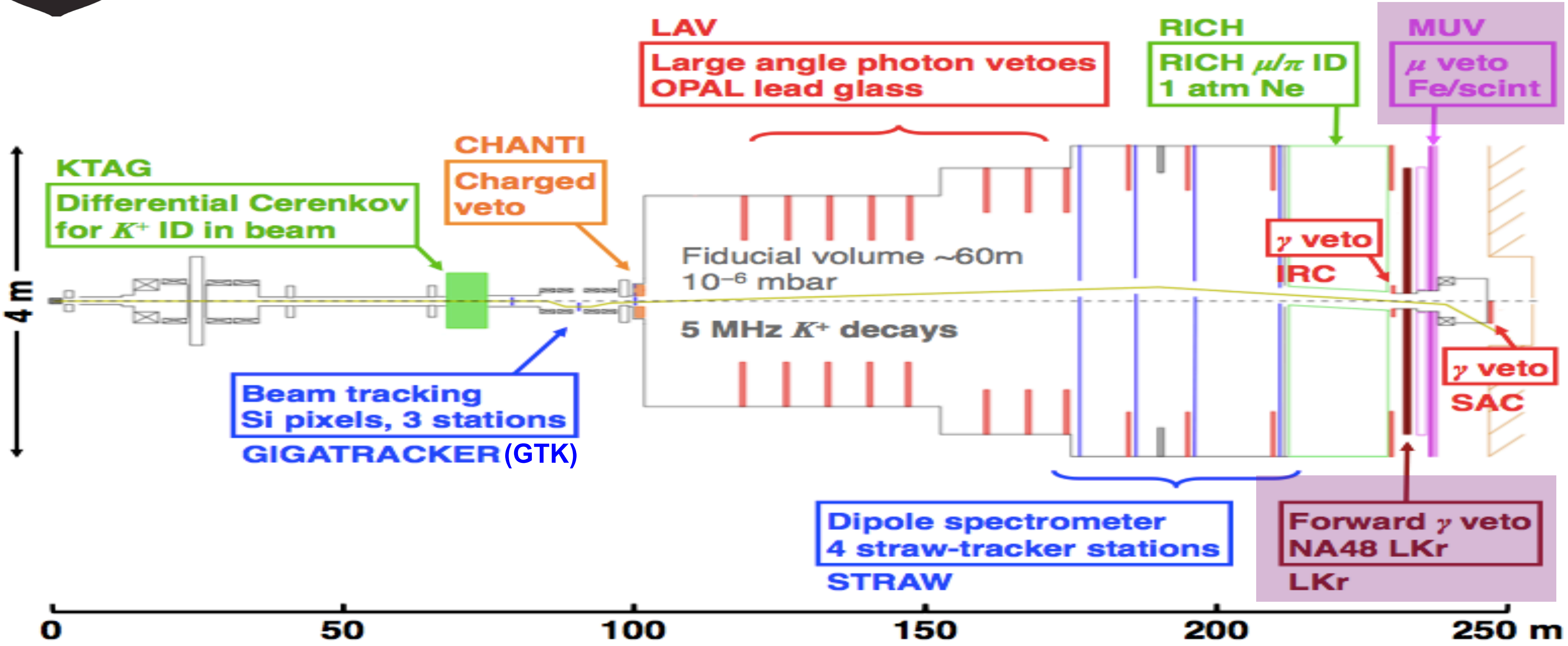


Background suppression:

PID K/π/p for bkg coming from accidental tracks (KTAG)

PID π/μ for main (BR~64%) bkg K->μν (RICH)

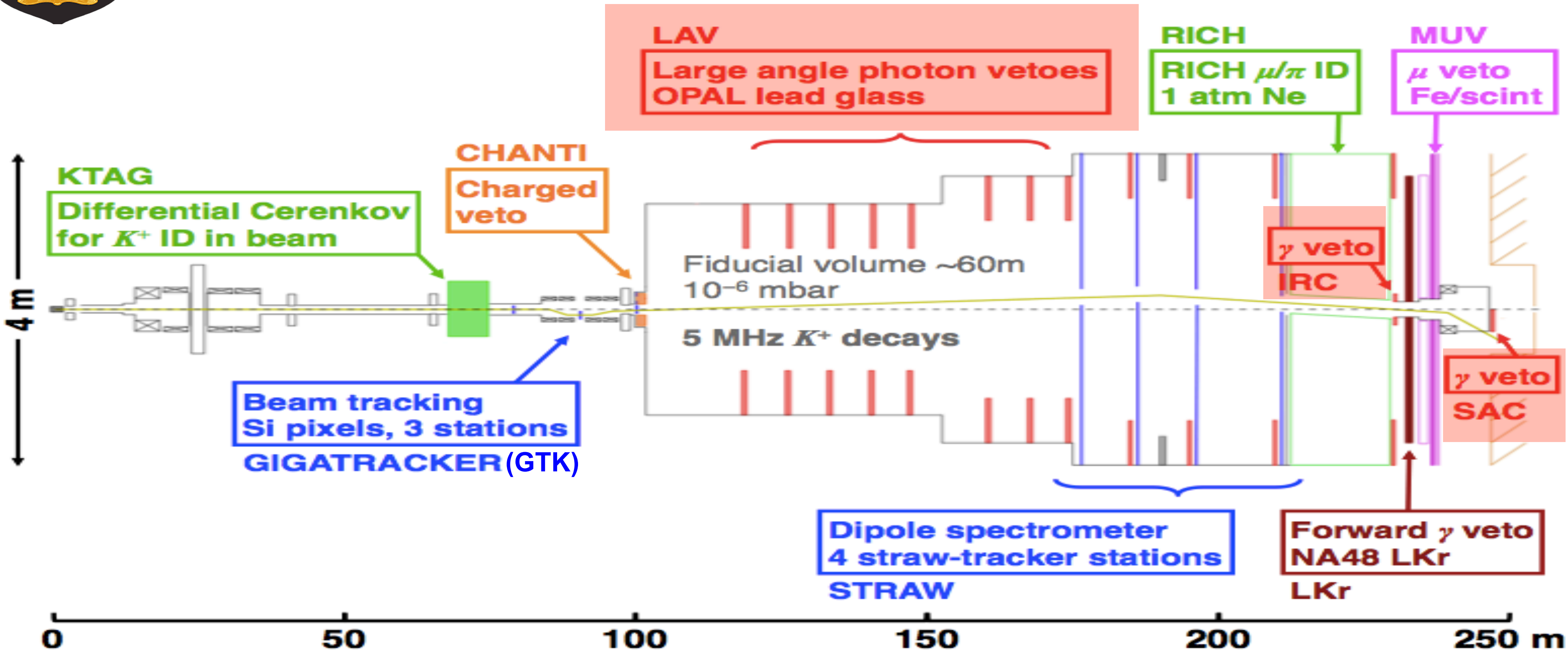
The NA62 Detector



Background suppression:

μ/e separation for bkg with leptons in final state (LKr, MUV)

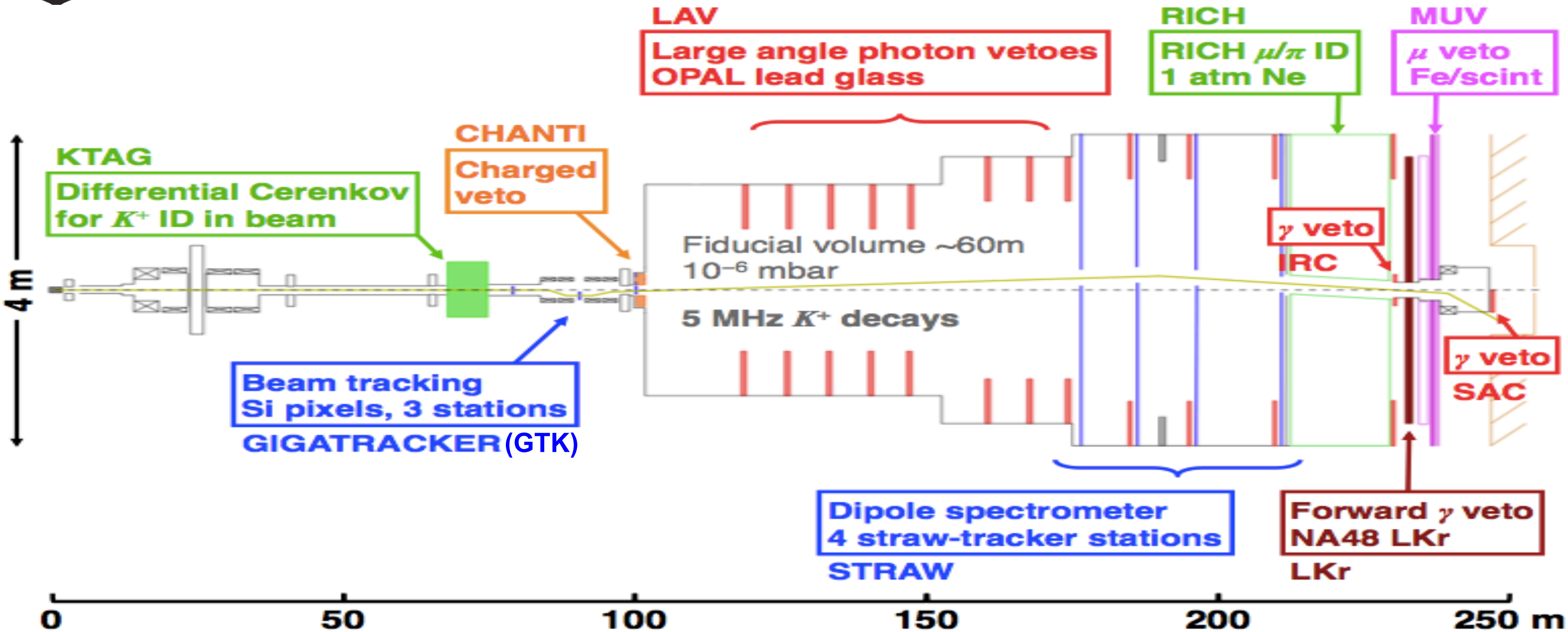
The NA62 Detector



Background suppression:

Photon rejection for bkg with γs in final state (LAV, IRC, SAC)

The $K^+ \to \pi^+ \nu \bar{\nu}$ selection

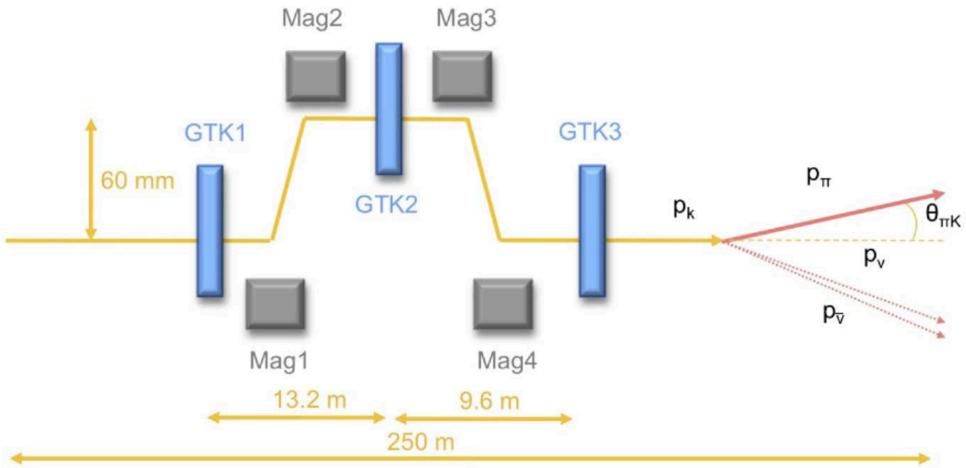


Event reconstruction:

- ✓ single π^+ in final state (RICH, LKr, MUV)
- ✓ K^+ - π^+ time association (GTK, RICH, KTAG),
- ✓ m^2_{miss} reconstruction for signal definition,
- ✓ 15 GeV/c < P_π < 35 GeV/c (>40GeV missing energy)

Beam Reconstruction

GIGATRACKER (GTK)



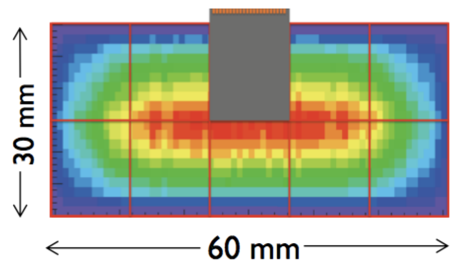
Spectrometer layout

- 3 stations of hybrid silicon pixel detectors
- 4 achromat magnets (beam displacement ~60mm)
- 18, 000 pixels/station of size 300 × 300 μm²

P_K momentum and position: **GTK**
K^+ timing: **GTK** and **KTAG**

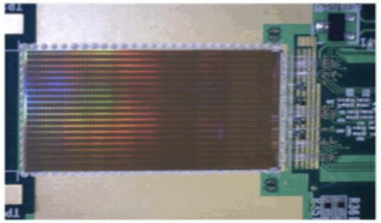
Tracking of K^+:

- high and non-uniform beam rate @ GTK (750 MHz)



- minimal amount of material X/X0 < 0.5%/station
- σ_t~ 200 ps match the π tracking info from downstream detectors

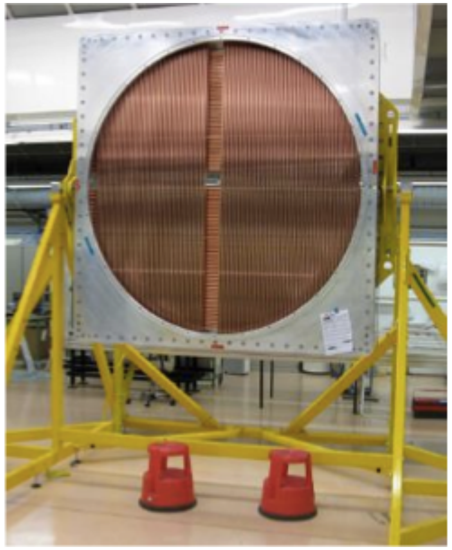
bump-bonded chips on sensor



- σ_p/p ~ 0.2% and σ_θ = 16 μrad

Pion Reconstruction

STRAW



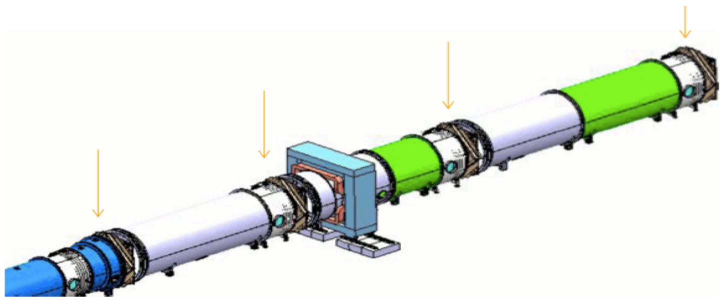
Tracking of secondary charged particles:

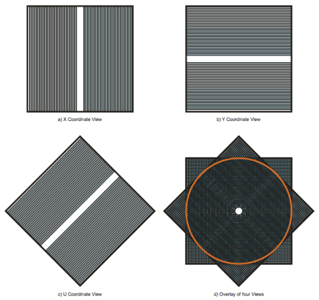
- operation in vacuum;
- ultra-light material X/X0 ~ 0.1%/"View"
- spatial resolution $\sigma \leq 130\mu m$ (1 "View")
- $\sigma_p/p \sim 0.32\% \oplus 0.008\%\, p$ [GeV/c]
- $\sigma_{\theta(K\pi)}$ = 20-50 μrad

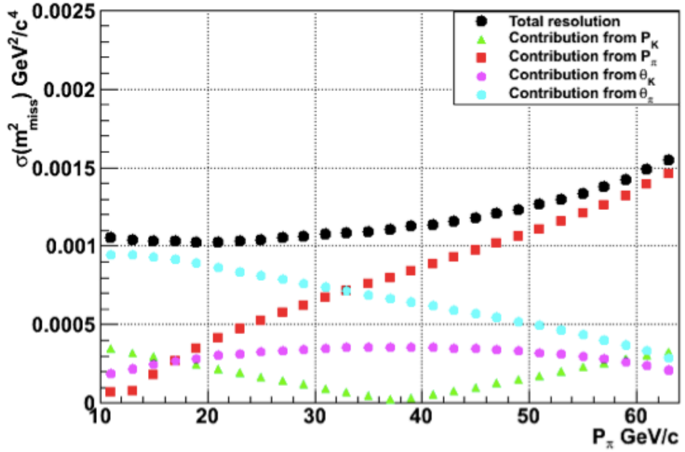
P_π momentum and position: STRAW
π^+ timing: RICH

Spectrometer layout

- high aperture dipole magnet (B-field ~ 0.36 T; $\Delta p_\perp$ = 270 MeV)
- 4 straw-tube chambers (2.1 m in diameter)







- 1,792 straw tubes/chamber (16 layers - 4 "Views")

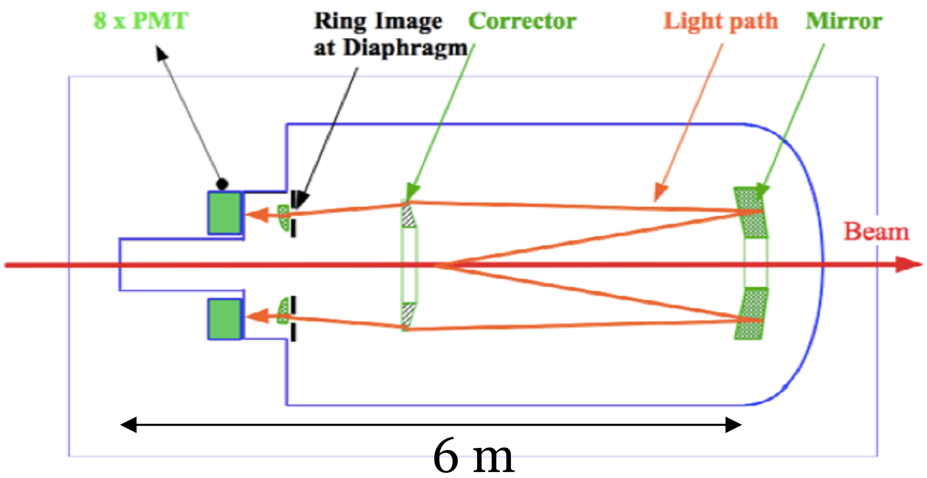
Kaon ID – Beam Timing

Kaon ID

to suppress background from particle interactions with material on the beam line

Beam Timing

to match upstream info from GTK (~750MHz) with downstream π detection(~10MHz)



K^+ ID and tagging under conditions:

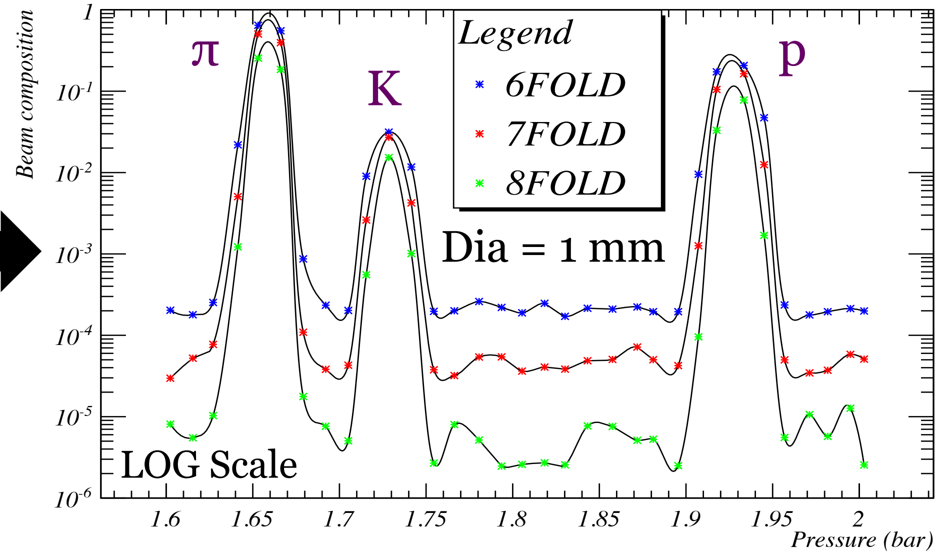
- High-intensity hadron beam (~750 MHz)
- K beam composition ~ 6% (~45MHz)
- Cherenkov light yield ~ 200 γ /K (~ few MHz/mm²)

KTAG layout and principles:

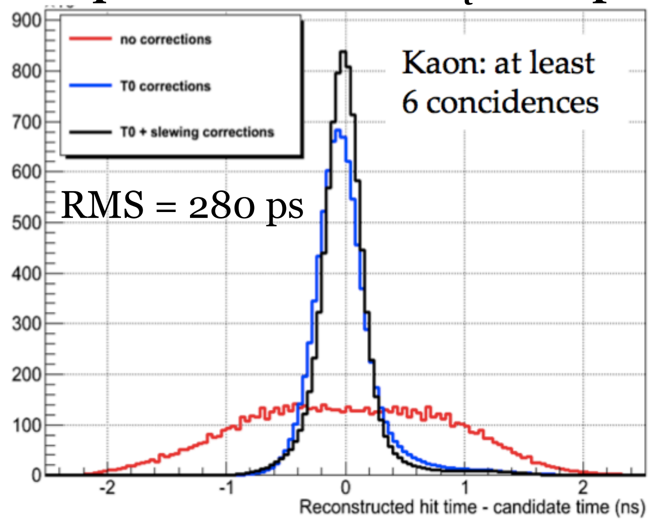
- Original CEDAR counter used at CERN SPS for secondary beam tagging
- Vessel filled with gas (H2 or N2) of controlled pressure
- Insensitive to pion and protons (95% K efficiency, sub-percent pion mis-tag)
- New external optics, PMTs, front-end and readout
- Kaon tagging with σ_t < 100 ps time resolution

KTAG Tests & Results

✓ Hadron beam @ 75 GeV (~40KHz)
✓ Beam composition from Pressure scan

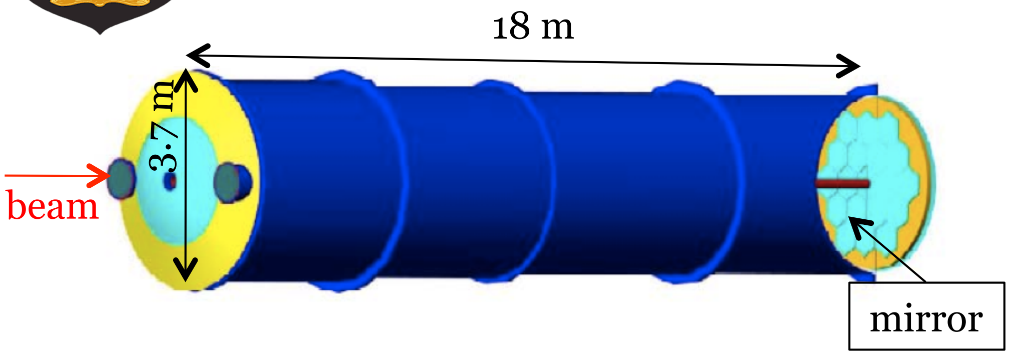


Required resolution σ_t ~ 100ps



with half-detector equipped

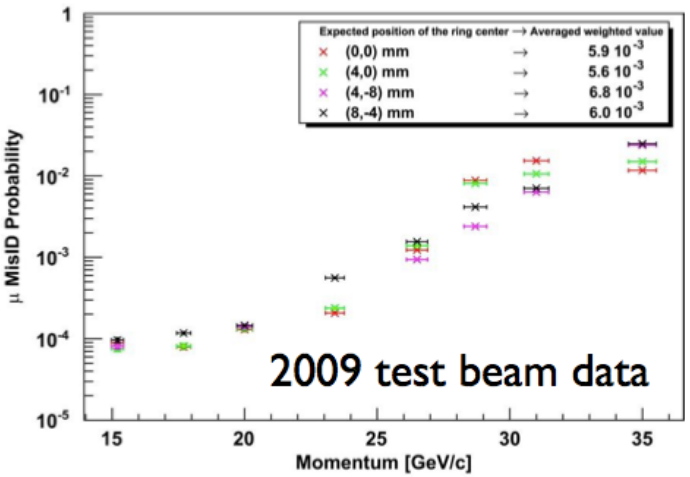
Pion ID: RICH



Suppression of $K^+ \rightarrow \mu^+\nu$ (BR ~ 63%)
- L0 trigger for charged particles
- μ suppression better than 1%

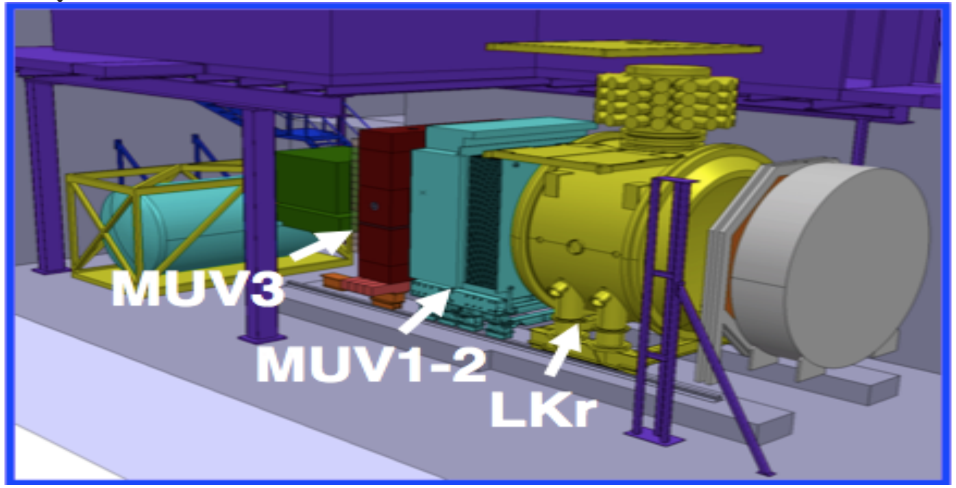
RICH layout and principles

- Cherenkov light ring radius prop to β of particle
- Ne gas at 1 atm;
- 14 GeV/c threshold for π
- High granularity γ detector (2000 PMTs)



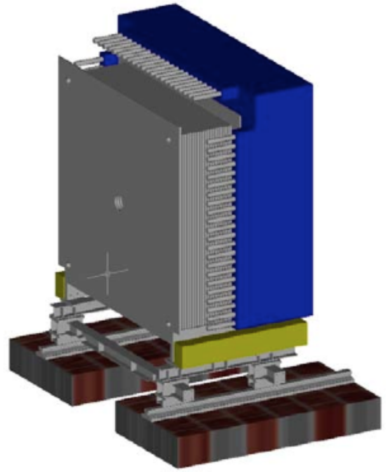
- Full length prototype tested in 2009 (test beam)
- Final detector installed on beam line
  - front-end in place during next weeks
- π^+/μ^+ separation > 10^2 up to 35 GeV/c
- Resolution on pion crossing time σ_t < 100 ps

PID: LKr, MUV



Suppression of $K^+ \to \mu^+ \nu$ (BR ~ 63%)

- μ mis-ID as a π -> down to ~10^{-5}
- muon crossing time with $\sigma_t < 1$ns

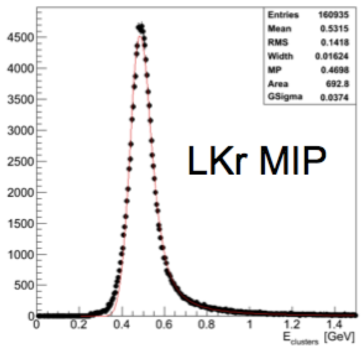


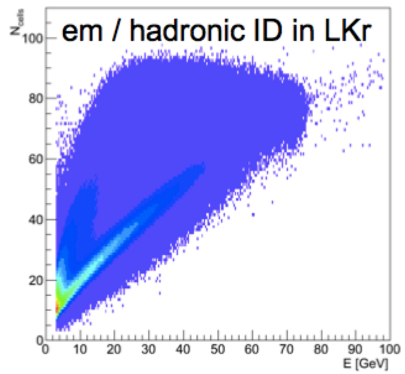
$\pi/\mu/e$ separation

NA48 LKr em calorimeter:
- em/hadr/mip cluster ID

MUV1-2:
- Fe-scintillators calorimeter
- hadr/mip cluster ID
- suppress μ "catastrophic" energy loss

MUV3:
- scintillation tiles counter
- detect non-showering muons (<% ineff)
- used in L0 trigger (10MHz)





Photon Veto Systems

Photon Veto system: LAV, LKr, IRC, SAC

- Suppression of $K^+ \rightarrow \pi^+\pi^0$ (BR ~ 21%)
- Hermetic photon coverage up to 50 mrad
- $O(10^8)$ on rejection of $\pi^0 \rightarrow \gamma\gamma$
- Kinematic cut on $p_\pi < 35$ GeV gives $\pi^0 \rightarrow \gamma\gamma$ with > 40 GeV

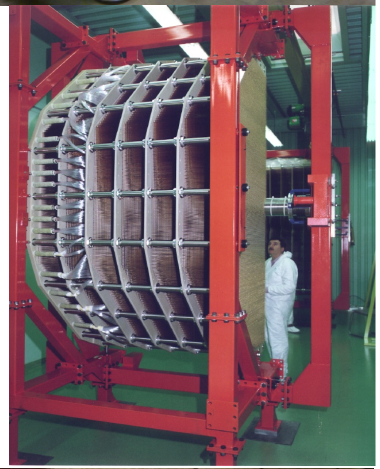
Simulations showed:

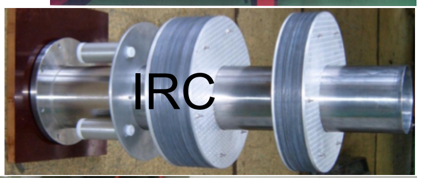
- $K^+ \rightarrow \pi^+\pi^0$ kinematic rejection (m^2_{miss}) ~ 10^{-4}
- 81.2% - 2γs in forward region (LKr/SAC)
- 18.6% - 1γ in LKr/SAC, 1γ at large angle (LAV)
- 0.2% - 1γ in LAV, 1 γ out of acceptance (>50mrad)

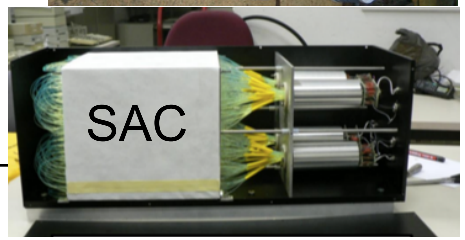
Detector	Technology	θ [mrad]	Max. (1-e)
LAV	Lead-glass block from OPAL	8.5 - 50	10^{-4} at 200MeV
LKr	NA48 EM calorimeter	1 - 8.5	10^{-3} at 1 GeV 10^{-5} at 10 GeV (data)
IRC+SAC	Shashlik	< 1	10^{-4} at 5 GeV

First LAV station

LKr







Expected Performance

K ID KTAG efficiency	> 95%
π ID RICH efficiency	> 90%
π ID MUV1-2 efficiency	> 90%
Kinematic rejection	$10^{-3} \div 10^{-4}$
μ ID RICH inefficiency	$10^{-2} \div 10^{-3}$
e^+ ID RICH inefficiency	$\sim 10^{-3}$
μ ID MUV1-2 inefficiency	$\sim 10^{-5}$
e^+ ID LKr inefficiency	$\sim 10^{-2}$
γ inefficiency in LKr	$\sim 10^{-5}$
γ inefficiency in LAV	$10^{-3} \div 10^{-4}$
Signal Acceptance	~ 12%

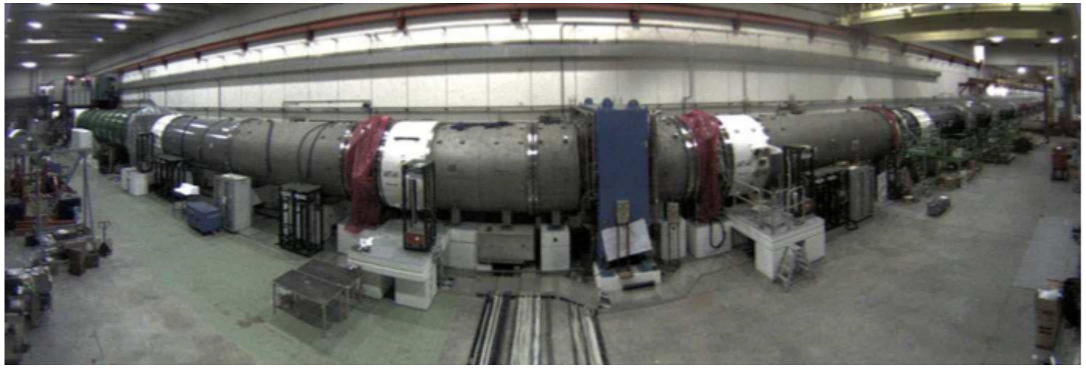
NA62 Physics Sensitivity

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

Cut & count analysis without any optimization
Background must be measured with at least 10% precision (data-driven)

Conclusions

CERN Live NA62 CAM - May 2014



NA62 Beam line ready ✔

Detector installation completed by the end of September 2014

6 October 2014: start of pilot physics run (60 days) **!**

Goals:

✓ Commissioning of hardware and readout with particles at lower intensity

✓ Address SM sensitivity

Nominal intensity beam in 2015-2017 for full physics runs (~100 days) officially scheduled by CERN **!**

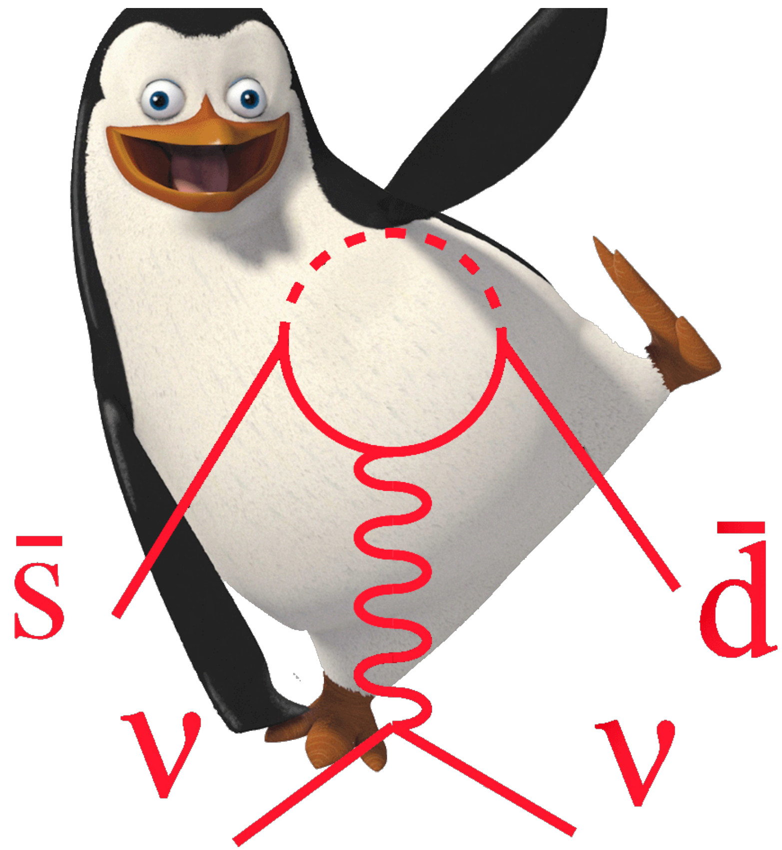
Goals:

✓ collect O(100) SM $K^+ \to \pi^+\nu\bar{\nu}$ events

✓ measure BR($K^+ \to \pi^+\nu\bar{\nu}$) with ~10% accuracy

Conclusions

Stay Tuned !



NA62 Beam line ready ✔

Detector installation completed by the end of September 2014

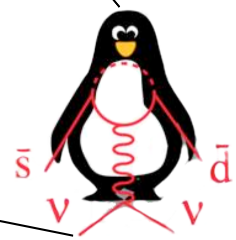
6 October 2014: start of pilot physics run (60 days) **!**

Goals:

- ✓ Commissioning of hardware and readout with particles at lower intensity
- ✓ Address SM sensitivity

8 for full physics runs

d by CERN **!**



✓ measure BR($K^+ \to \pi^+ \nu \bar{\nu}$) with ~10% accuracy

SPARES

Background Rejection

NA62 strategy: Detect ~100 $K^+ \to \pi^+\nu\nu$ decays with S/B ~ 10

Required Background rejection at level 10^{12} :

- ✓ **Kinematic Rejection:** (P_π, P_K, $\theta_{\pi K}$);

  Low mass tracking (GTK + STRAW)
- ✓ **Particle Identification:** (K, π, μ);

  K/π (KTAG), π/μ (RICH), μ (MUV1-2)
- ✓ High efficiency **Vetoes**:

  γ (LAV + LKr + SAC), μ (MUV3)

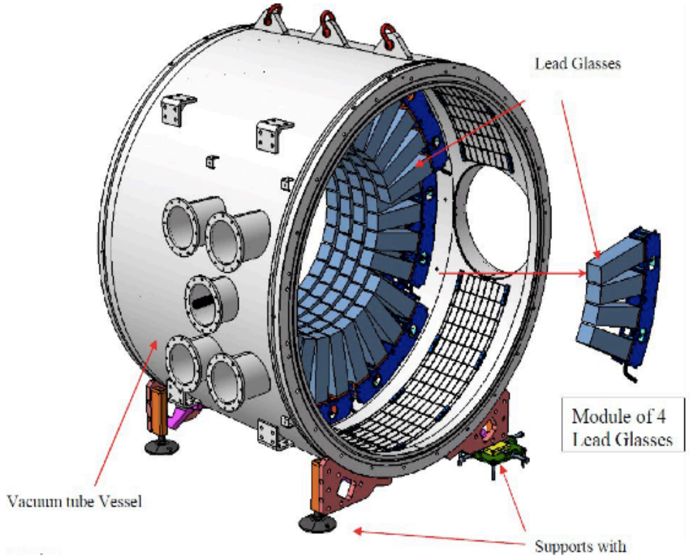
Main Backgrounds

Decay	BR	Rejection mode
$K^+ \to \mu^+\nu_\mu$	63%	Kinematics + μ-PID
$K^+ \to \pi^+\pi^0$	21%	Kinematics + γ-Veto
$K^+ \to \pi^+\pi^+\pi^-$	6%	Kinematics + π^--Veto
$K^+ \to \pi^+\pi^0\pi^0$	2%	Kinematics + γ-Veto
$K^+ \to \pi^0 e^+\nu$	5%	e-PID + γ-Veto
$K^+ \to \pi^0\mu^+\nu$	3%	μ-PID + γ-Veto

- ✓ **Precise timing**: association of daughter particle (π^+) to the correct beam particle (K^+) in a ~750 MHz beam
  - mismatch leads to 3× increase in $\sigma(m^2_{miss})$
  - GTK σ(t) < 200 ps/station
  - KTAG σ(t) < 100 ps
  - RICH σ(t) < 100 ps

→ Mismatch Probability < 1%

Photon Veto Systems - II



-12 **LAV** stations distributed along the decay volume and covering the angular region: (8.5÷50) mrad;

- Photon energy range (10MeV÷30GeV);

- each **LAV**: 4/5 staggered layers of lead-glass crystals from OPAL EM barrel calorimeter;

- test beam with e^- at 200MeV showed (1-ε) ~10^{-4}

- **LKr** fundamental detector constructed for the studies of direct CP-violation in the neutral kaon system (NA48);

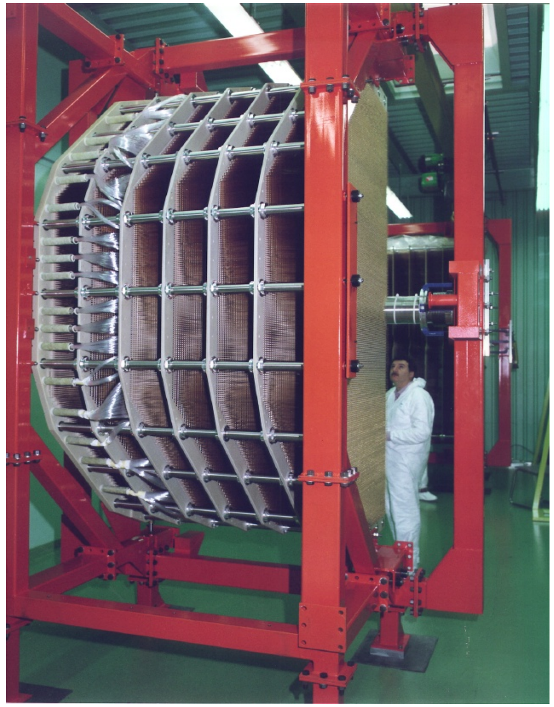
- quasi-homogeneous ionization chamber;

- Photon energy range (>1GeV);

- high energy (>10GeV) EM showers contained in compact detector (27 X_0);

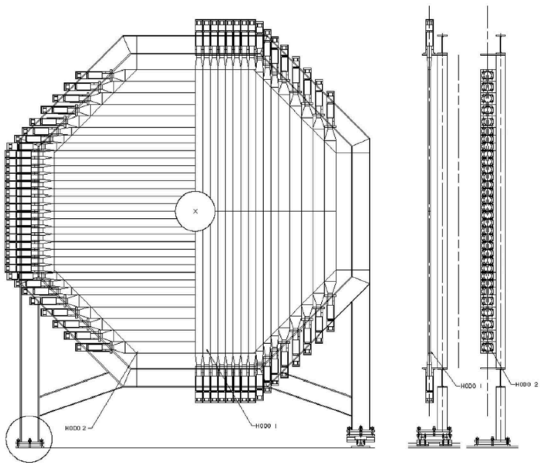
- 13, 248 readout cells with a transverse size of ~2×2 cm^2 each and no longitudinal segmentation;

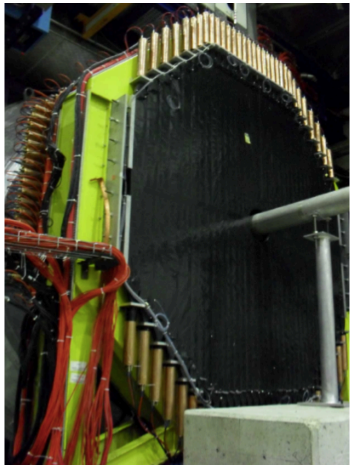
- from studies with e^- at E>10GeV -> (1-ε) ~ $8x10^{-6}$



Charged Tracks Veto System

CHOD
(NA48 Charged Hodoscope)

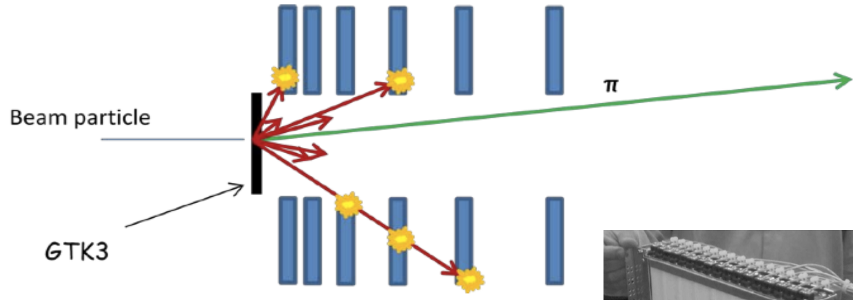


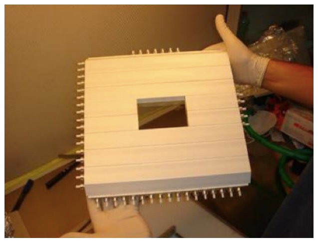


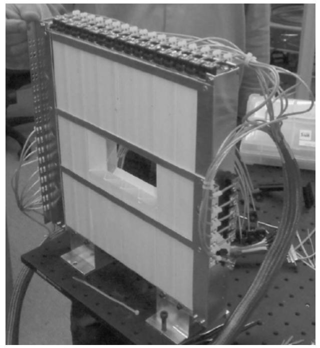
- 2 planes of plastic scintillation counters (horizontal & vertical)
- ~ 0.05 X0 each plane
- time resolution σ_t ~ 200 ps;

Fast charged particles signal for trigger

CHANTI



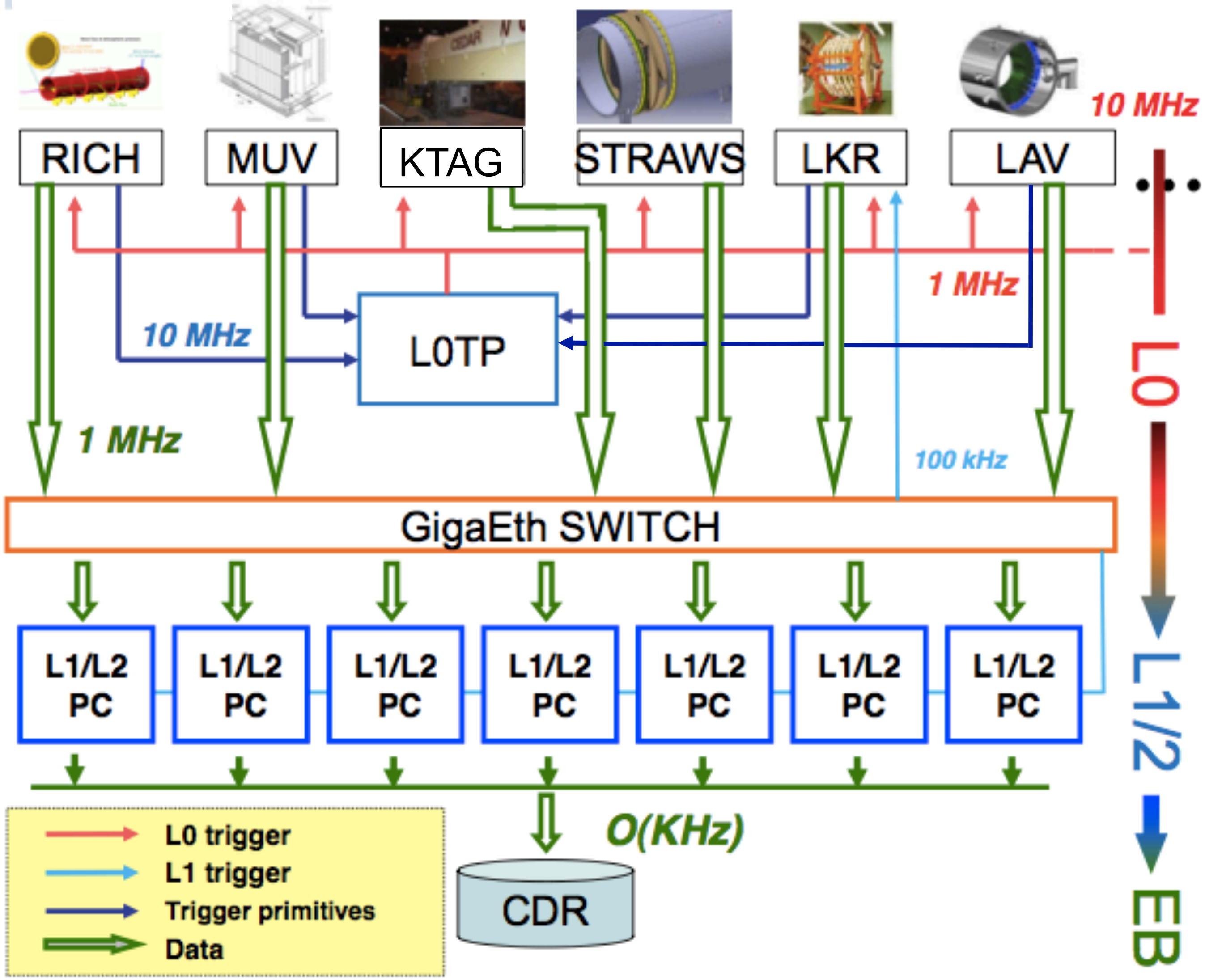




- 6 scintillator stations in vacuum
- WLS + SiPM readout
- angle coverage (1.3-4.9) mrad

Veto for charged particles from inelastic interactions in GTK3

NA62 Trigger Technique: The TDAQ System



- L0: Hardware synchronous level. 10 MHz to 1 MHz. Max latency 1 ms.
- L1: Software level. "Single detector". 1 MHz to 100 kHz
- L2: Software level. "Complete information level". 100 kHz to few kHz.