June 11th-13th, 2016, Anacapri, Italy: 6th international workshop on Theory, Phenomenology and Experiments in Flavour Physics

Recent results and prospects for NA62 experiment

Silvia Martellotti*, on behalf of the NA62 collaboration

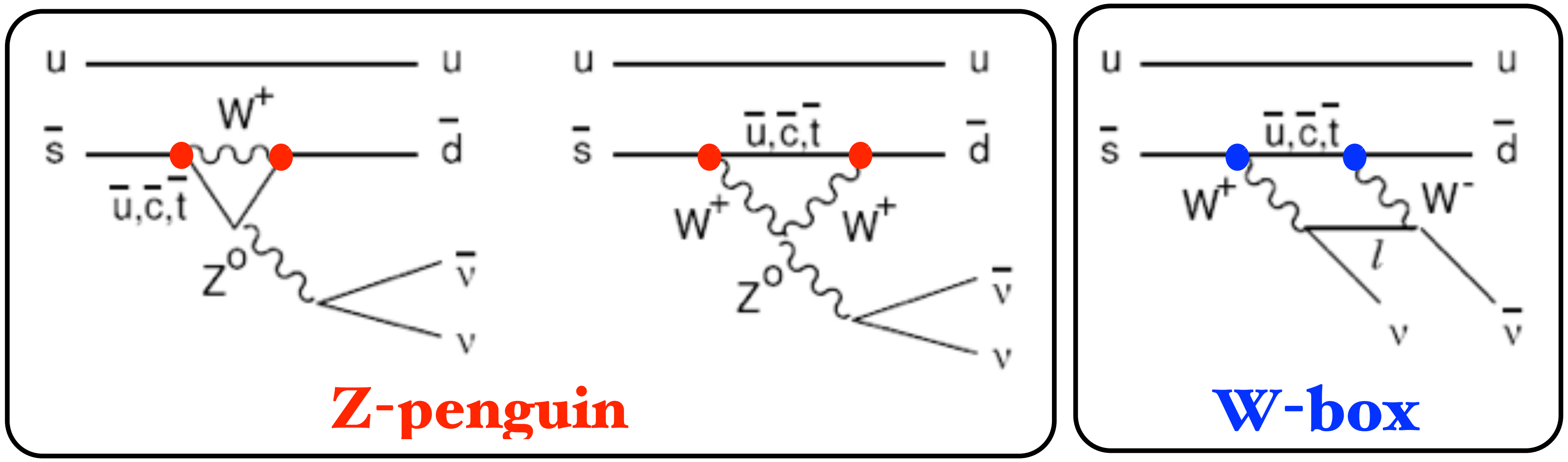
* *INFN Laboratori Nazionali di Frascati(Italy)*

Outline

- Theoretical introduction to the $K^+ \rightarrow \pi^+ \bar{\nu}\nu$ rare decay
- NA62 experiment aim and strategy
- Detector overview
- Status and prospects
- First look at 2015 data

SM theoretical framework

The **$K^+ \rightarrow \pi^+\nu\bar{\nu}$** decay is extremely suppressed and is characterized by a theoretical cleanness in the SM prediction of the BR($K^+ \rightarrow \pi^+\nu\bar{\nu}$)



Flavor-changing neutral current quark transition $s \rightarrow d\nu\nu$.

Forbidden at tree-level, dominated by short-distance dynamics (GIM mechanism)

<u>SM prediction takes in to account:</u>

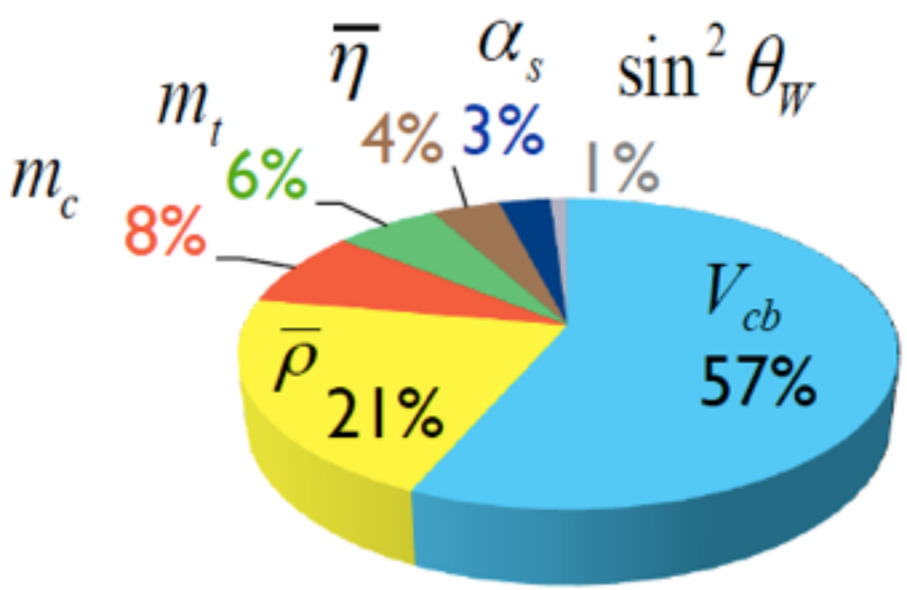
✳ 1-loop contributions at the leading order.
✳ NLO QCD corrections to the top quark contributions
✳ NLO electroweak corrections to both top and charm contributions
✳ NNLO QCD corrections to the charm contributions
✳ isospin breaking and non-perturbative effects

Stringent test of the SM and possible **evidence for New Physics**, complementary to LHC

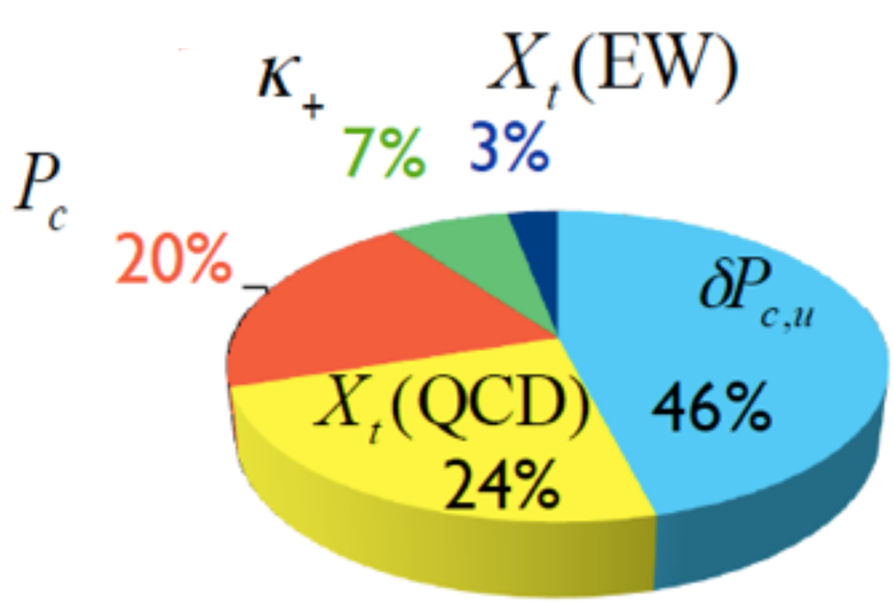
Past measurement and prediction

Current theoretical prediction [1] [2]

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$$



Input parameters (10%)



Theoretical uncertainty (4%)

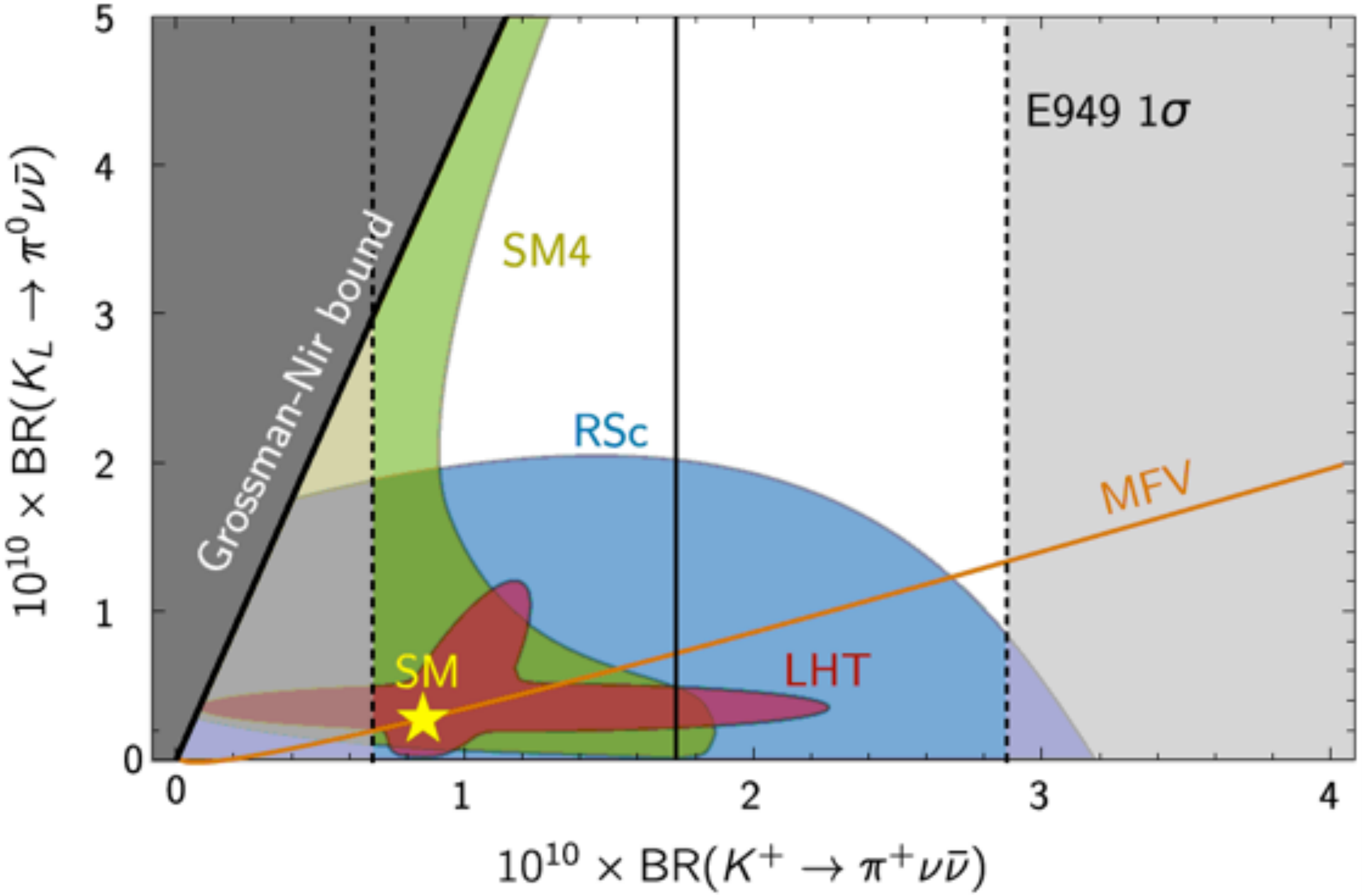
Experimental status: the only measurement has been obtained by E787 and E949 experiments at BNL by studying stopped kaon decays [3]:

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

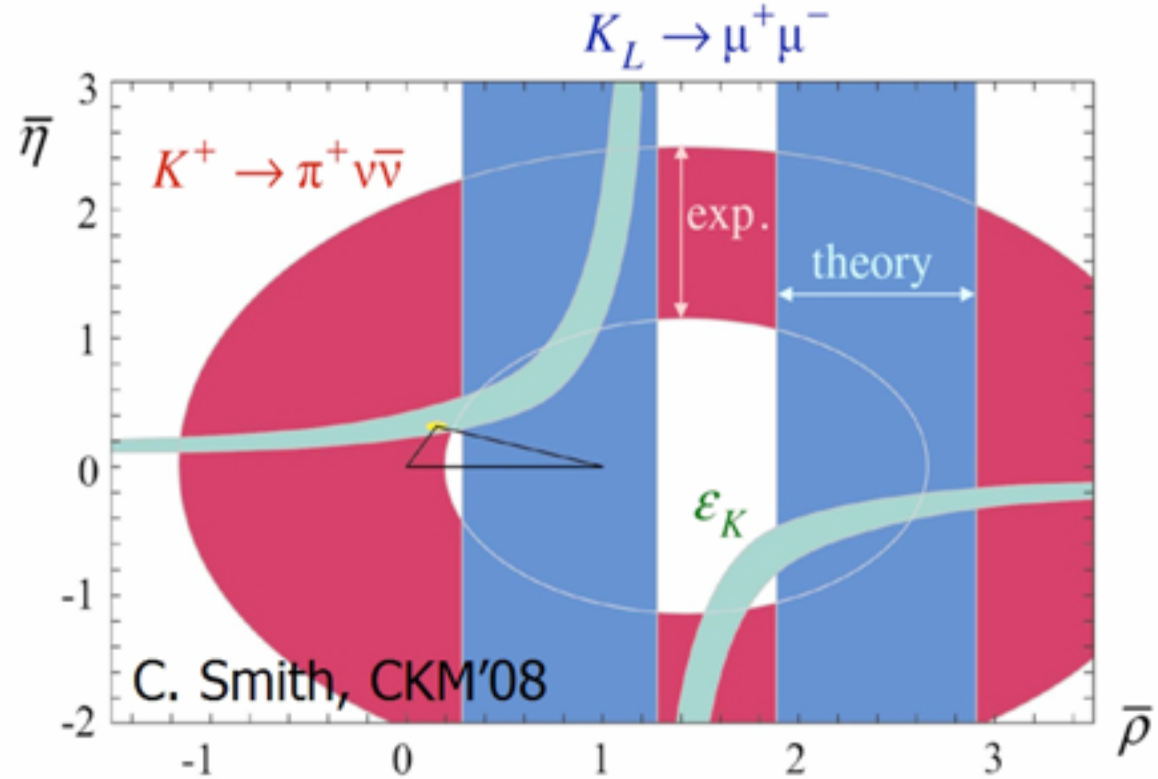
Gap between theoretical precision and large experimental error motivates a strong experimental effort. Significant new constraints can be obtained with a measurement of the BR at the level of 10% or better

New Physics from K→πνν decays

Measurement of charged ($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) and neutral ($K_L \rightarrow \pi^0 \nu\bar{\nu}$) modes can discriminate different NP scenarios



SM4:
SM with 4th generation [4]
RSc:
Randall Sundrum mechanism [5]
LHT:
Littlest Higgs with T-parity [6]
MFV:
Minimal Flavor Violation [7]



Measurement of $|V_{td}|$ complementary to those from B-B mixing

δ(BR)/BR = 10% would lead to
δ($|V_{td}|$)/$|V_{td}|$ = 7%

Experimental requirements

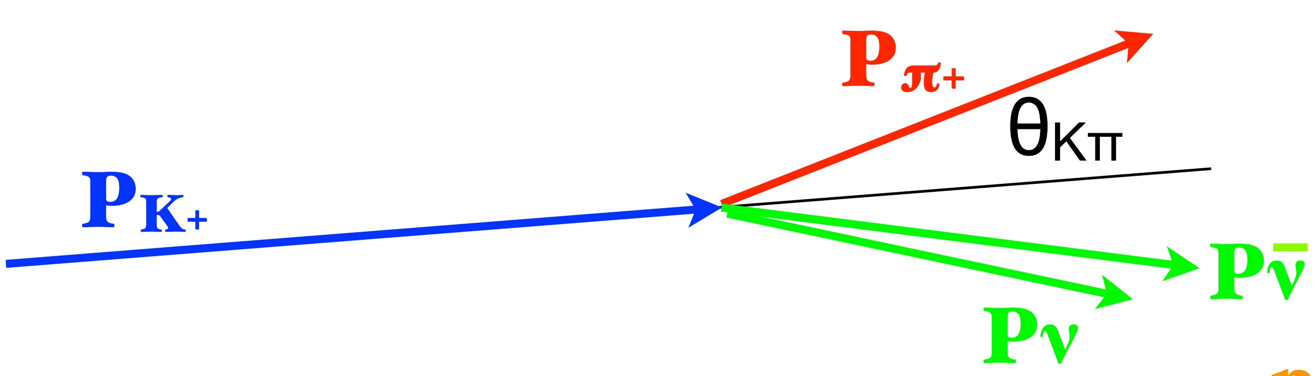
GOAL: measure BR($K^+ \to \pi^+\nu\bar{\nu}$) with 10% accuracy

O(100) SM events + systematics control at % level

- Assuming a 10% signal acceptance and a BR($K^+ \to \pi^+\nu\nu$) ~10^{-10} at least 10^{13} K^+ decays are required
- Required a rejection factor for dominant kaon decays of the order of 10^{12} (<20% background)

NA62 design criteria: **kaon intensity, signal acceptance, background suppression**

Decay in flight technique, Kaon with high momentum



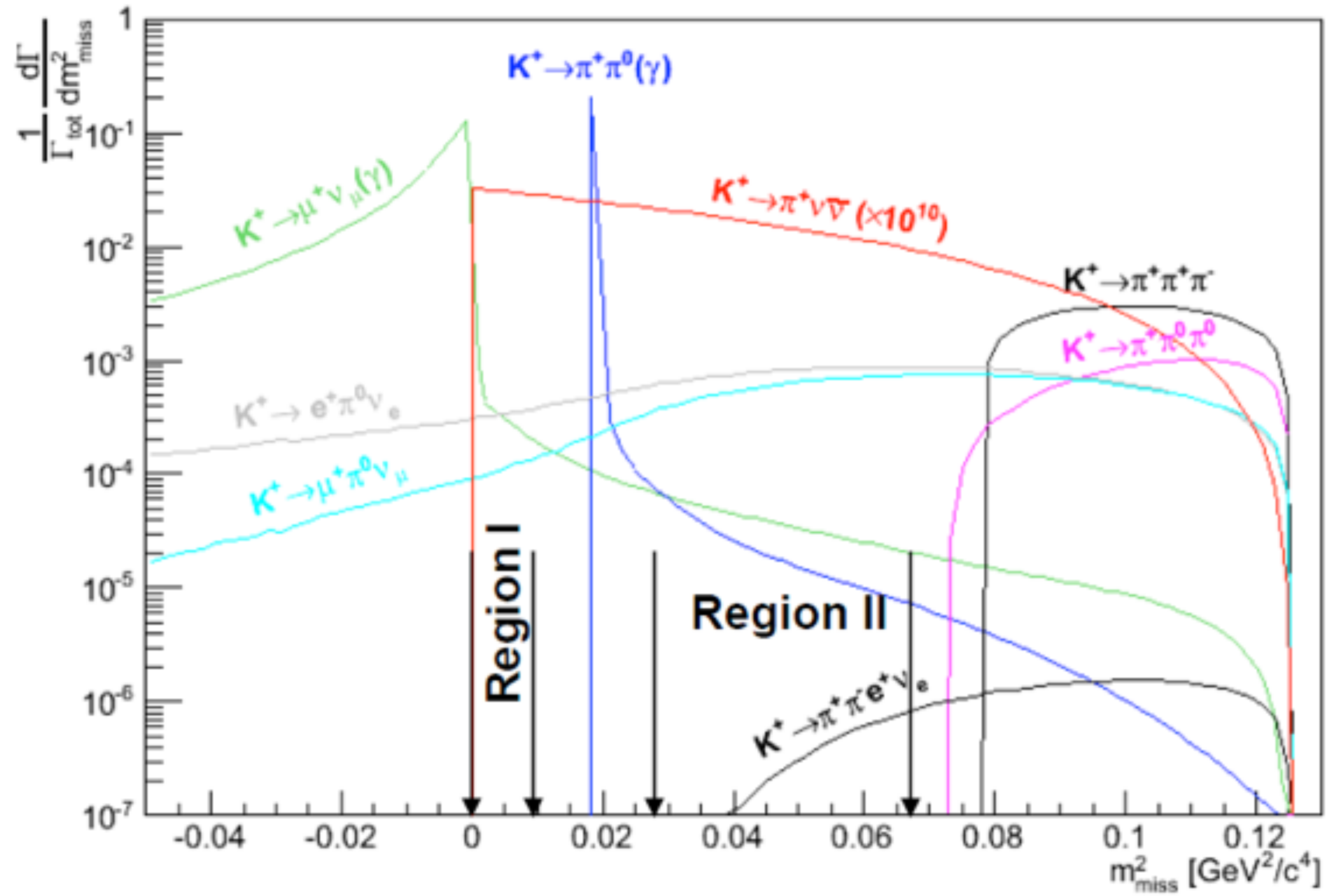
Signal signature:
one K^+ track & one π^+ track

Basic ingredients:
precise timing & kinematics cuts

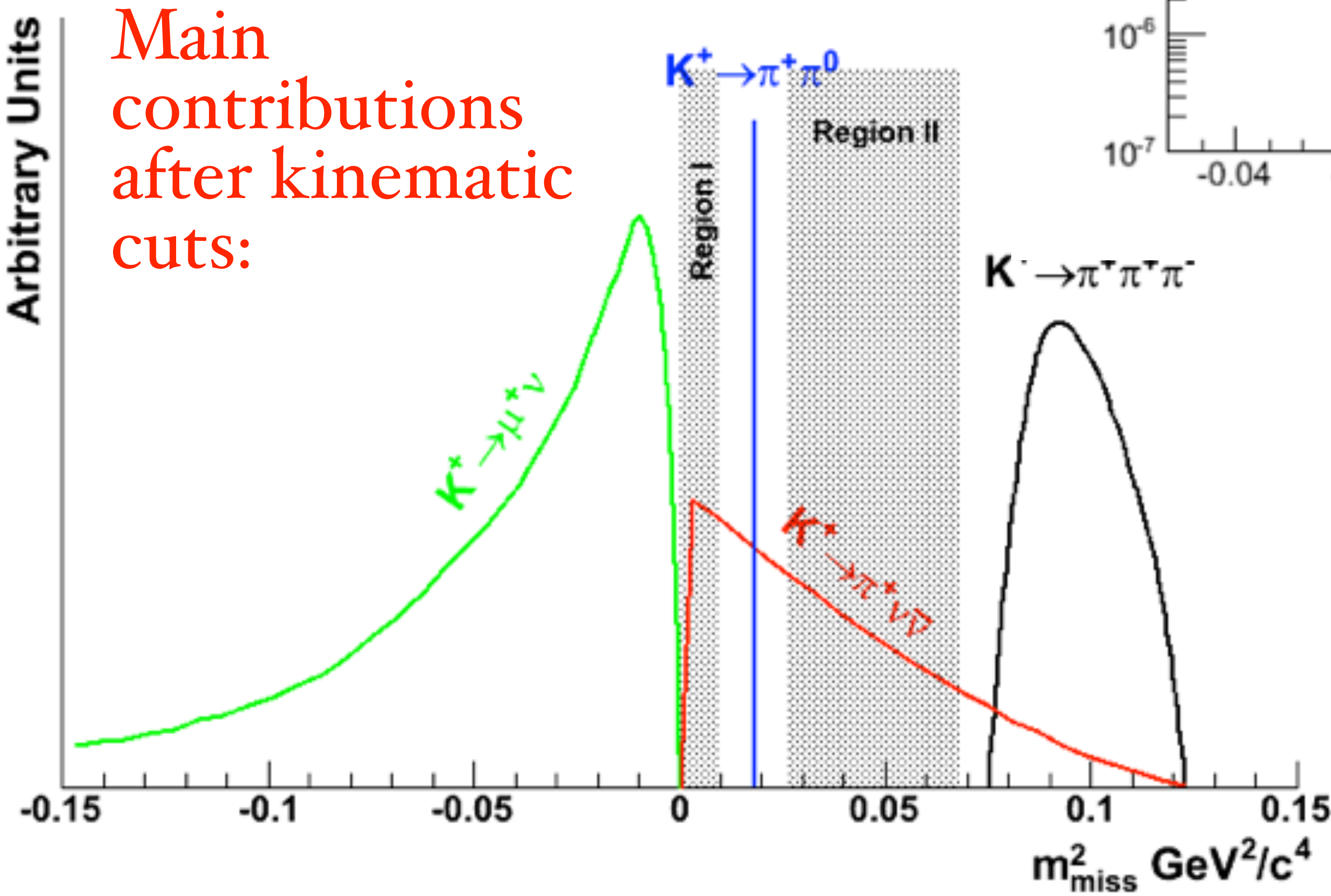
Analysis strategy

Most discriminating variable:
$m^2_{miss} = (P_{K+} - P_{\pi+})^2$

Where the daughter charged particle is assumed to be a pion



Main contributions after kinematic cuts:



2 signal regions, on each side of the $K^+ \to \pi^+\pi^0$ peak, are chosen, where more than 90% of main K^+ decays are no longer dominant.

- $15 < P_{\pi+} < 35$ GeV/c
- 65 m long decay region

Background rejection

Background:

Decay	BR	Main Rejection Tools
$K^+ \to \mu^+\nu_\mu(\gamma)$	63%	μ-ID + kinematics
$K^+ \to \pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	multi-track + kinematics
$K^+ \to \pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+\nu_e$	5%	e-ID + γ-veto
$K^+ \to \pi^0\mu^+\nu_\mu$	3%	μ-ID + γ-veto

Subdetector requirements:

- Beam tracking system
- Photon veto system
- Muon veto system
- π/μ/e identification system

NA62 design sensitivity

Decay	Events/year
$K^+ \to \pi^+\nu\bar{\nu}$	45
$K^+ \to \pi^+\pi^0$	5
$K^+ \to \pi^+\pi^+\pi^-$	1
$K^+ \to \pi^+\pi^- e^+\nu_e$	< 1
$K^+ \to \pi^+\pi^0\gamma$	< 1
$K^+ \to \mu^+\nu_\mu\gamma$	1.5
other rare decays	0.5
Total backgrounds	< 10

Required background suppression:

Kinematics $O(10^4\text{-}10^5)$

Charged Particle ID $O(10^7)$

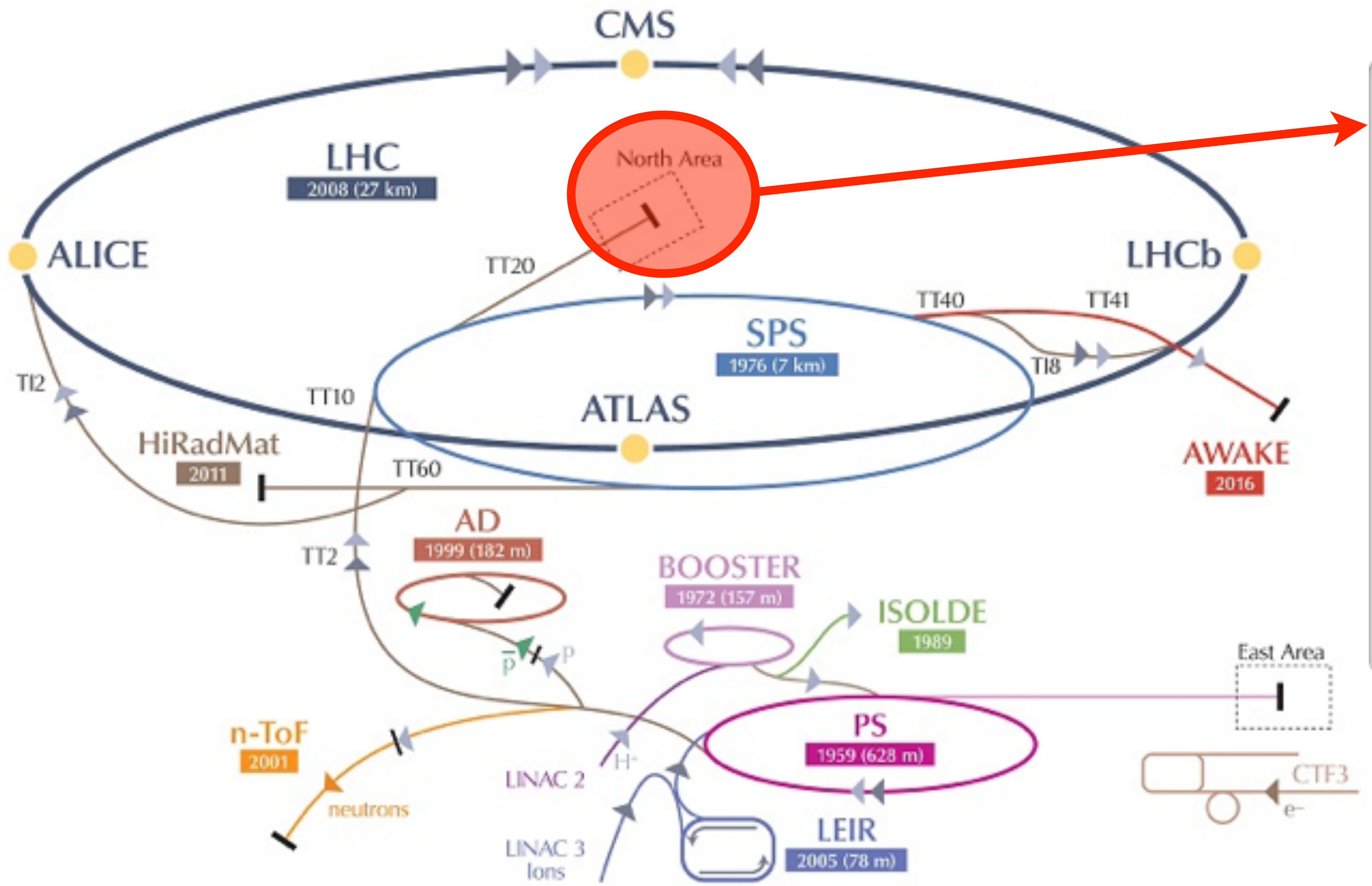
γ detection $O(10^8)$

($P_{\pi+}$<35 GeV to ensure $P_{\pi 0}$ > 40 GeV: such a large energy deposit can hardly be missed)

Timing $O(10^2)$

Kaon @ CERN - SPS

The **CERN-SPS** secondary beam line already used for the NA48 experiment can deliver the required K^+ intensity



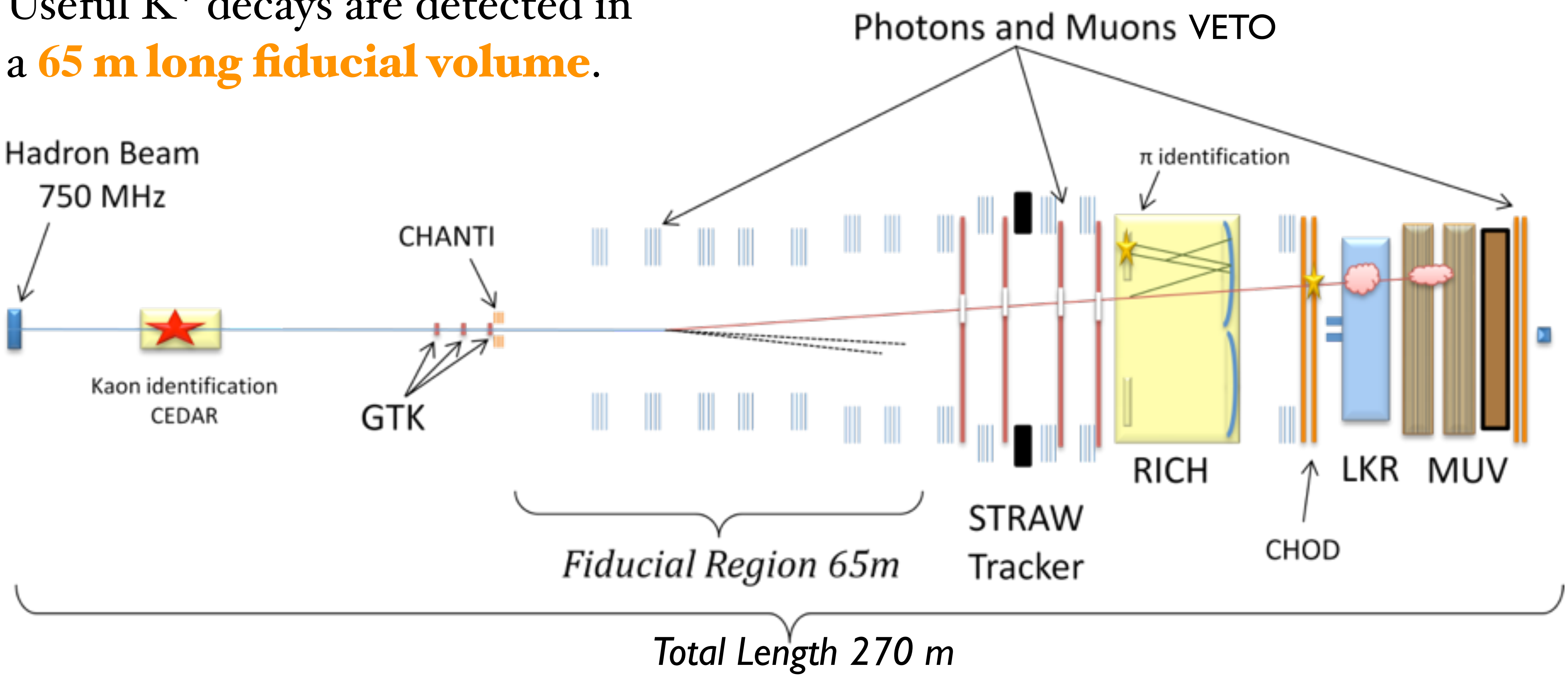
The NA62 is housed in the CERN North Area. A new beam line provides a secondary charged hadron beam 50 times more intense than in the past, with only 30% more SPS protons on target

data taking foreseen till LHC LS2 (end 2018)

Protons from the SPS at 400 GeV/c impinge on a beryllium target and produce a secondary charged hadron beam with 6% of K^+ unseparated from π^+ and protons. Signal acceptance considerations drives the choice of a **75 GeV/c K^+** with a 1% momentum bite and a divergence ~ 100 μrad (in x and y)

NA62 Apparatus

The main elements for the detection of the K^+ decay products are spread along **a 270 m long** region starting about 100 m downstream of the beryllium target.
Useful K^+ decays are detected in a **65 m long fiducial volume**.



Approximately cylindrical shape around the beam axis for the main detectors. Diameter varies from 12 to 220 cm, in order to let the very intense flux of **undecayed beam particles passing through**.

The overall rate integrated over these detectors is ~ 10 MHz

Kaon ID and timing: KTAG & GTK

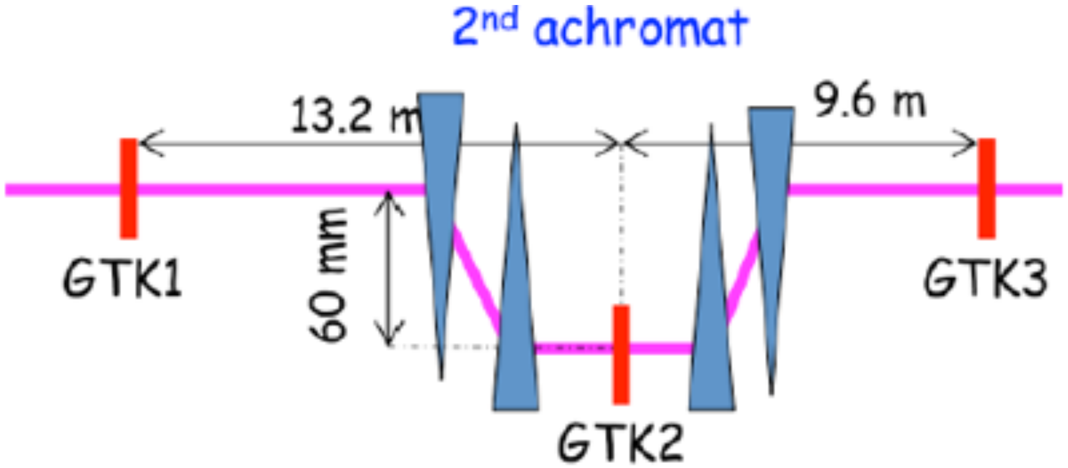
K^+ identification in the hadron beam

A ChErenkov Differential counter with Achromatic Ring focus is operated being blind to all particles but kaons of appropriate momentum (**75 GeV**).

Steel vessel, 4.5 m long and filled with compressed hydrogen.

- overall time resolution ~ 66 ps
- K-ID efficiency > 95%, K mis-ID < 10^{-3}

K^+ spectrometer for momentum and timing measurement



GTK must provide, (in a 750 MHz beam environment) a precise timing of the kaon in coincidence with the particle from the decay detected in downstream detectors.

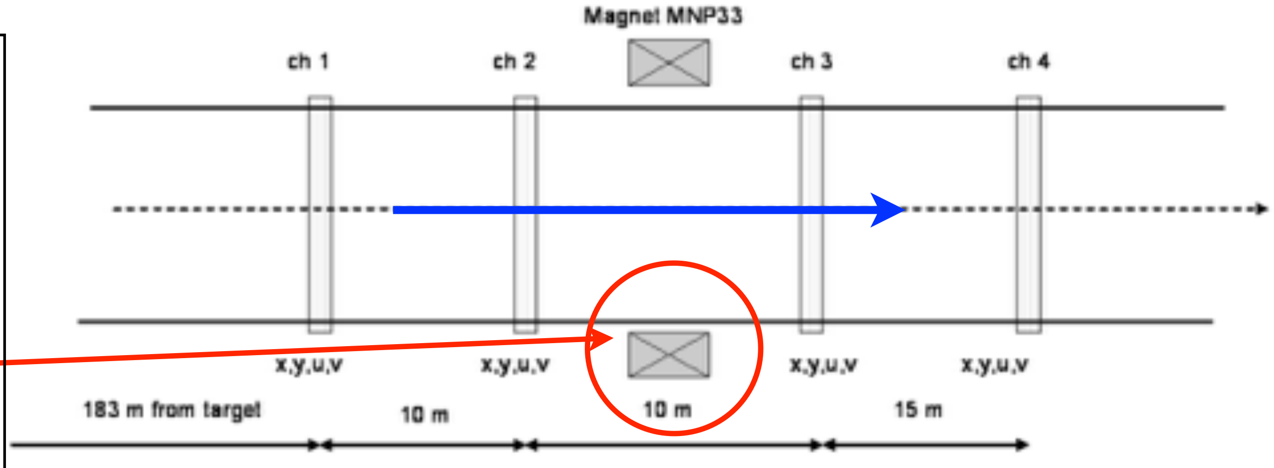
- time resolution ~ 200 ps per station
- direction resolution ~16 μrad

3 stations of silicon pixels matching the beam dimensions placed in vacuum. (18000 pixels per station, 10 read out chips)

Secondary particle Tracking System and ID

STRAW Spectrometer: momentum measurement

4 chambers in vacuum, 7168 STRAW tubes with ⊘1cm, 4 layers per chamber (< 0.5 X0). Magnet after the 2nd STRAW chamber provides a 270 MeV/c momentum kick in the horizontal plane.



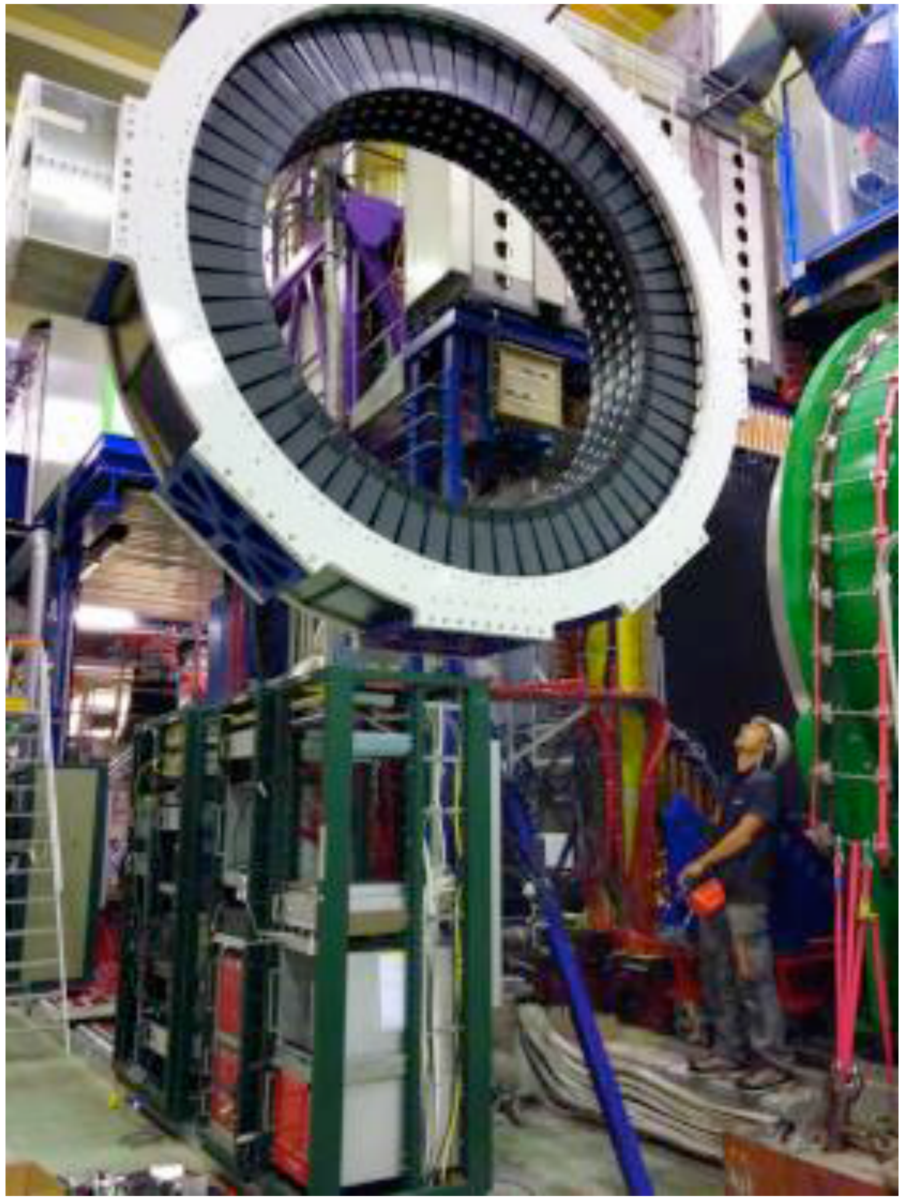
σ(p)/p ~ 1%. Spatial resolution 130 μm

Ring Imaging CHerenkov detector: particle identification and crossing time

17 m long tank filled with neon gas at atmospheric pressure. Downstream end: mosaic of 20 spherical mirrors. Upstream end: ~2000 PMTs. Internal Al beam pipe keeps the beam particles in vacuum.

-μ/π separation at 15÷35 GeV ~ 10^{-2}
-particle crossing time resolution < 100 ps

Photon Vetoes: Large and Small Angle



Large Angle Veto (LAV): 12 photon veto stations (11 in vacuum) covering 8.5 <θ <50 mrad

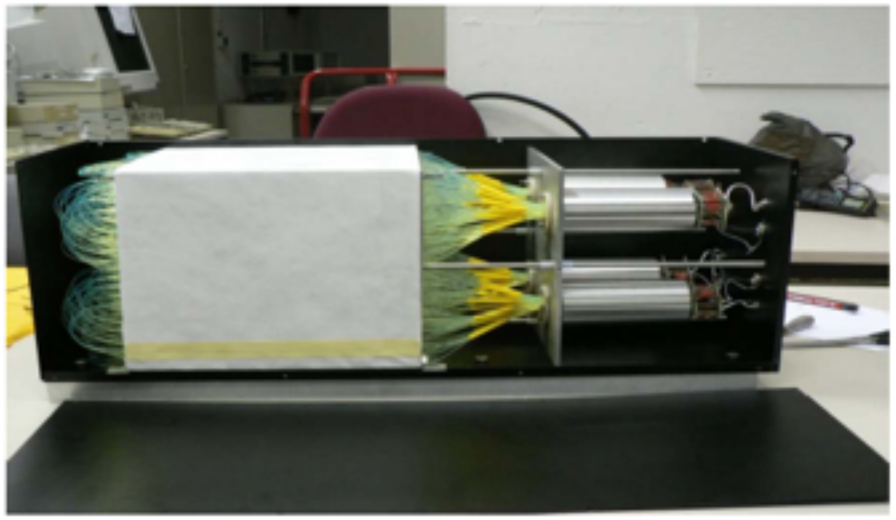
Lead glass crystals read out by PMTs.
Each LAV station is made of 4 or 5 rings of crystals.

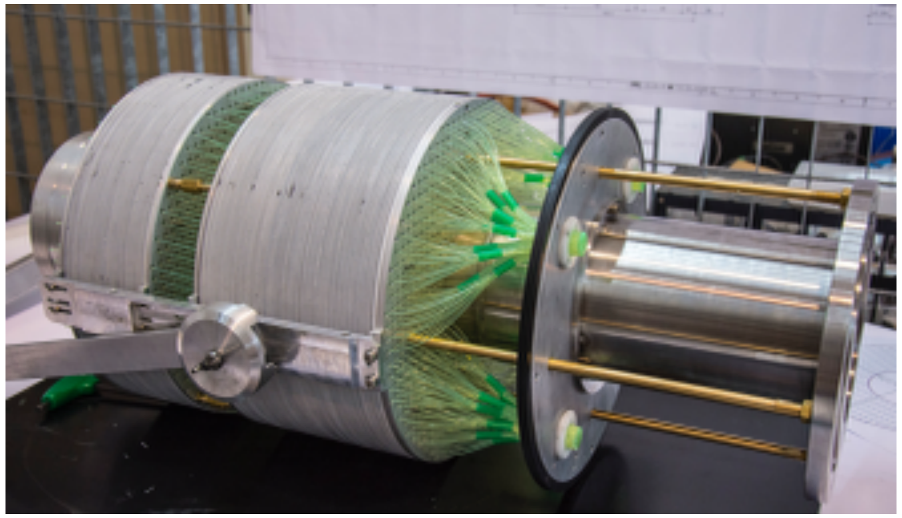
10^{-3} to 10^{-5} inefficiency on γ down to 150 MeV
- time resolution ~ 1 ns

Small Angle Veto (IRC&SAC): for photons emitted at angles less than 1 mrad.

- 10^{-4} inefficiency for > 1 GeV photons

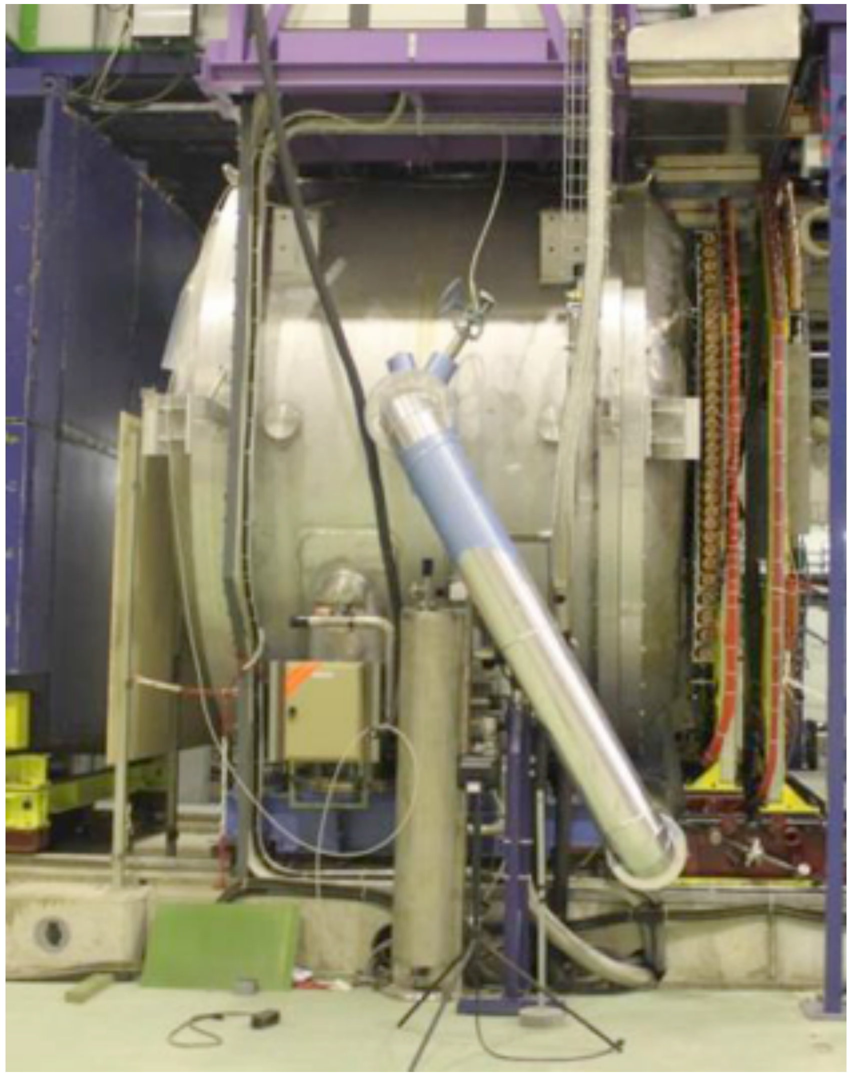
- Lead and plastic scintillator plates
- Electromagnetic showers detected through Shashlik calorimeters





Particle ID: LKr Calorimeter & Muon Veto

LKr Calorimeter: Photon veto covering 1 <θ < 8.5 mrad



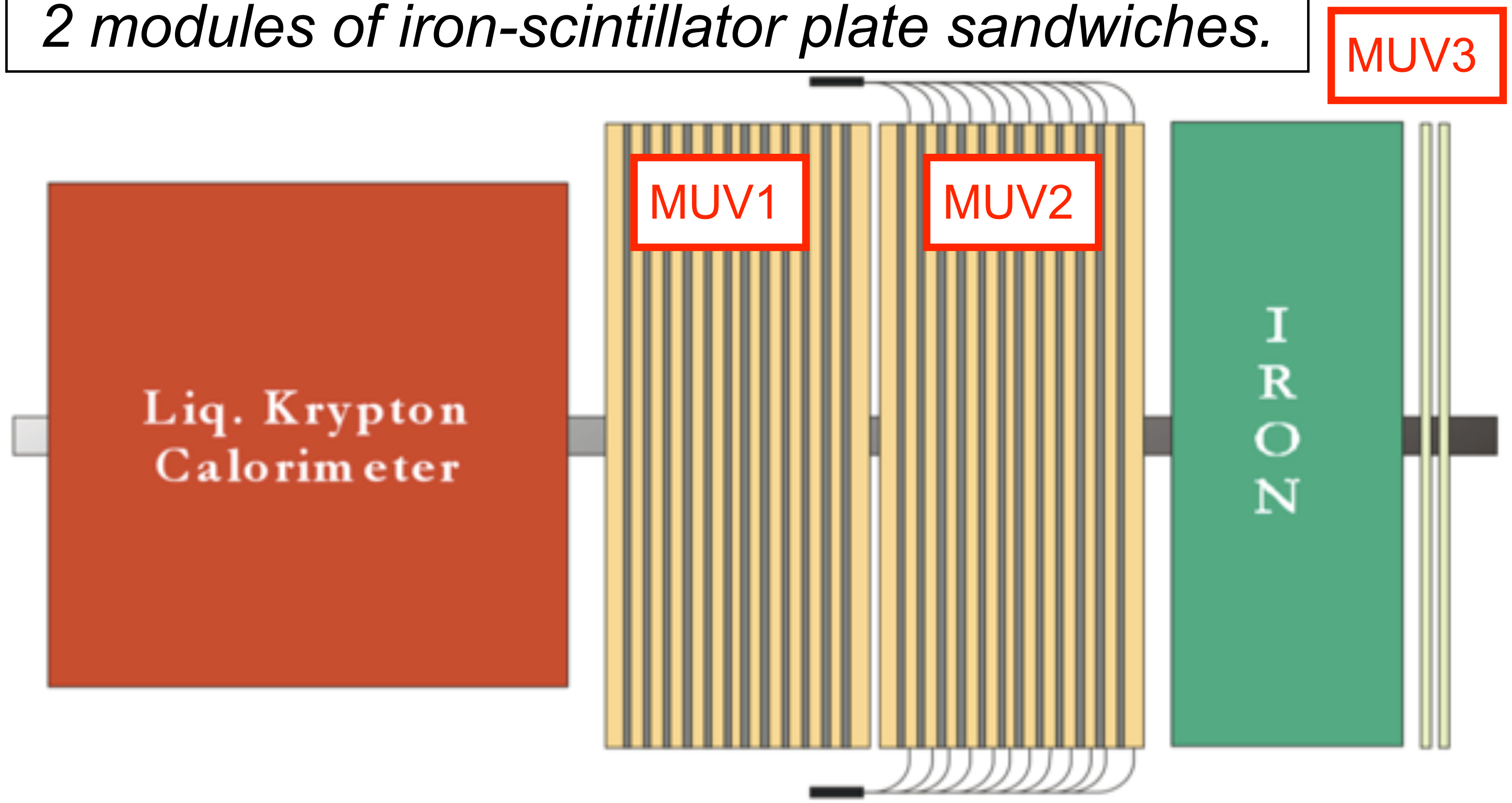
Ionization chamber + liquid Krypton, 2x2 cm^2 cells. Inherited from NA48 and equipped with new readout electronics.

- Shower time resolution ~500 ps, space resolution 1 mm
- expected inefficiency < 10^{-5} for Eγ > 10 GeV

MUon Veto detector: essential to suppress muons from kaon decays

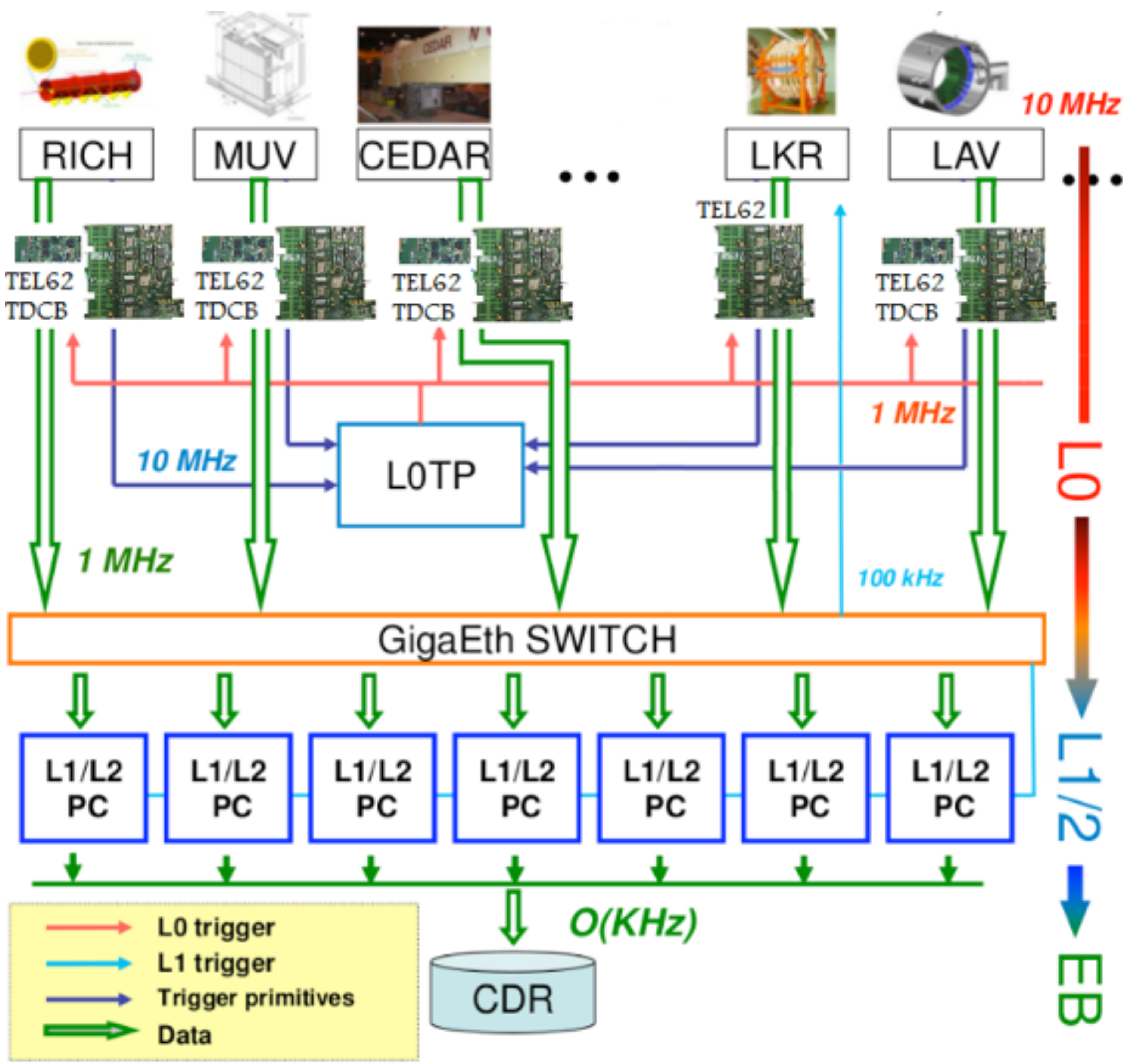
MUV1 and MUV2, hadronic calorimeters: 2 modules of iron-scintillator plate sandwiches.

MUV3: efficient fast μ-veto used in the hardware trigger level. 1 plane of 148 5cm thick scintillator tiles, each readout by 2 PMTs.



Trigger and Data acquisition

NA62 trigger is broken into 3 stages: L0, L1, L2



L0:

RICH & CHOD & MUV3 & LKr & LAV

Implemented in **hardware** (FPGA)
Rate reduction from 10 to ~ **1 MHz**

L1 & L2:

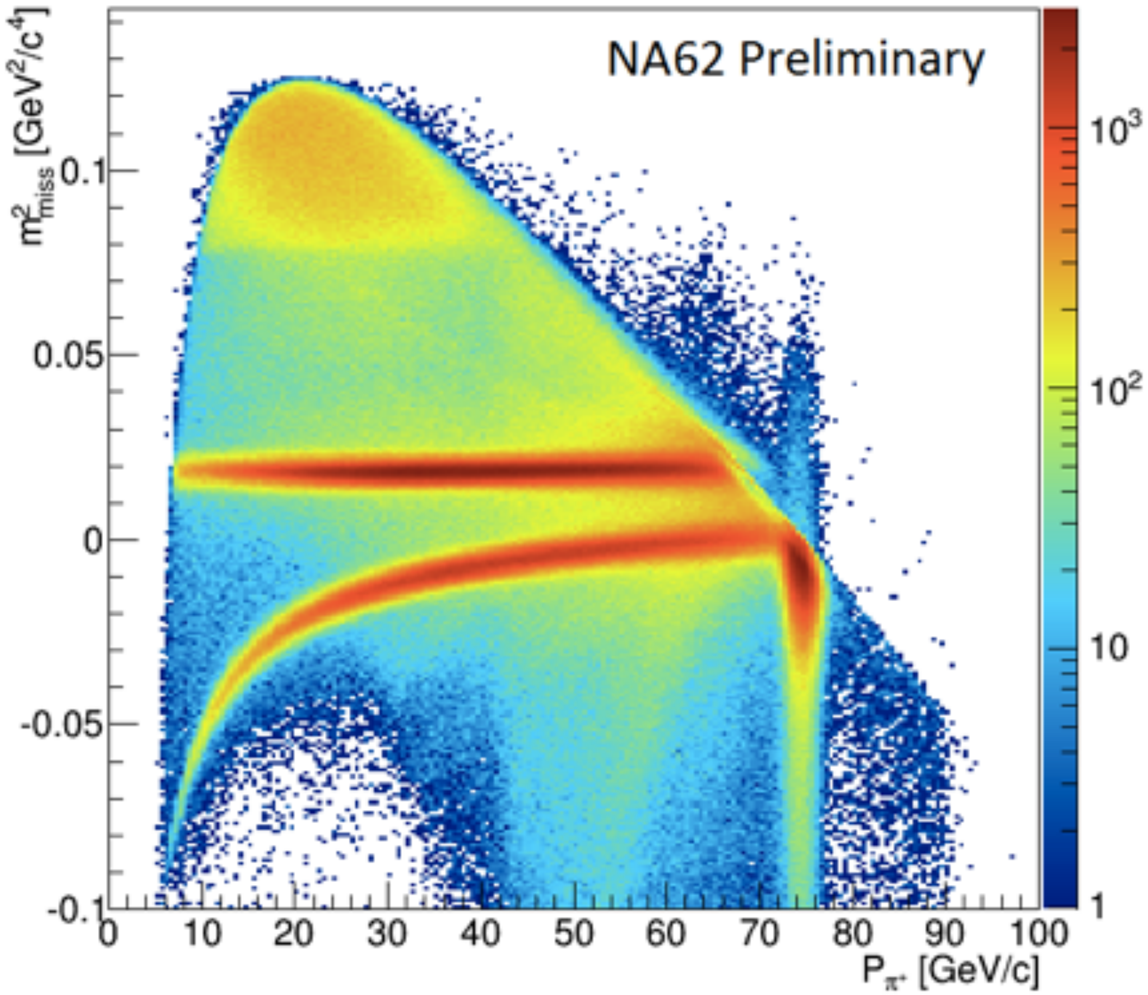
Software based: programs running on a dedicated PCfarm.
Rate reduction to **~10 kHz**

Experimental Status

✓	2006	Proposal
✓	2009	Approved
✓	2010	Technical Design
✓	2012	Technical Run
✓	2014	Pilot run
✓	2015-2018	Physics run

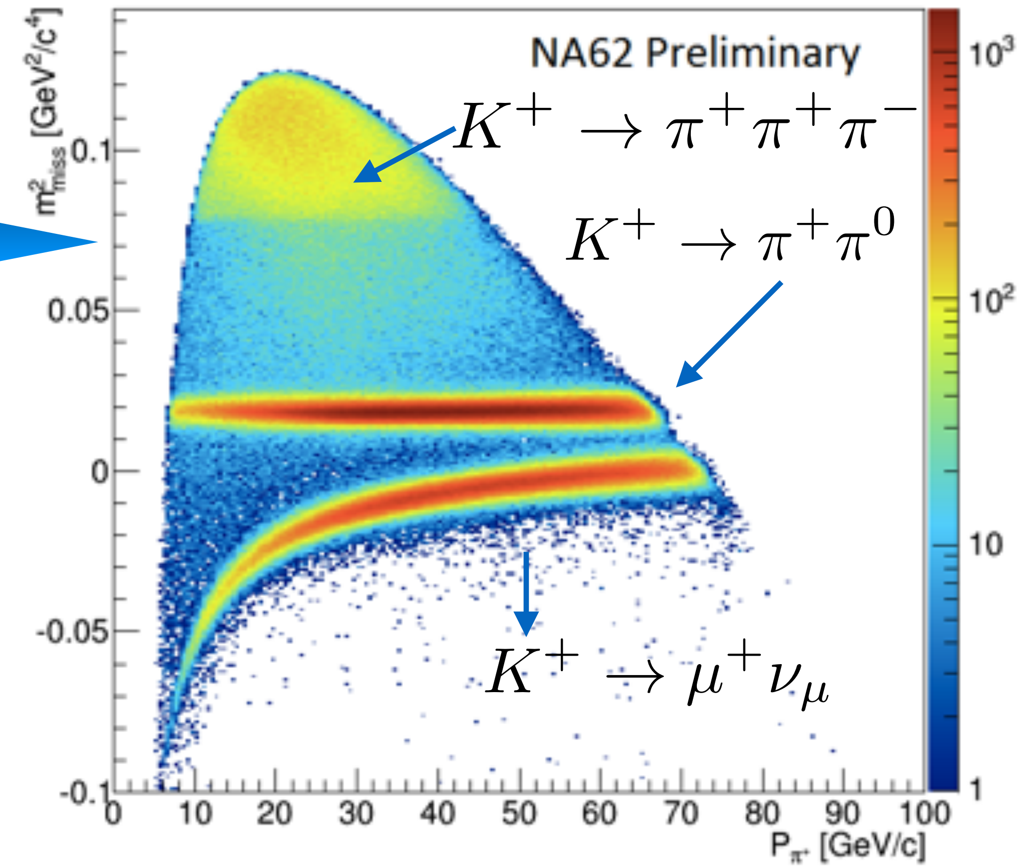
- **NA62 took data in 2014 and 2015 and is now taking data**
- **Beam commissioned up to nominal intensity**
- **Tracker:**
  - STRAW spectrometer commissioned
  - Beam tracker (GTK) partially commissioned
- **Cherenkov detectors:**
  - Beam Kaon ID (KTAG) commissioned
  - RICH commissioned
- **Photon and Muon Vetoes commissioned**
- **Trigger**
  - L0 commissioned
  - L1(2) partially commissioned
- **Data samples for data quality study have been collected**
  - Low intensity data taken with a minimum bias trigger are shown in this talk.

2015 data: Signal topology and Kaon ID

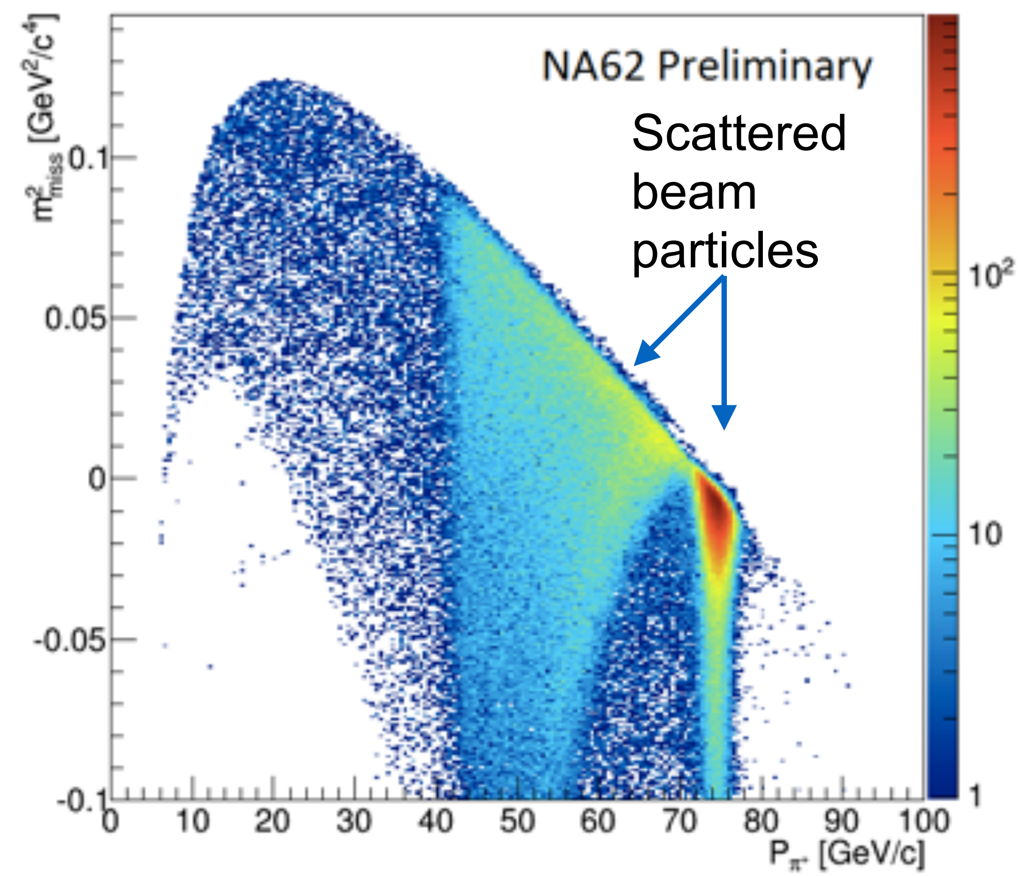


Kaon ID →

Track origin in the fiducial region



Not Kaon ID

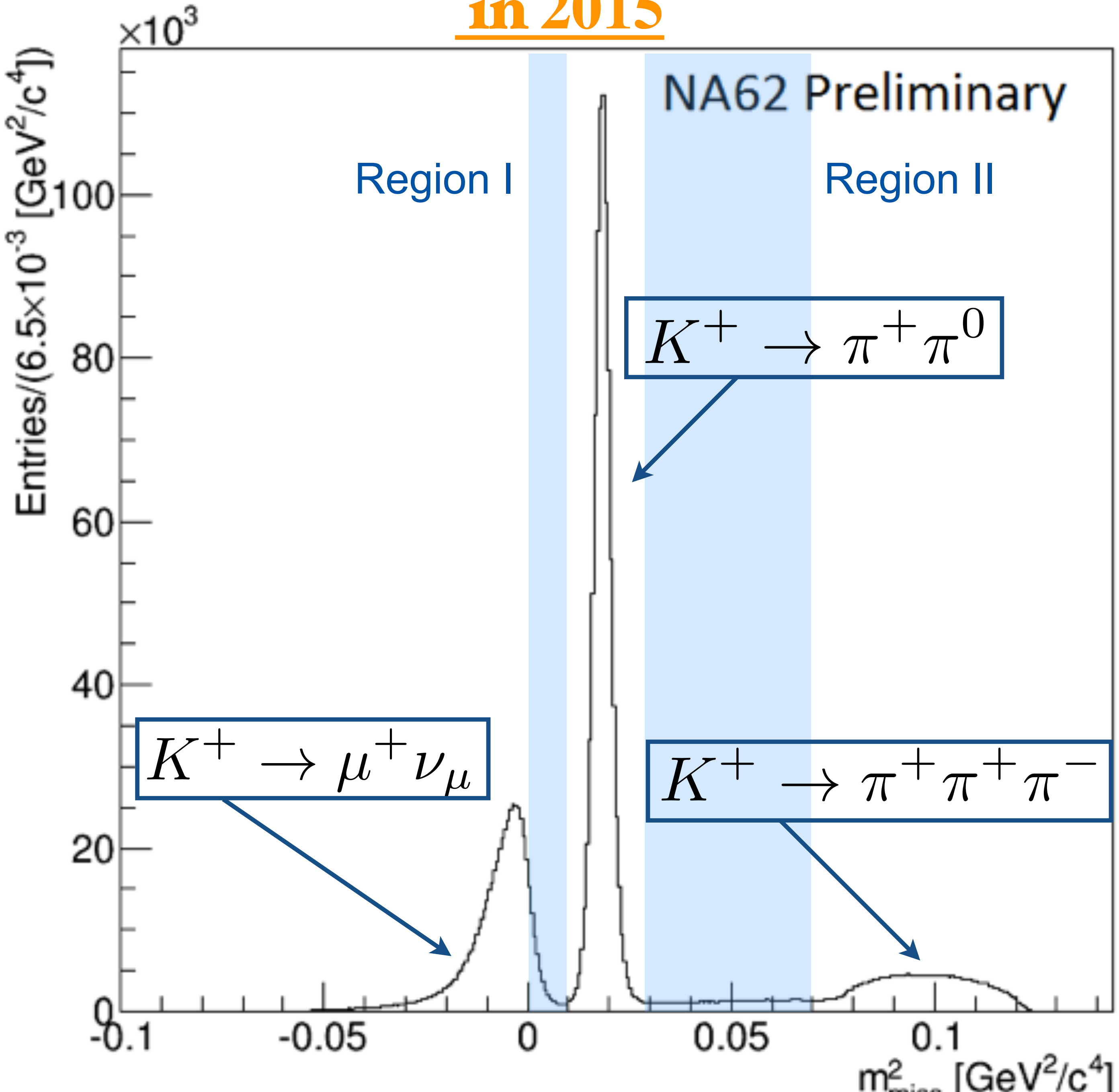


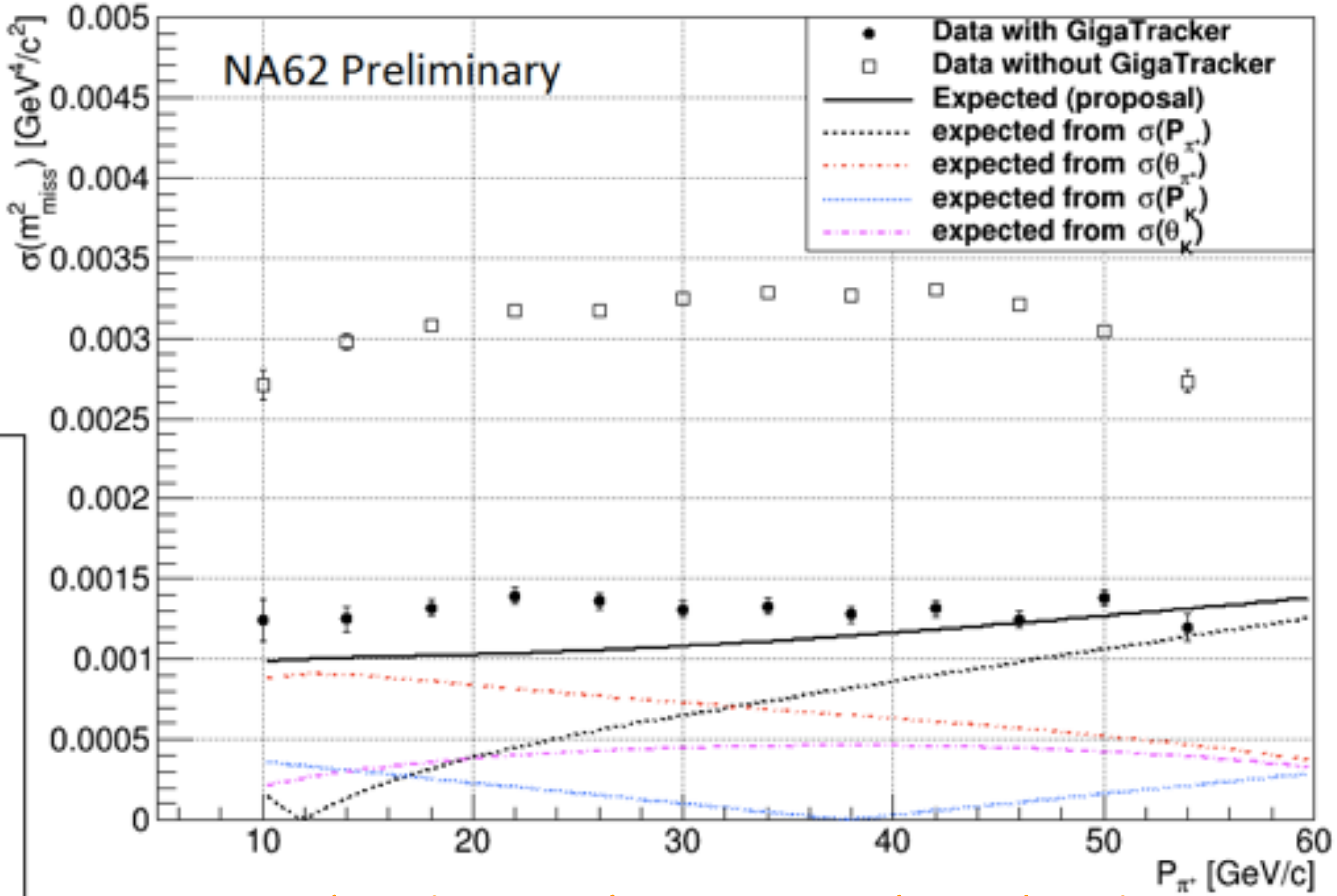
- **One track selection**
  - Single downstream track
  - Beam track matching the downstream track
  - Beam track matching a K^+ signal in Kaon ID
  - Downstream track matching energy in calorimeters
- **Time resolutions**
  - Kaon ID < 100 ps, downstream track < 200 ps
  - Calorimeters < 1-2 ns

2015 data: Kinematics $m^2_{miss} = (P_k - P_{\pi+})^2$

GOAL: $O(10^4 \div 10^5)$ suppression factor of the main K+ decay modes

O(10³) kinematic suppression factor in 2015

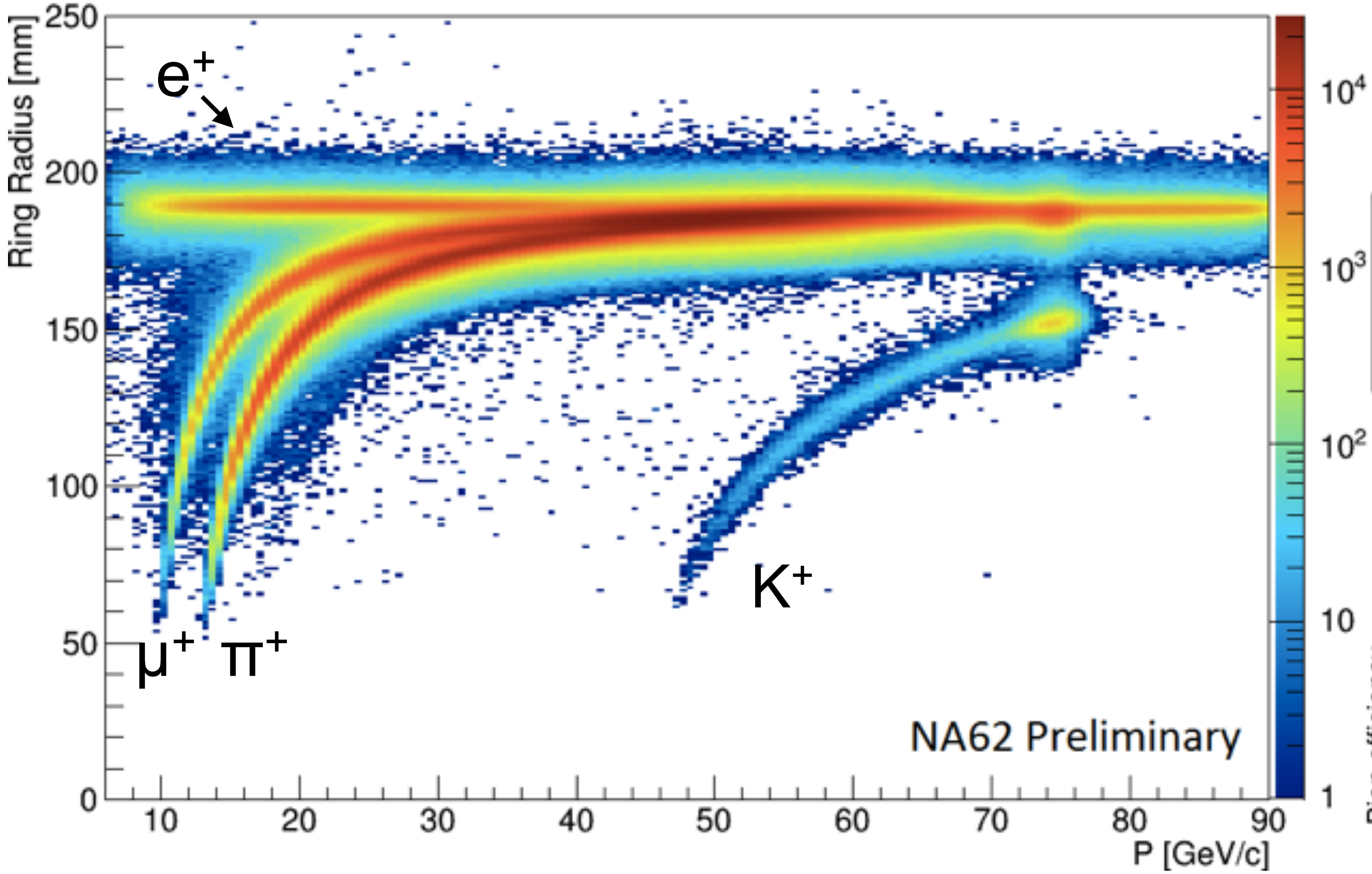




Resolution close to the design

- **Selection**
  - Kaon identification
  - One secondary track identification
  - Vertex reconstructed in the fiducial region (105 m < Z_{vertex} <165 m)
  - $P\pi^+$ < 35 GeV/c (best $K^+ \to \mu^+\nu$ suppression)

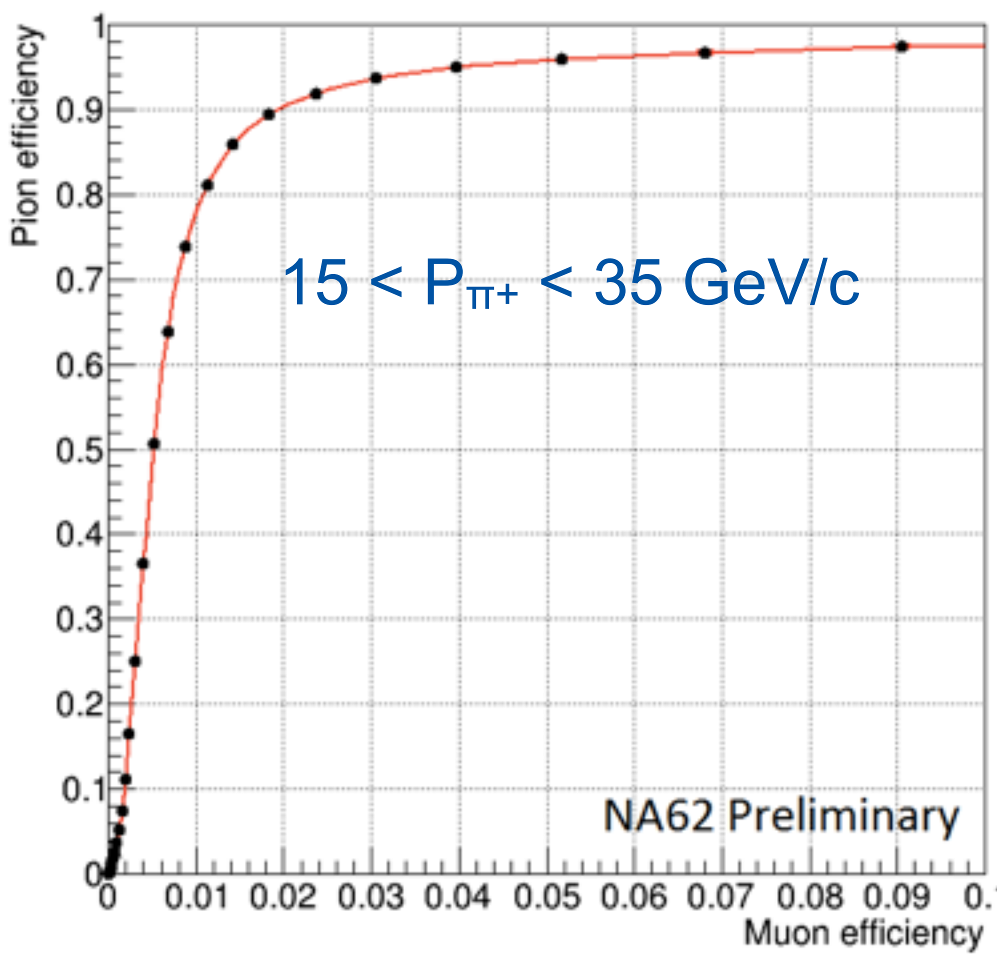
2015 data: Secondary particles ID



RICH (Cherenkov) & Calorimeters

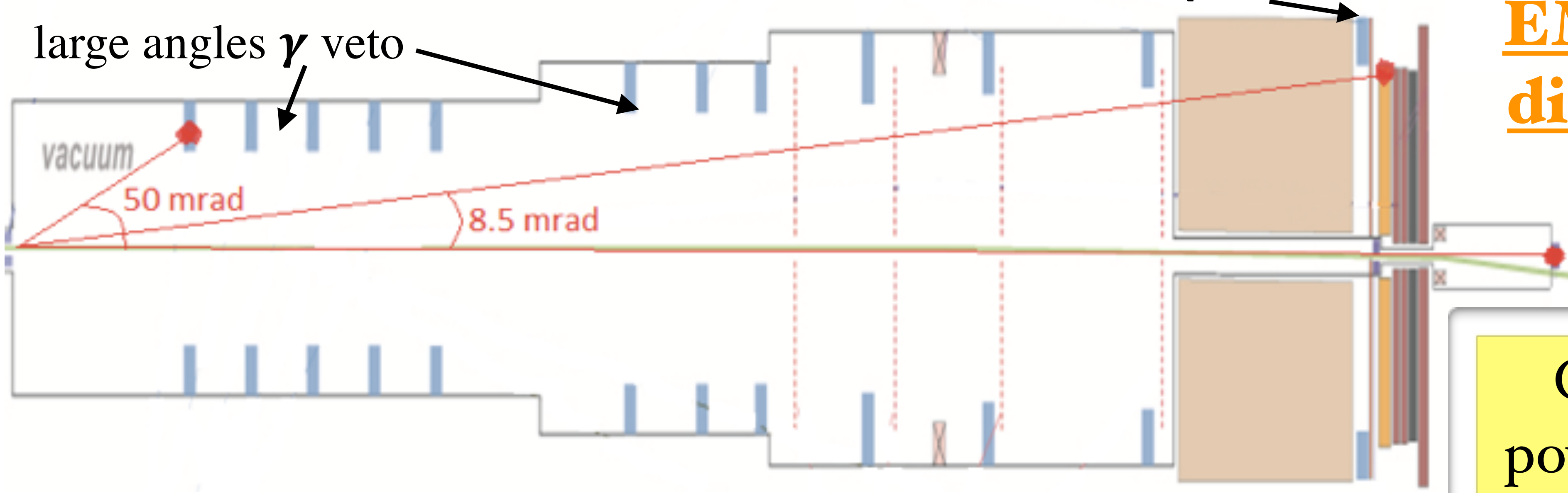
GOAL: $O(10^7)$ μ/π separation to suppress mainly $K^+ \to \mu^+\nu$

$15 < P_{\pi+} < 35$ GeV/c: best μ/π separation in RICH



- time resolution < 100 ps
- 80% π+ efficiency in RICH with $O(10^2)$ μ/π separation
- Simple cut analysis on calorimeters provides $(10^4 \div 10^6)$ μ suppression, with (90%÷40%) π+ efficiency.

2015 data: Photon Rejection

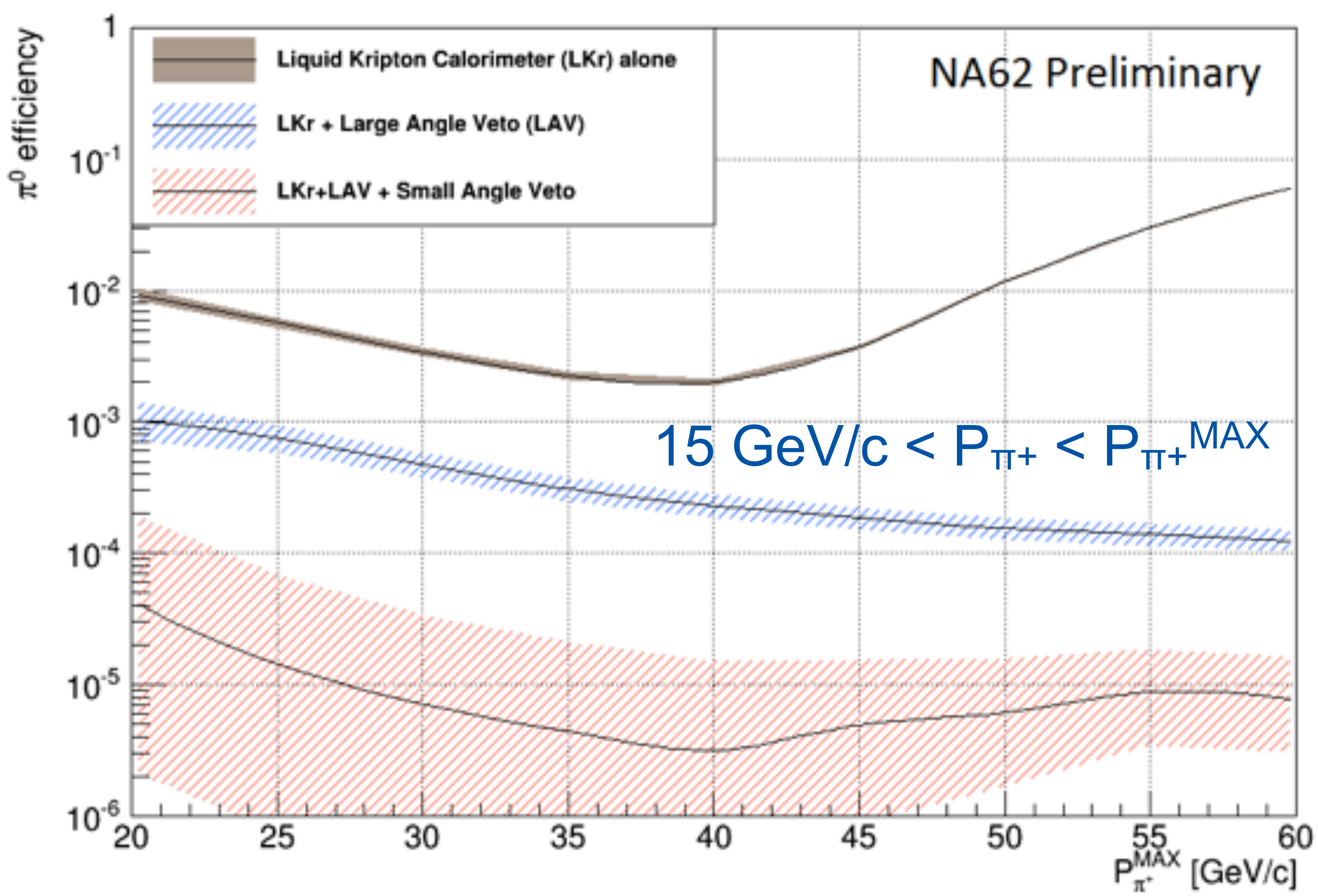


EM calorimeters with different angles range

GOAL: $O(10^8)$ rejection power of π^0 from $K^+ \to \pi^+ \pi^0$

$P_{\pi+} < 35$ GeV/c $\to$ $E_{\pi 0} > 40$ GeV

- efficiency measured on data using $K^+ \to \pi^+ \pi^0$ selected kinematically
- $O(10^6)$ π^0 rejection already obtained
- 2015 measurement statistically limited



Summary from 2015 data quality studies

- **Time resolution:**
  - Close to the design
- **Kinematics:**
  - Resolution close to the design
  - Prospect to reach the desired signal-background separation
- **Pion/Muon ID:**
  - Separation with RICH close to expectations.
  - Study of the separation with calorimeters on going.
  - Results from simple cut analysis promising

- **Photon Vetos**
  - $O(10^6)$ π^0 rejection already obtained.
  - More statistics needed to push the study at the design sensitivity.

NA62 Physics Program

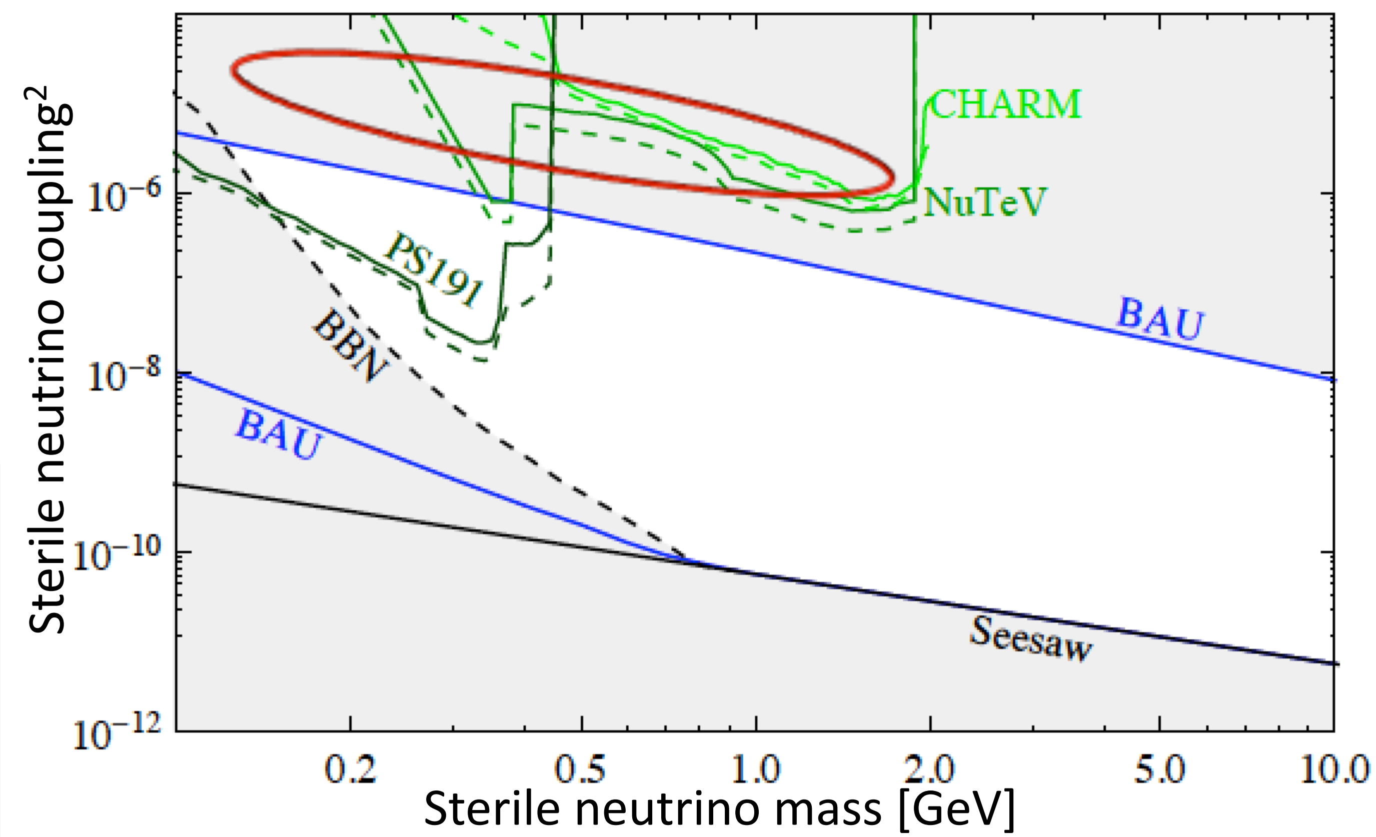
- **Standard Kaon Physics**
  - 10% precision BR($K^+ \to \pi^+ \nu\nu$) measurement
  - Measurements of the BR of all the main K^+ decay modes
  - χPT studies: $K^+ \to \pi^+ \gamma\gamma$, $K^+ \to \pi^+ \pi^0 e^+ e^-$, $K^+ \to \pi^{0(+)} \pi^{0(-)} l^+ \nu$
  - Precision measurement of $R_K = \Gamma(K^+ \to e^+ \nu_e)/(K^+ \to \mu^+ \nu_\mu)$
- **LFV with Kaons**
  - $K^+ \to \pi^+ \mu^\pm e^\mp$, $K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^- l^+ l^+$ searches
- **Heavy neutrino searches**
  - $K^+ \to l^+ \nu_h$ ($\nu_h \to \pi^\pm l^\mp$)
- **π^0 decays**
  - $\pi^0 \to$ invisible, $\pi^0 \to \gamma\gamma\gamma(\gamma)$
- **Dark sector searches**
  - Long living dark photon decaying in $l^+ l^-$ and produced by $\pi^0/\eta/\eta'/\Phi/\boldsymbol{\rho}/\omega$

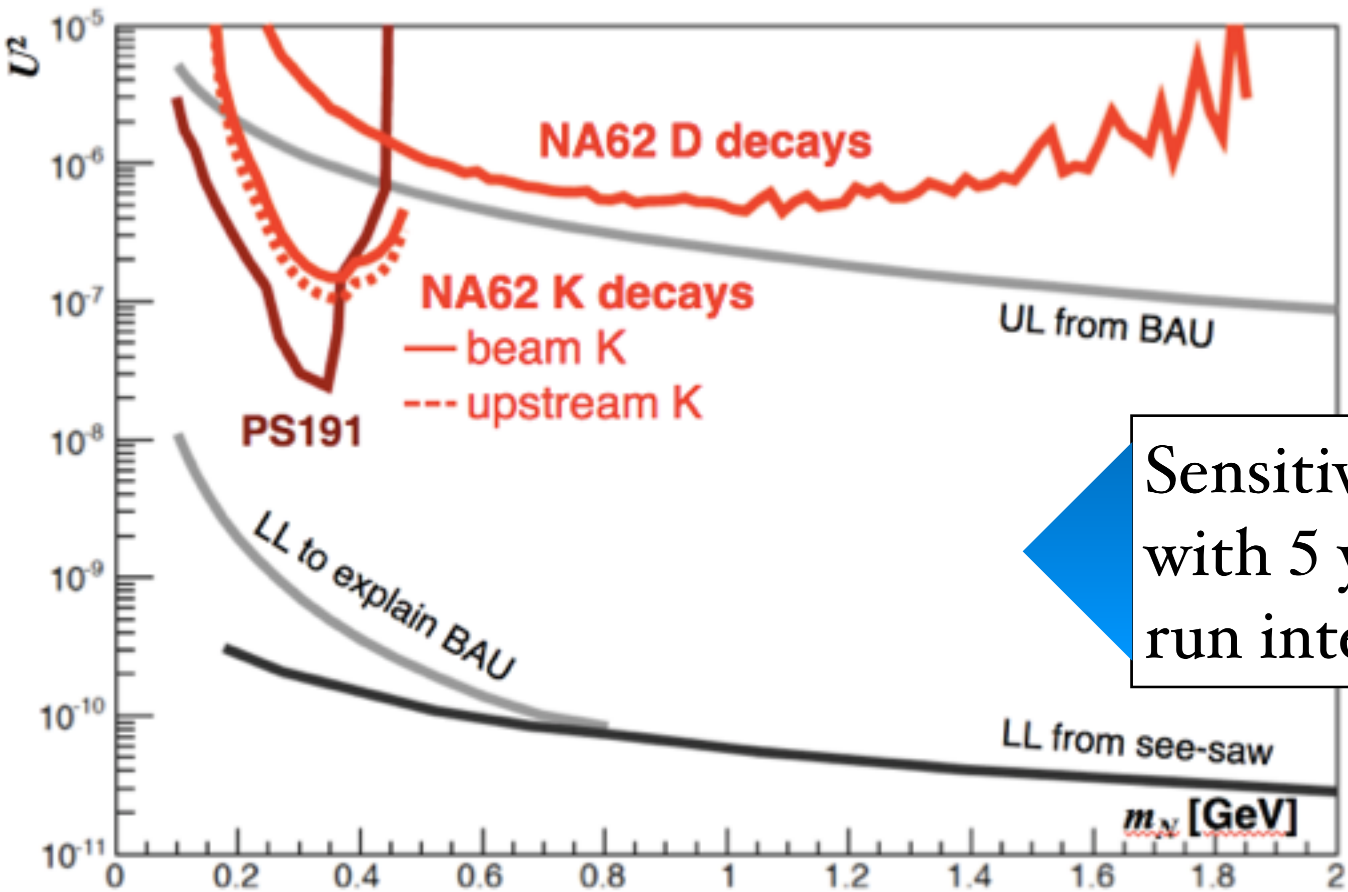
Heavy Lepton Searches in NA62

NA62 intensity allow LFV searches from K decays and also from other mesons (D)

Mesons produced at target might decay into long-lived exotic particles (axion-like decaying in $\gamma\gamma$) reaching the NA62 decay volume

- The simplest signatures correspond to:
- two body semi-leptonic decay πe, πμ for the sterile neutrino
- two body leptonic decay ee, μμ for the dark vectors





Sensitivity for exclusive search for N → eπ or μπ with 5 years of data at nominal 3×10^{12} ppp NA62 K^+ run intensity ($O(10^{15})$ D^{+-}, D_S^{+-} produced per year)

Specific L1 trigger algorithms ready

Conclusions

- Commissioning of the NA62 experiment for $K^+ \to \pi^+\nu\nu$ is almost completed
- From preliminary study of the quality of the data taken at low intensity:
  - Physics sensitivity for $K+\to\pi+\nu\ \nu$measurement in line with the design.
  - A further compelling physics program is going to be addressed.
  - Analysis of data at higher intensity is on going.
- NA62 started to collect new data at the end of April
(~200 days of data taking for 2016). Data taking will continue in 2017 and 2018

NA62 COLLABORATION:
Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax,
Ferrara, Florence, Frascati, George Mason, Glasgow, Liverpool, Louvain-la-Neuve,
Mainz, Merced, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP), Rome I, Rome II, San Luis Potosi, Stanford, Sofia, TRIUMF, Turin, UBC

Bibliography

[1] J. Brod, M. Gorbahn and E. Stamou, \Two-Loop Electroweak Corrections for the K+ --> pi+ nu nubar Decays," Phys. Rev. D 83 (2011) 034030 [arXiv:1009.0947 [hep-ph]].

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

[3] E949 COLLABORATION; ARTAMONOV, A.V. ET AL. New Measurement of the K+ --> pi+ nu nubar branching ratio. **Phys. Rev. Lett. 101 191802**, 2008.

[4] BURAS, A. J. et al. Patterns of Flavour Violation in the Presence of a Fourth Generation of Quarks and Leptons. **TUM-HEP-750-10; e-Print: arXiv:1002.2126**, 2010.

[5] BLANKE, M. et al. Rare K and B Decays in a Warped Extra Dimension with Custodial Protection. **JHEP 0903:108, e-Print: arXiv:0812.3803 [hep-ph]**, 2009.

[6] BLANKE, M. et al. FCNC Processes in the Littlest Higgs Model with T-parity: a 2009 Look. **Acta Phys.Polon.B41:657,2010 e-Print: arXiv:0906.5454 [hep-ph]**, 2009.

[7] ALTMANNSHOFER, W.; BURAS, A. J.; GORI, S.; PARADISI, P.; STRAUB, D. M. ET AL. Anatomy and Phenomenology of FCNC and CPV Effects in SUSY Theories. **Nucl. Phys. B830**, 2010.