The 3rd International Conference on Particle Physics and Astrophysics

# Search for $K^+ \rightarrow \pi^+ \nu \nu$ at NA62


Silvia Martellotti*, on behalf of NA62 Collaboration

*INFN Laboratori Nazionali di Frascati & CERN


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# Outline

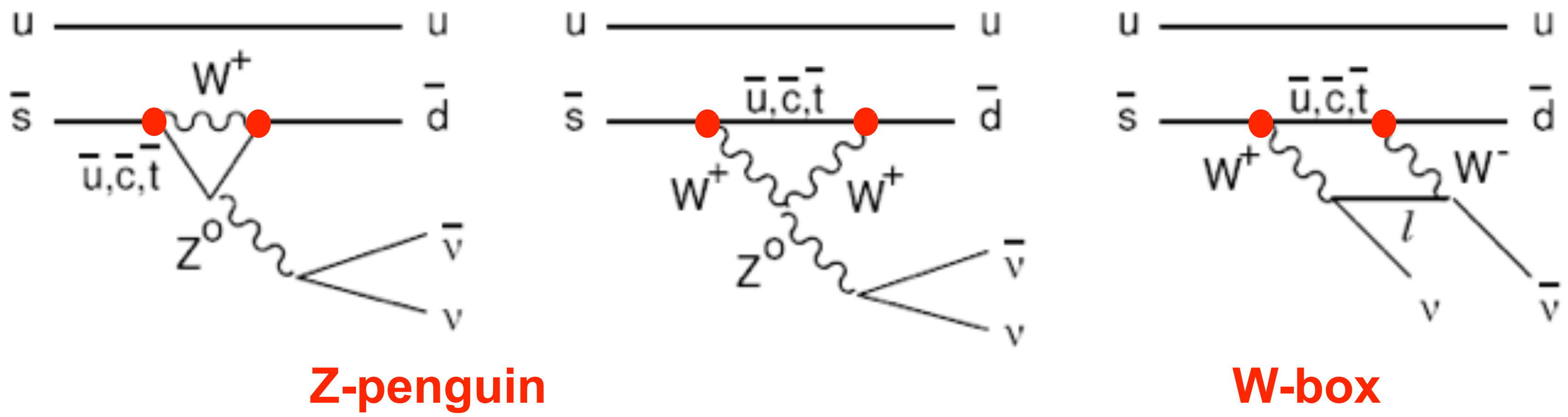
- Theoretical introduction to the $K \rightarrow \pi\nu\nu$ rare decays
- NA62 experiment at the CERN SpS
  - Aim and strategy for the $BR(K^+ \rightarrow \pi^+\nu\nu)$ measurement
  - Detector overview
  - Preliminary results with NA62 data
  - Prospects

# SM theoretical framework

The $K^+ \rightarrow \pi^+\nu\nu$ decay is extremely suppressed

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

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




Is characterized by a theoretical cleanness in the SM prediction of the BR($K^+ \rightarrow \pi^+\nu\nu$): loops and radiative corrections are under control.

**Highly suppressed & Very well predicted** ▶ **Excellent laboratory complementary to LHC**

Stringent test of the SM and possible **evidence for New Physics**

# Past measurement and prediction

## Current theoretical prediction:

$BR(K^+ \rightarrow \pi^+ \nu\nu)_{SM} = (9.11 \pm 0.72) \times 10^{-11}$

$BR(K_L \rightarrow \pi^0 \nu\nu)_{SM} = (3.00 \pm 0.30) \times 10^{-11}$

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

- Main contribution to the errors comes from the uncertainties on the SM input parameters
- Intrinsic theoretical uncertainties (1-3%) slightly larger for the charged channel because of the corrections from lighter-quark contributions

## Experimental status:

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

Only measurement obtained by E787 and E949 experiments at BNL with **stopped kaon decays (7 events)**

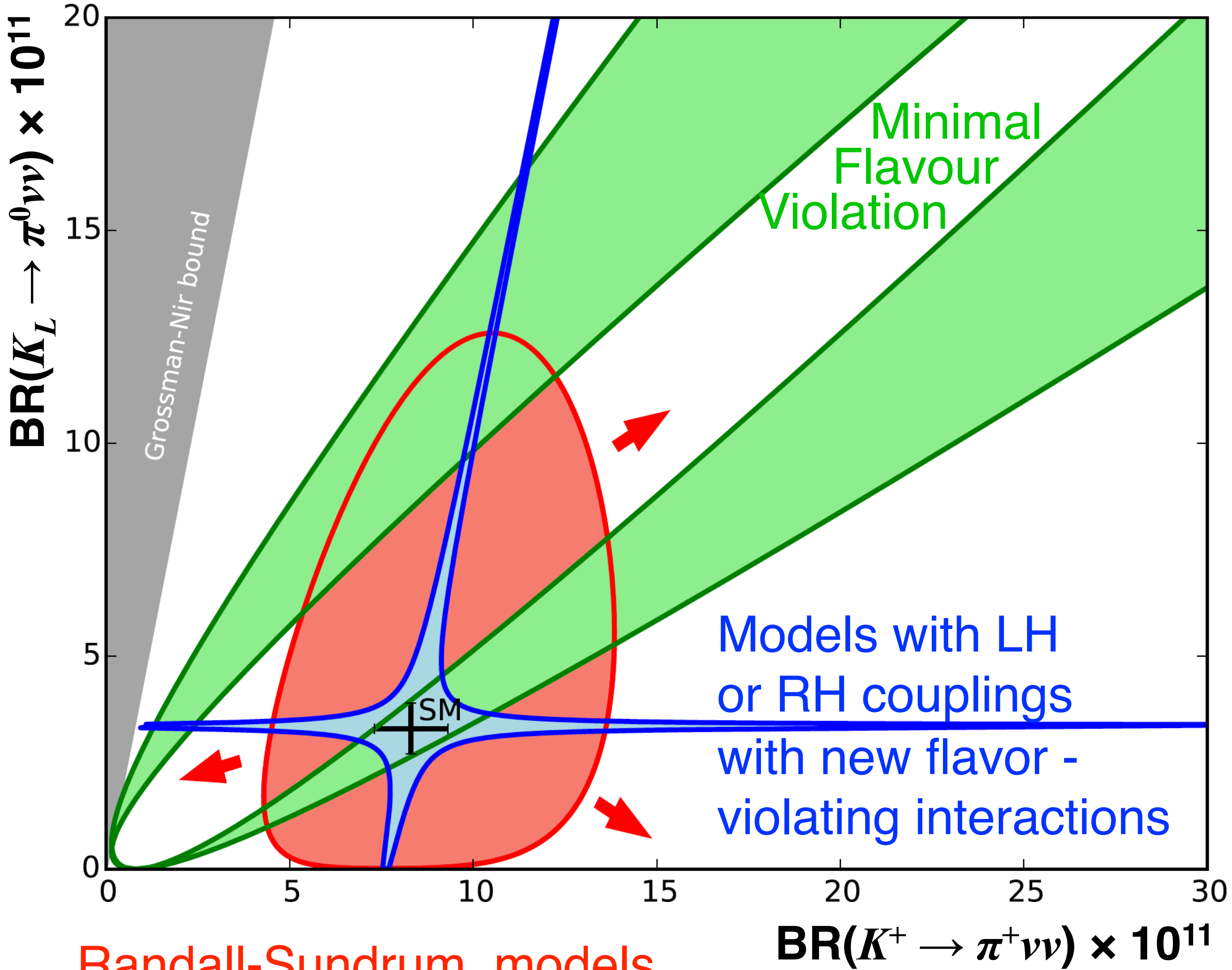
- Gap between theoretical precision and large experimental error motivates a strong experimental effort. **Significant new constraints can be obtained.**

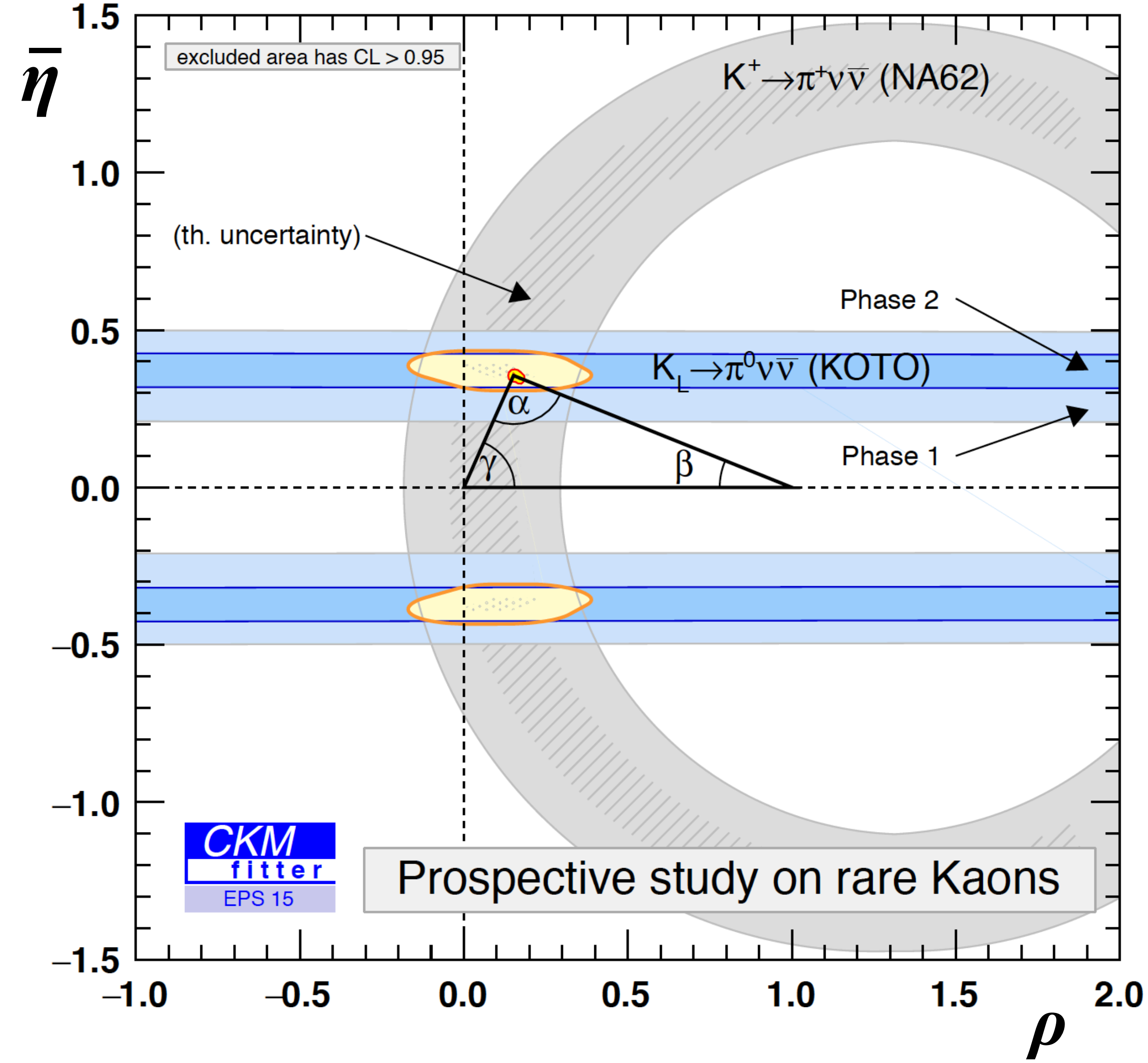
Neutral decay $K_L \rightarrow \pi^0 \nu\nu$ has never been measured

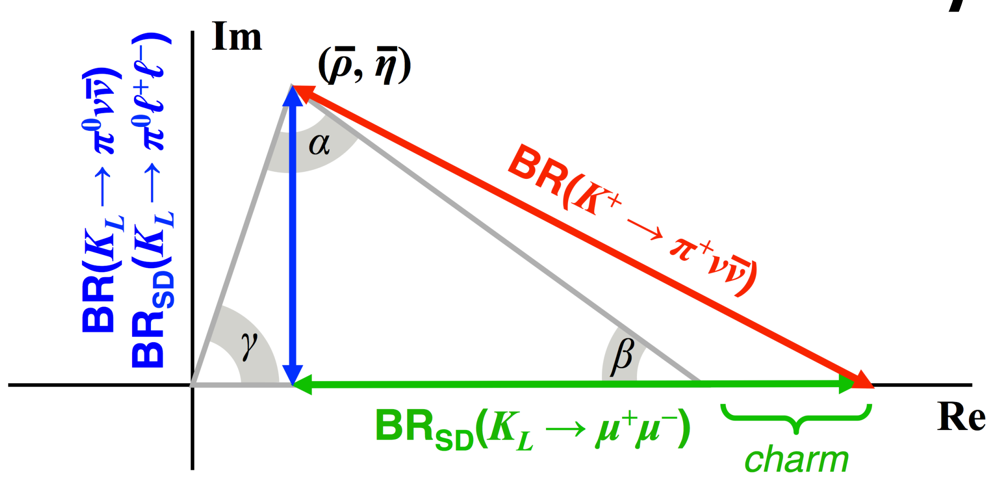
# New Physics from K→πνν decays

Measurement of BR of charged ($K^+ \to \pi^+\nu\nu$) and neutral ($K_L \to \pi^0\nu\nu$) modes can determine the **unitarity triangle** independently from B inputs

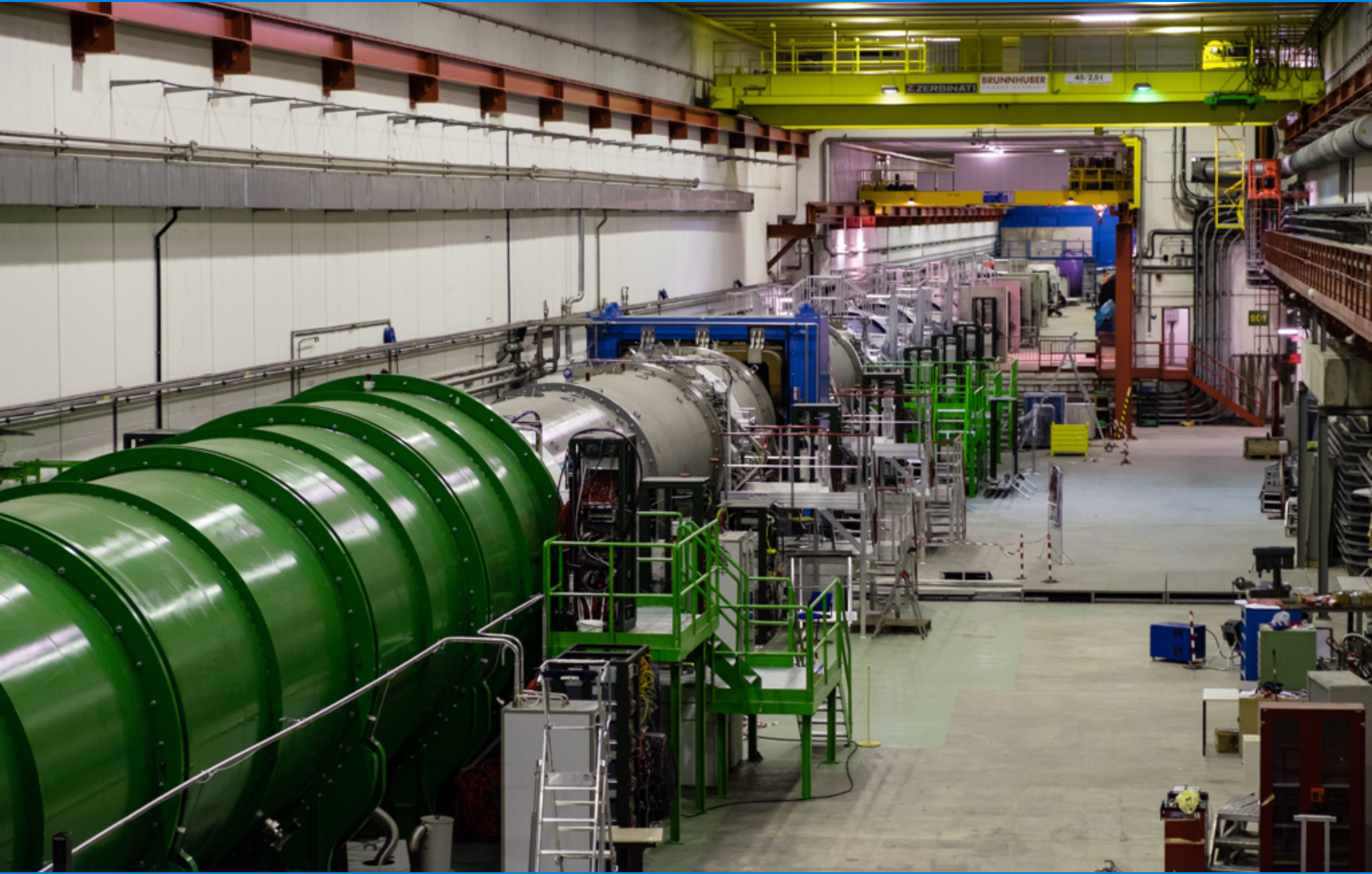
and can discriminate among NP scenarios:



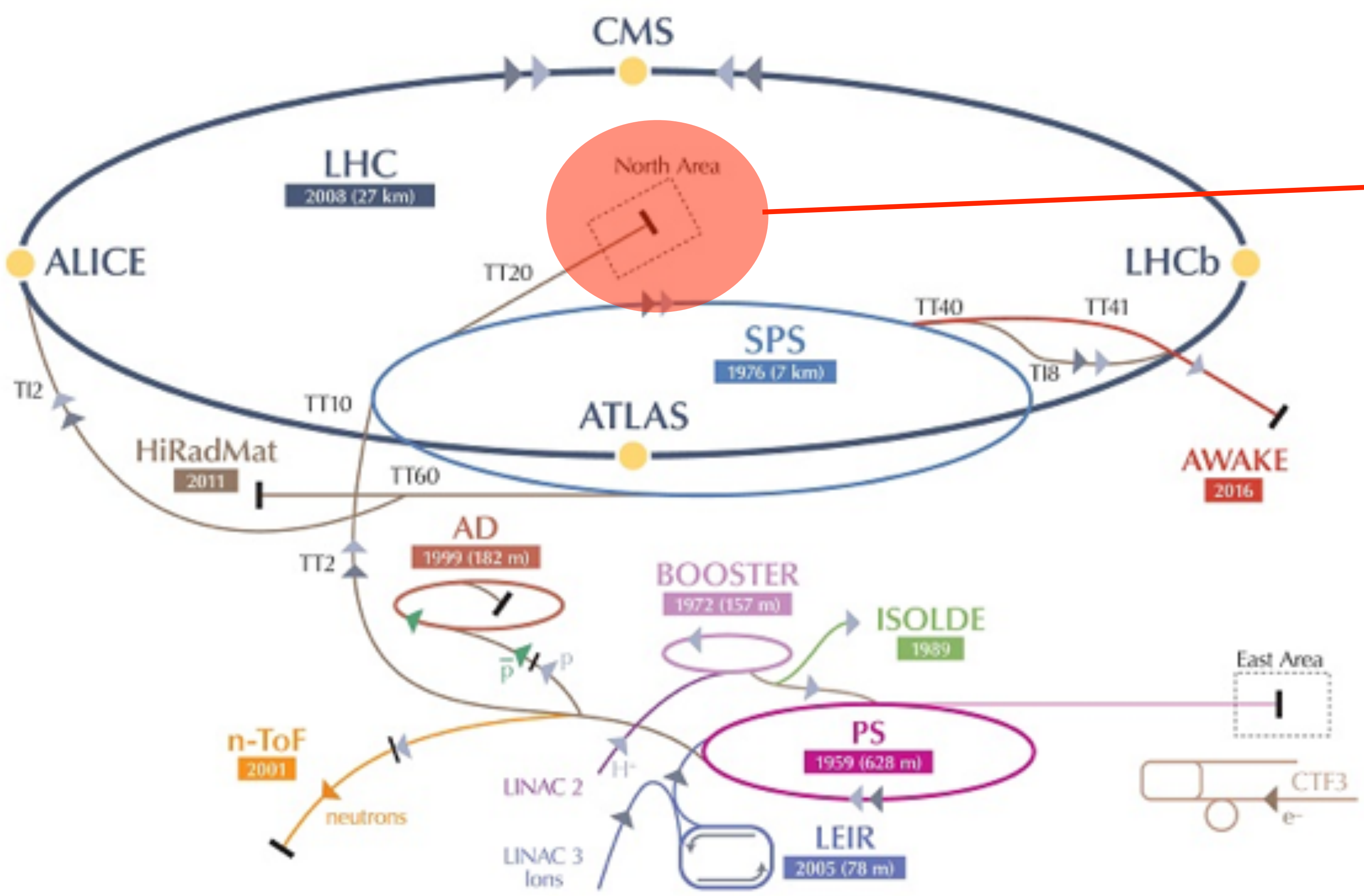



# NA62 Experiment



# Kaon at CERN SPS

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




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

**400 GeV/c protons** impinge on a beryllium target and produce a secondary charged beam: **6% are $K^+$** (mixed with π and protons).

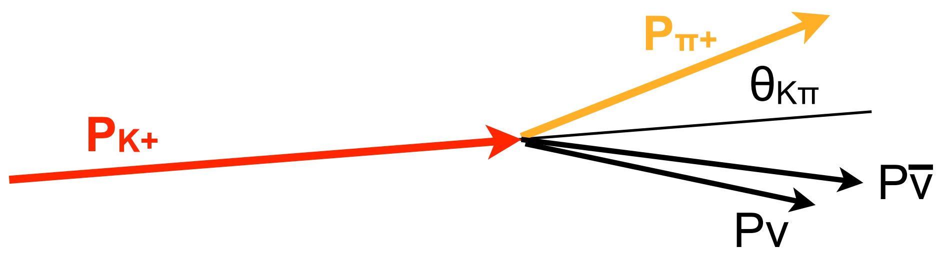
Signal acceptance considerations drive the choice of a **75 GeV/c $K^+$**

(1% momentum bite, ~ 100 μrad divergence)

# NA62 Goal and Time Scale

Design criteria: **kaon intensity, signal acceptance, background suppression**

**Decay in flight technique.**
Kaons with high momentum.
Signal signature: **$K^+$ track** + **$\pi^+$ track**




**Basic ingredients:**

- O(100 ps) Timing between sub-detectors
- $O(10^4)$ Background suppression from kinematics
- $O(10^7)$ μ-suppression ($K^+ \to \mu^+\nu$)
- $O(10^7)$ $\gamma$-suppression (from $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$)

$BR(K^+ \to \pi^+\nu\nu)$ with 10% accuracy: O(100) SM events + control of systematics at % level

Assuming 10% signal acceptance and a $BR(K^+ \to \pi^+\nu\nu) \sim 10^{-10}$ at least **$10^{13}$ $K^+$ decays are required**

**2014** Pilot Run

**2015** Commissioning Run

**2016** Commissioning + Physics Run → SM sensitivity reached $O(10^{-10})$.

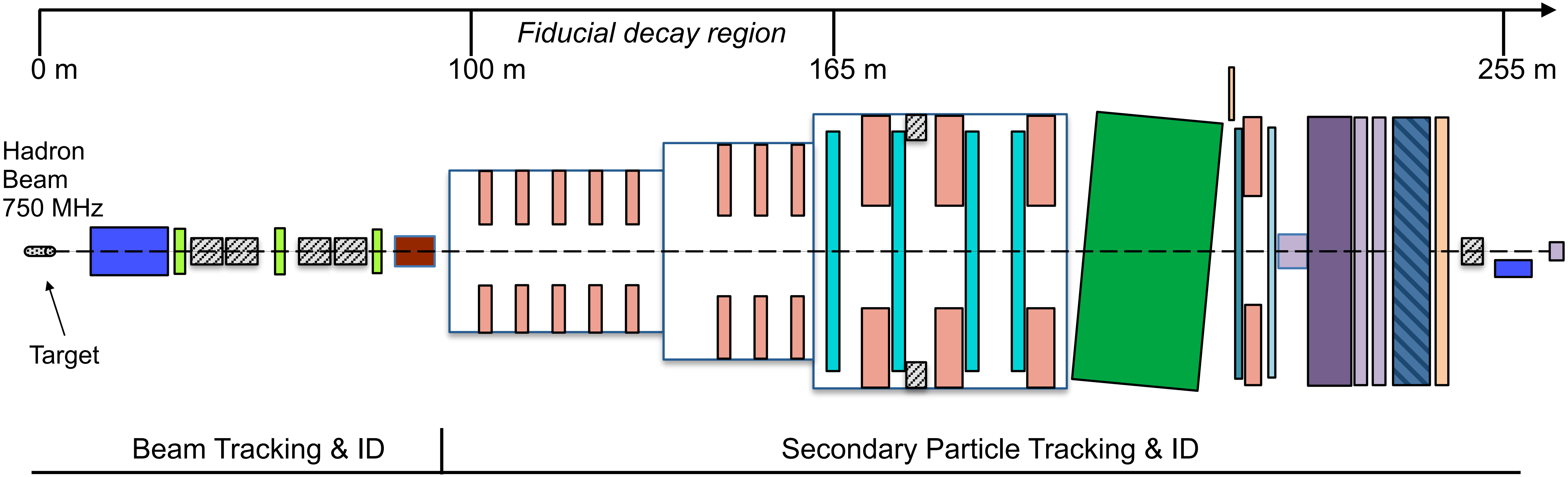
**2017** Physics Run on going (May-October) → Improve on the present state of the art.

**2018** >= 4 months of data taking expected…

…The target of $10^{13}$ $K^+$ decays by end of 2018 is reachable.

# NA62 Apparatus

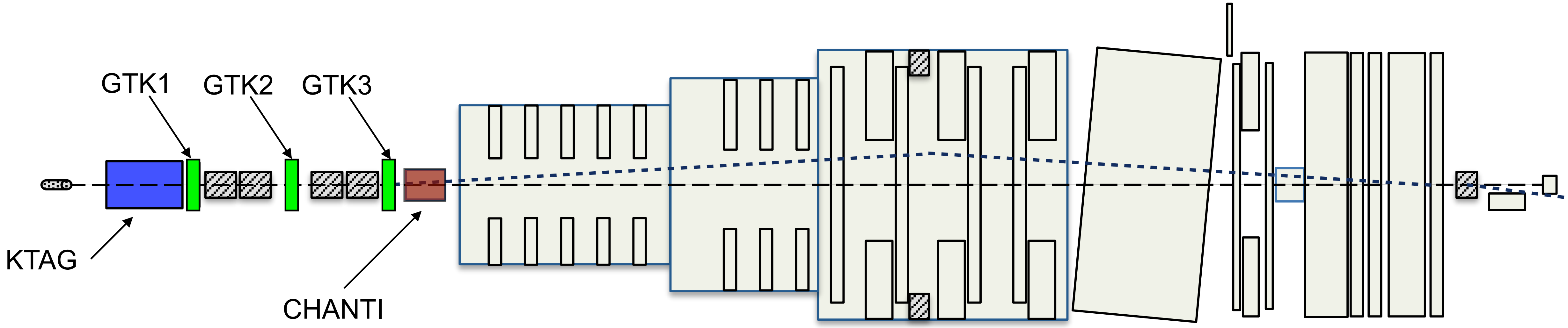
**170 m long** region starting about 100 m downstream of the beryllium target.
Useful $K^+$ decays will be detected in a **65 m long fiducial volume.**




Approximately cylindrical shape around the beam axis for the main detectors.
Diameter varies from 20 to 400 cm.

Each detector send ~ 10 MHz of raw input data to the Level 0 trigger (FPGA) that selects 1 MHz of events. L1 and L2 triggers (software) guarantee a maximum of 10 kHz of acquisition rate.

# Beam ID & Tracking: KTAG, GTK, CHANTI




**KTAG** is an upgrade of CERN **Cedar: ČE**renkov **D**ifferential counter with **A**chromatic **R**ing focus blind to all particles but kaons of appropriate momentum (75 GeV, K+ rate:~45MHz).

*Steel vessel, 4.5 m long, filled with compressed nitrogen. New photo-detectors & readout.*

**$\sigma_t$ ~70 ps**
**Efficiency > 99%**

**GTK**: **G**iga**T**rac**K**er Spectrometer for $K^+$ momentum and timing measurement

750 MHz beam environment. *Inside an achromat in vacuum, 3 stations of 18000 silicon pixels (140 KHz/pixel) matching the beam dimensions (60 x 27 mm² divided into 10 read-out chips).*

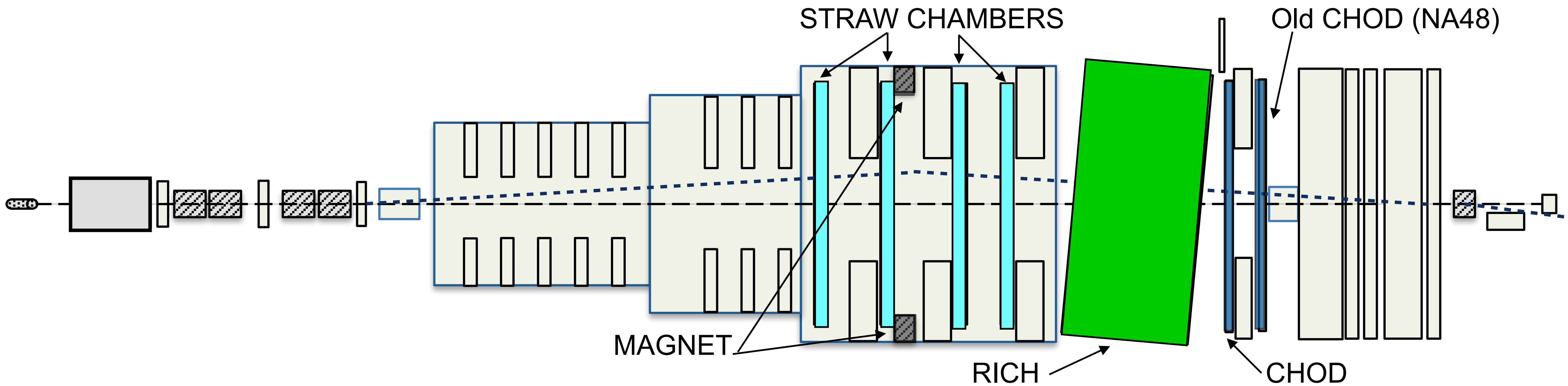
**$\sigma_t$ ~100 ps**
**$\sigma_{dx,dy} \approx$ 0.016 mrad**
**$\Delta P/P < 0.4\%$**

**CHANTI**: **CH**arged **ANTI**counter detector: charged particle veto to reduce the background induced by inelastic interactions of the beam with the GTK3

*6 stations of X-Y plastic scintillator bars coupled with optical fibers.*

**Efficiency > 99%**

# Secondary ID & Tracking: STRAW, RICH




**Spectrometer** with **STRAW** tubes for secondary particle momentum measurement

*4 chambers (4 layers < 0.5 $X_0$) in vacuum, 7168 STRAW tubes with ⊘1cm. Magnet provides a 270 MeV/c momentum kick in the horizontal plane.*

**$\sigma_t$ ~ 6 ns**

**$\sigma_{dx,dy}$ ~130 μm**

**CHOD**: **CH**arged **OD**oscope, plastic scintillator covering the acceptance that provide fast signal to drive the L0 trigger and the data acquisition

**Old CHOD $\sigma_t$ ~ 250 ns, CHOD $\sigma_t$ ~ 1 ns**

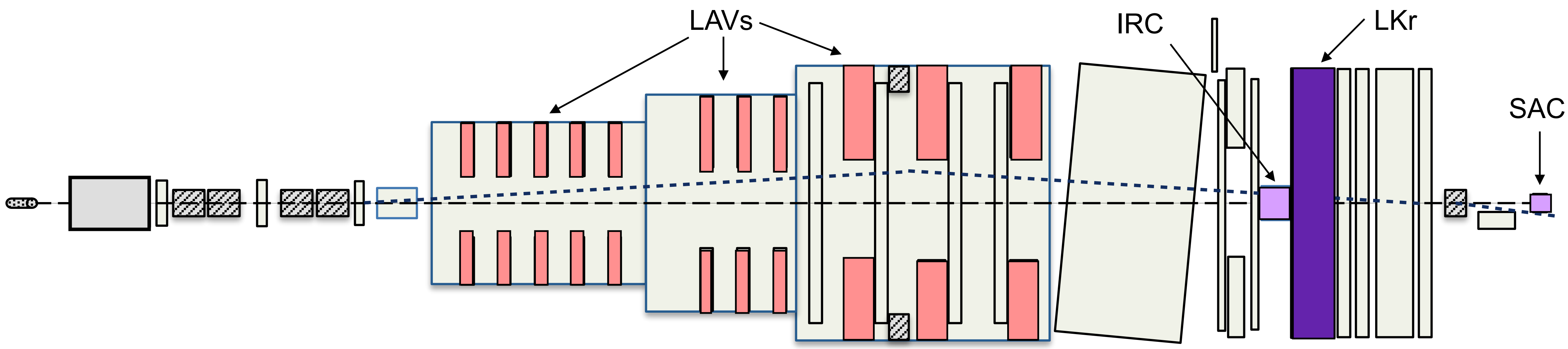
**RICH**: **R**ing **I**maging **CH**erenkov detector for the secondary particle identification

*17 m long tank filled with neon gas (1 atm).*
*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 ~ $10^{-2}$**

**$\sigma_t$ of a ring < 100 ps**

# Photon Veto: LAV, SAC & IRC




**LAV**: **L**arge **A**ngle **V**eto. 12 stations to veto $\gamma$ with angles 8.5 <θ <50 mrad

*Lead glass crystals read out by PMTs. First 11 stations are in vacuum. Each LAV station is made of 4 or 5 rings of crystals (160 – 256 lead glass blocks).*

**$\sigma_t$ ~ 1 ns**
**$10^{-3}$ to $10^{-5}$ inefficiency**
**(on $\gamma$ down to 150 MeV)**

**IRC**: **I**nner **R**ing **C**alorimeter. **SAC**: **S**mall **A**ngle **C**alorimeter. To veto $\gamma$ with angles <1 mrad

*Lead and plastic scintillator plates. Electromagnetic showers detected through Shashlik calorimeters*

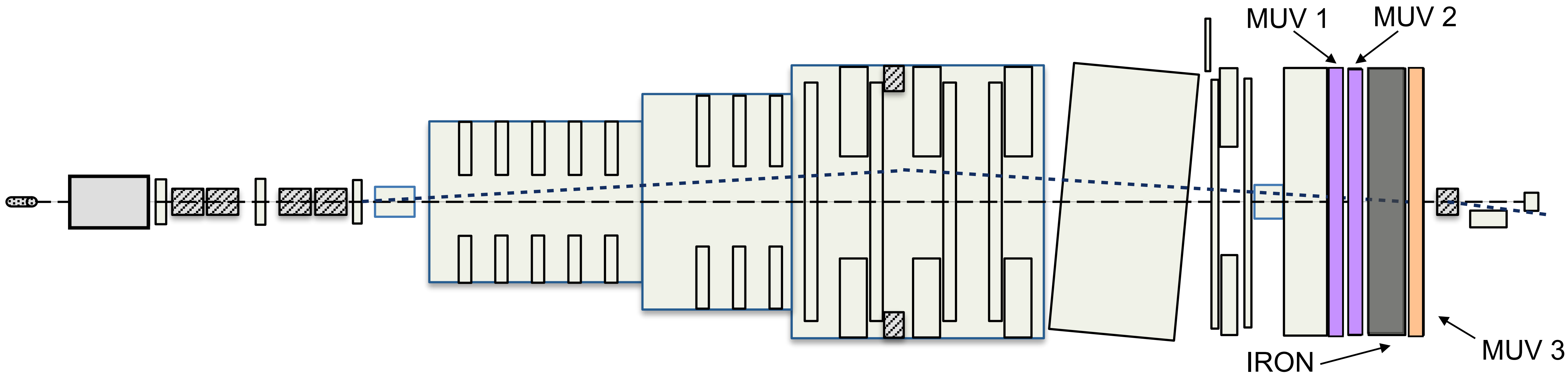
**$\sigma_t$ < 1 ns**
**$10^{-4}$ inefficiency on $\gamma$ with energy > 1 GeV**

**NA48 LKr** Calorimeter: to veto $\gamma$ with angles 1 <θ <8.5 mrad and for PID.

*Ionization chamber + liquid Krypton, 2x2 cm2 cells. Inherited from NA48 and equipped with new readout electronics.*

**$\sigma_t$~500 ps for electromagnetic clusters with energy > 3 GeV**
**$\sigma_t$~1 ns for hadronic and MIP clusters**
**$\sigma_{dx,dy}$ ~1 mm**
**$10^{-5}$ inefficiency on $\gamma$ with energy > 10 GeV**

# Muon Veto: MUV1, MUV2, MUV3




**MUV 3:** Efficient fast **M**uon **V**eto used in the hardware trigger level.

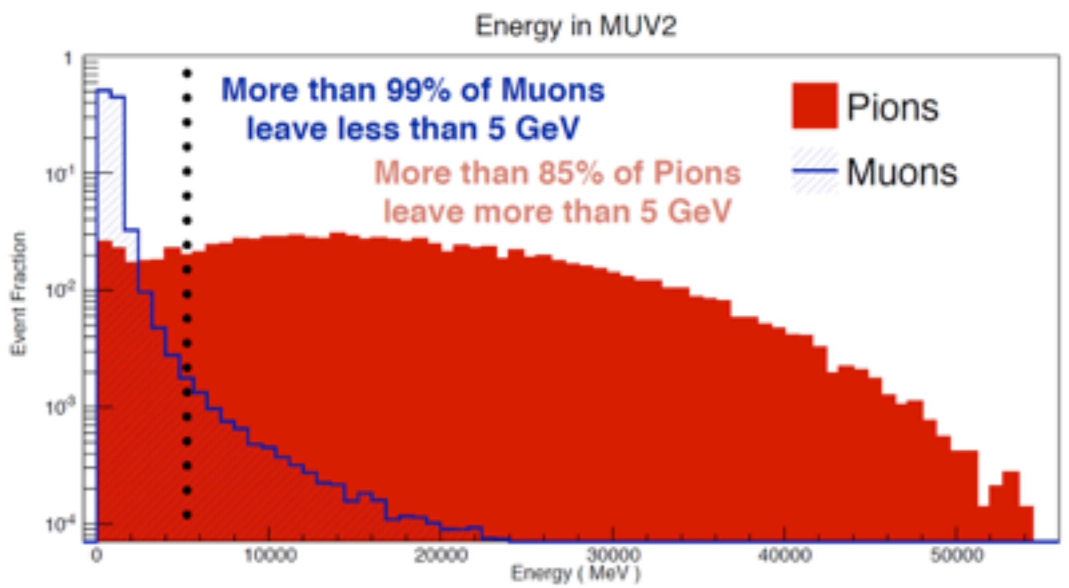
*Placed after an iron wall. 1 plane of 148 5cm thick scintillator tiles, each readout by 2 PMTs. Used in L0 trigger: reduction factor >10. Muon Rate: 10 MHz.*

**Time resolution ~500 ps**
**Muon detection efficiency ~99.5%**

**MUV 1** and **MUV 2**: Hadronic calorimeters for the μ/π separation

*2 modules of iron-scintillator plate sandwiches. Readout with LKr electronics.*

**cluster reconstruction within 20 ns from the track time at ±150 mm around the expected impact point**

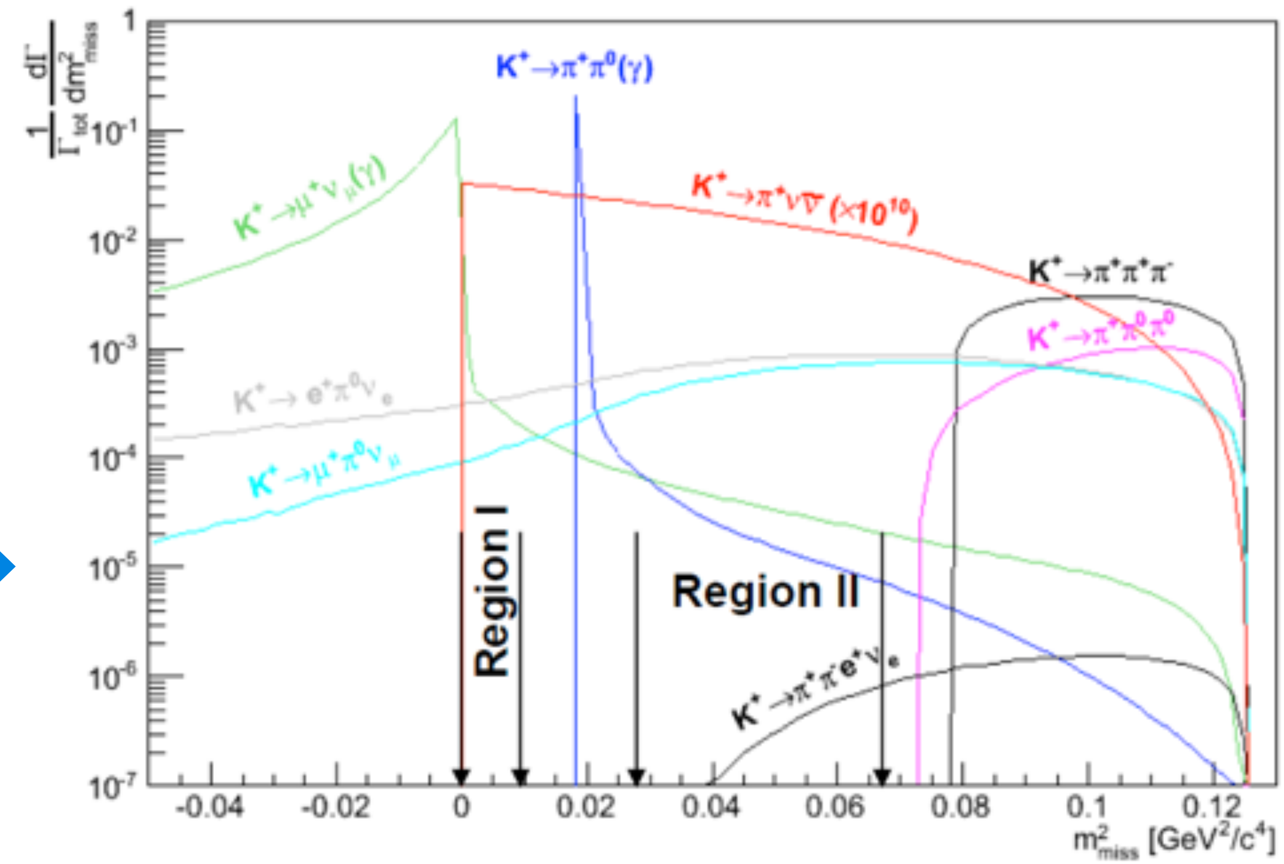


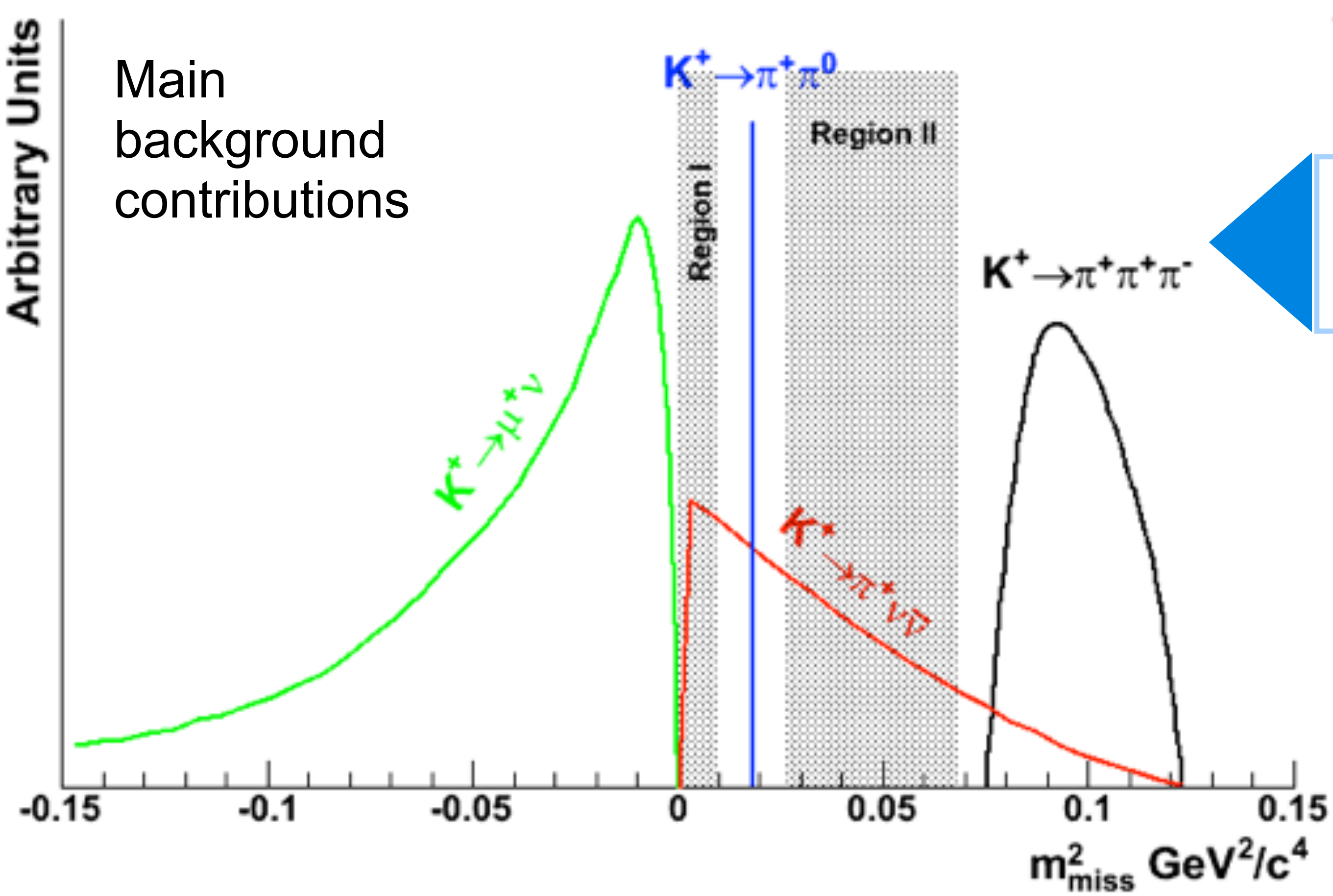
# Analysis Strategy

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

*Where the daughter charged particle is assumed to be a pion*

Theoretical $m^2_{miss}$ distribution for signal and backgrounds of the main $K^+$ decay modes: (signal is multiplied by a factor $10^{10}$).




**2 signal regions**, on each side of the $K^+ \to \pi^+\pi^0$ peak (to eliminate 92% of the $K^+$ width)

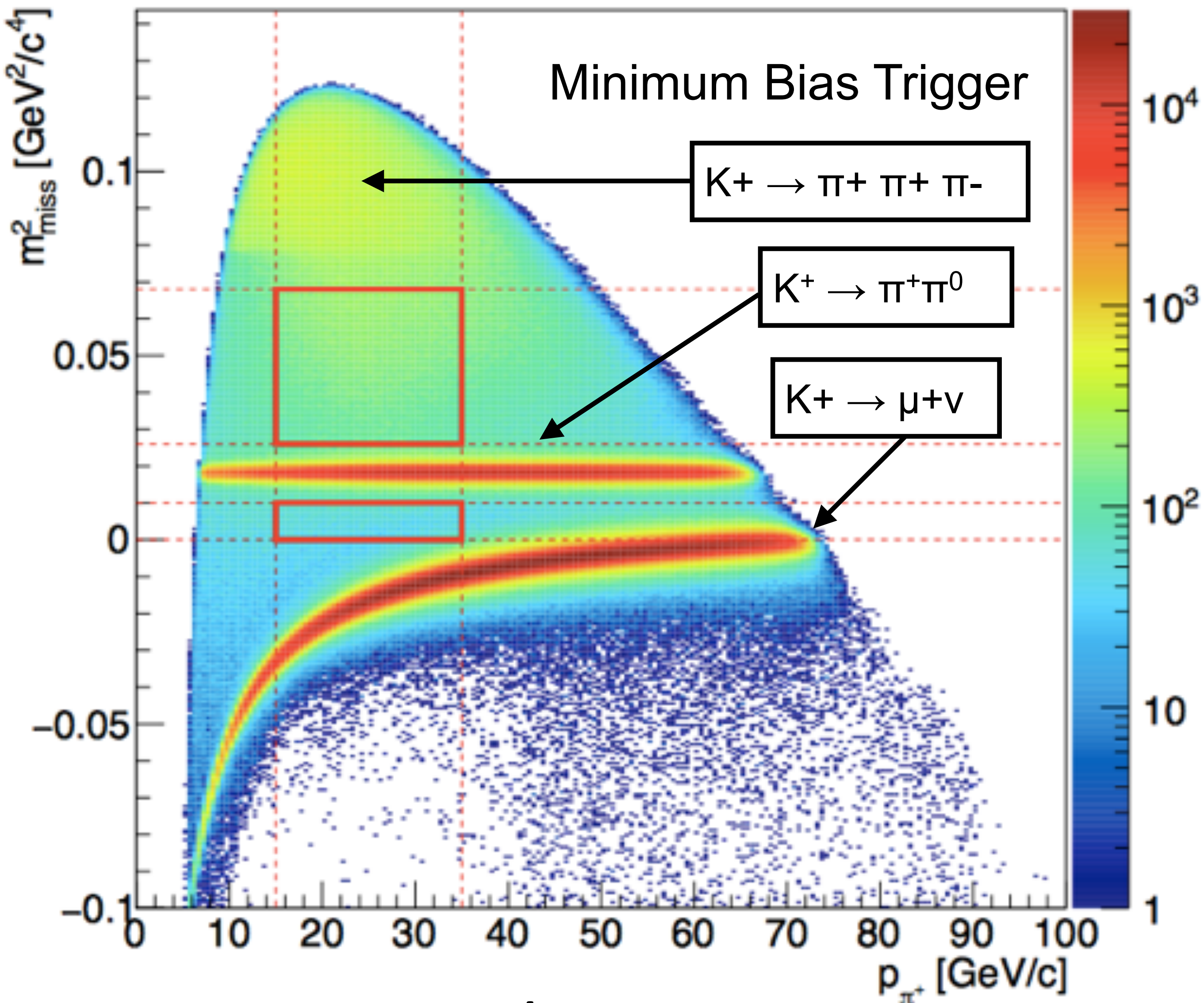
**Main background sources:**

- $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$ non gaussian resolution and radiative tails
- $K^+ \to \pi^+\pi^+\pi^-$ non gaussian resolution tails
- decays with neutrino in final state

# 2016 Data

**2016 data Goal**: study the single event sensitivity of the apparatus down to 1 event over $10^{10}$ (reach **SM-expectation sensitivity**).

**Data sample**: preliminary exploratory analysis has been performed on about **$2.3 \times 10^{10}$ $K^+$ decays** in fiducial region (**5%** of the total statistics: main physics sample at 40% of the nominal beam intensity)




**$15 < P_{\pi+} < 35$ GeV/c** selected,
to leave at least 40 GeV of missing energy.

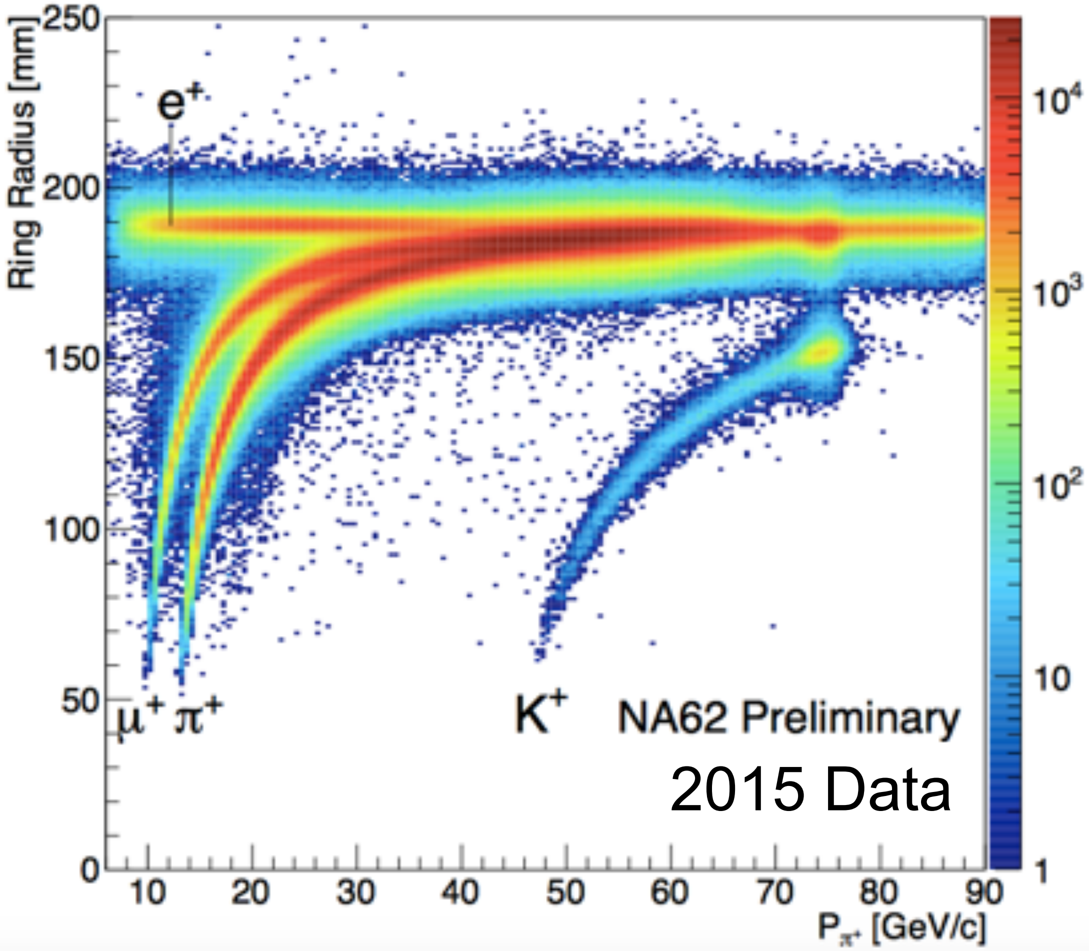
**Single downstream track selection with $K^+$ matching:**

- Timing $\pi^+$:
  $\sigma(T_{CHOD})$ ~ 250 ps, $\sigma(T_{RICH})$ ~ 150 ps
- Timing K+:
  $\sigma(T_{KTAG})$ ~ 80ps, $\sigma(T_{GTK})$ ~ 100 ps
- Spatial matching, i.e intersection of GTK and Straw track:
  $\sigma$(CDA) ~ 1.5 mm, $115 < Z_{vertex} < 165$ m
- Mis-tagging probability: ~1.7%

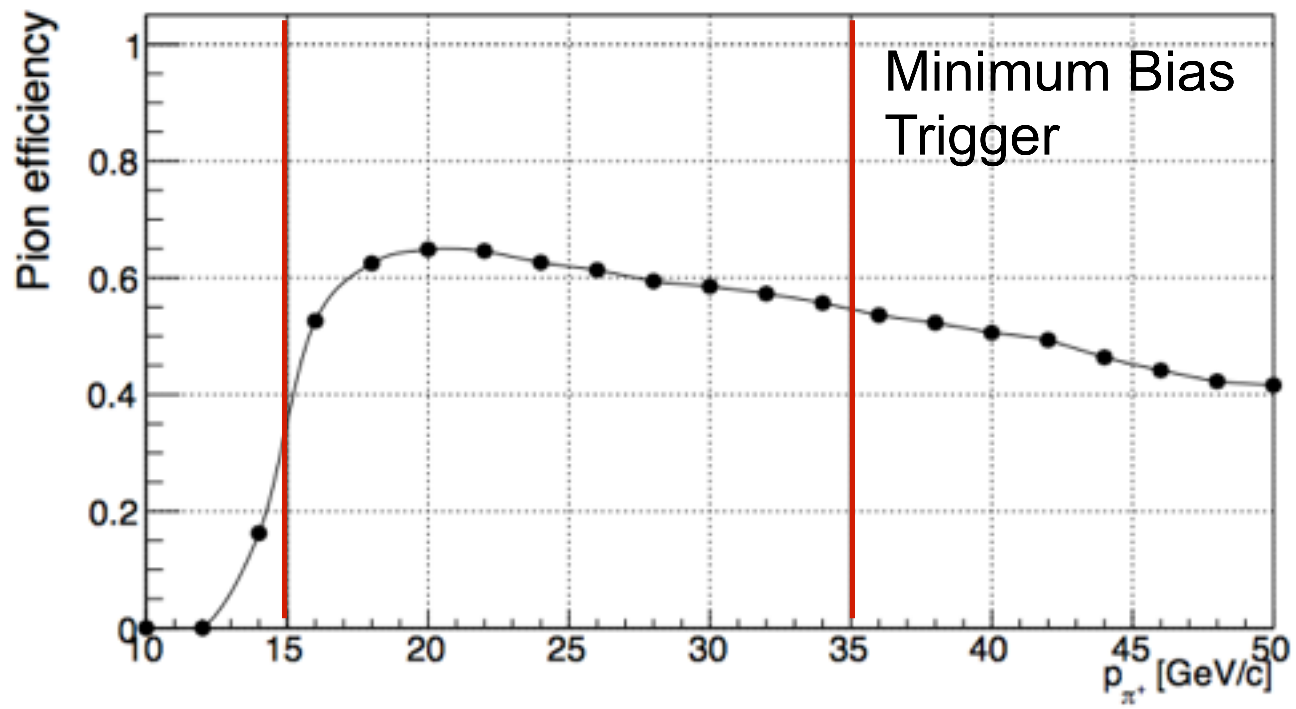
Measured kinematical background suppression:
$K^+ \rightarrow \pi^+\pi^0$: $6\times10^{-4}$; $K^+ \rightarrow \mu^+\nu$: $3\times10^{-4}$.

# Particle ID: π-μ separation

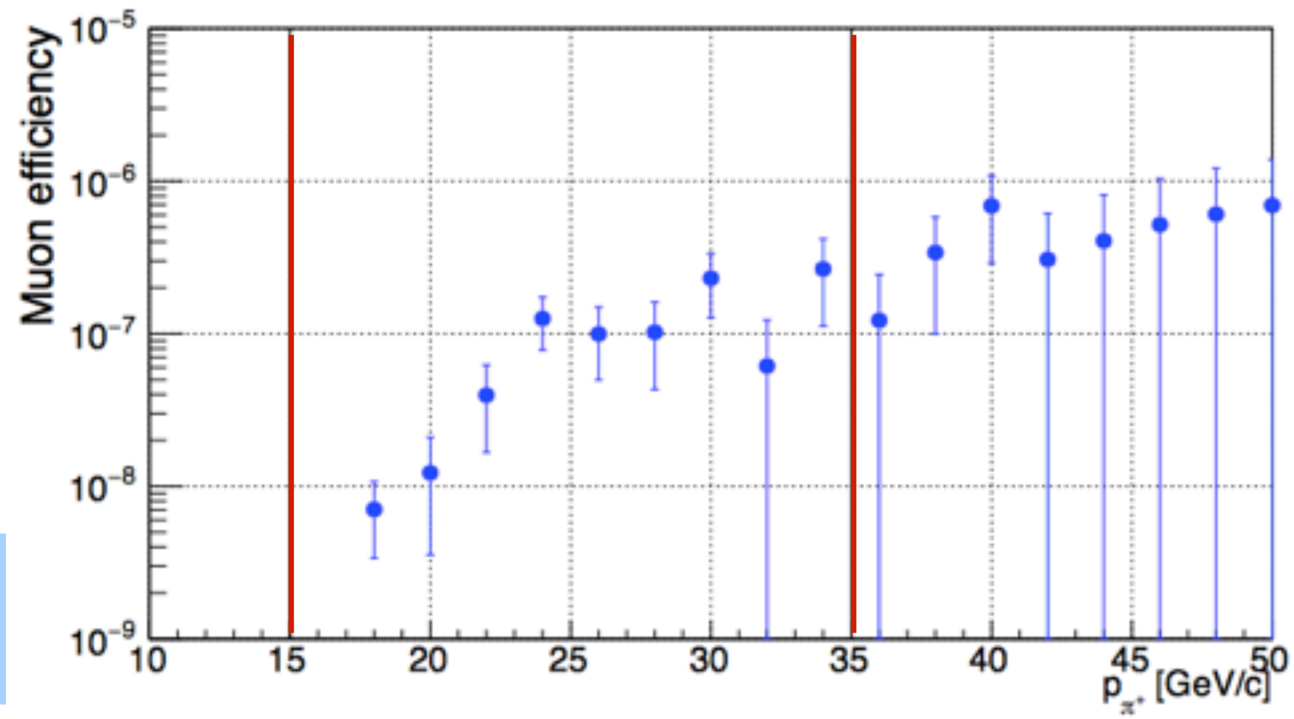
**RICH Ring Radius Vs Track Momentum:**




**Calorimeters + RICH π-ID efficiency:**




**Calorimeters + RICH μ-misID efficiency:**



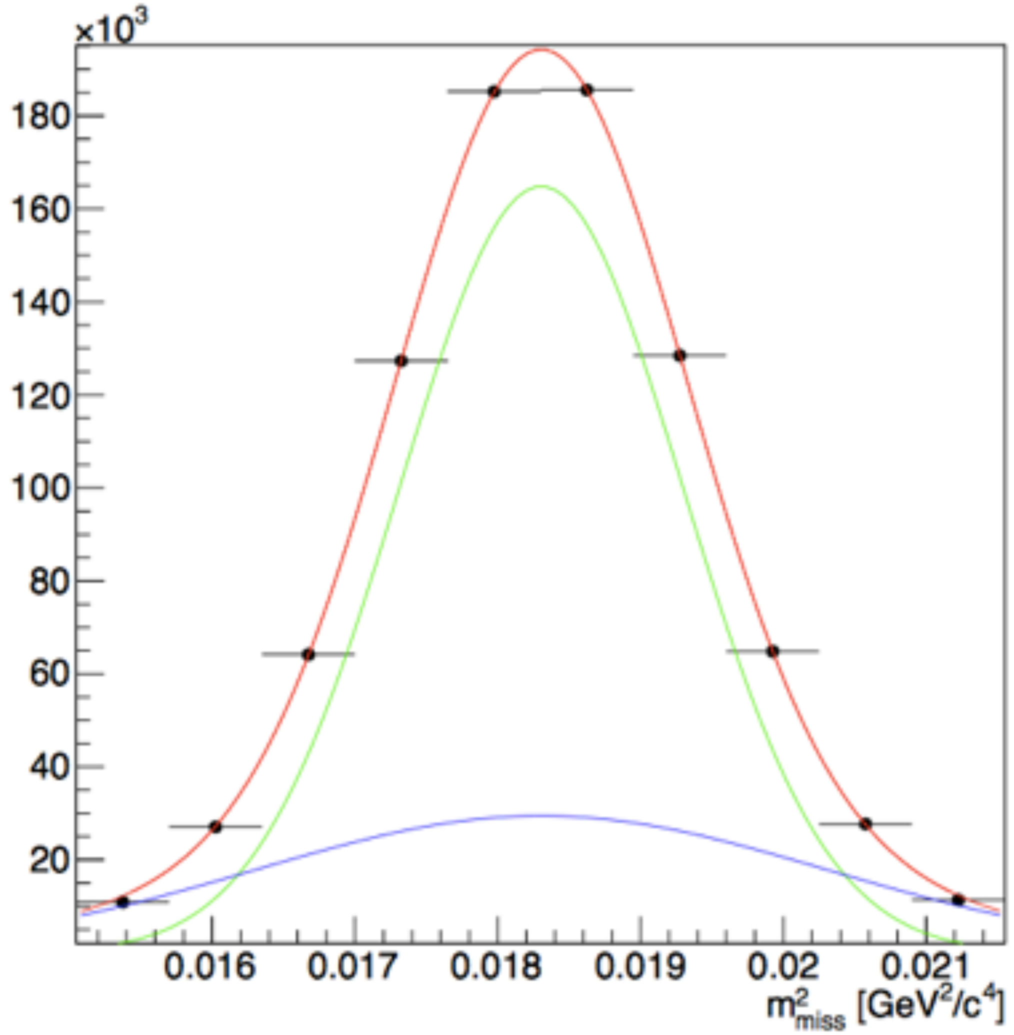

- Particle ID with calorimeters (MVA on LKr and MUVs): **$\varepsilon(\mu) \simeq 10^{-5}$, $\varepsilon(\pi) \simeq 80\%$**
- Particle ID with RICH: $\varepsilon(\pi)_{ring} \simeq 90\%$ (Pπ function), **$\varepsilon(\pi)_{ID} \simeq 80\%$, $\varepsilon(\mu) \simeq 10^{-2}$**

PID performance measurement with RICH and calorimeter combined: μ-suppression $<10^{-7}$

# Photon Rejection

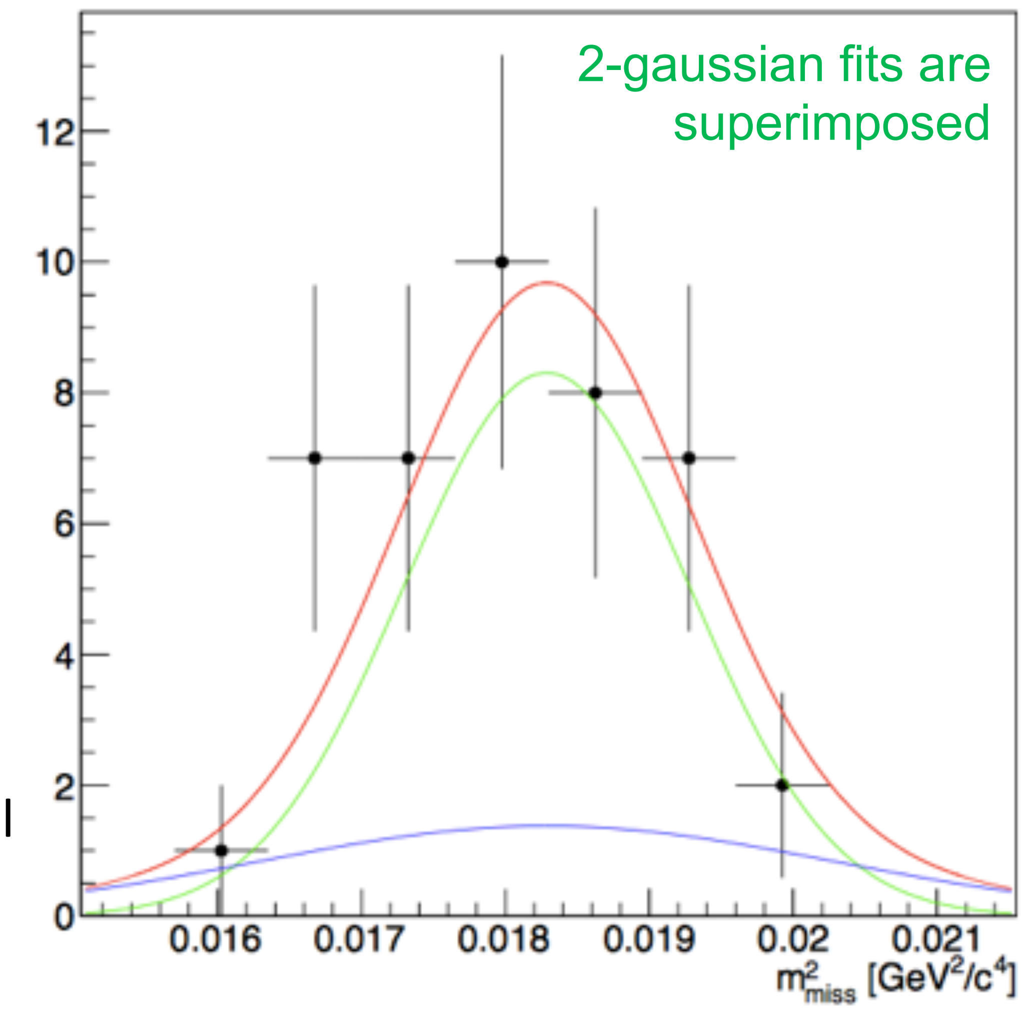
Photon Veto condition: LKr, LAV, IRC, SAC

**$K^+ \to \pi^+\pi^0$ events before the $\gamma$ rejection (minimum bias trigger*):**




*x 400 (Downscaling) to get the total number

**$K^+ \to \pi^+\pi^0$ events after $\gamma$ rejection (PNN trigger):**




- $K^+ \to \pi^+\pi^0$ suppression (in $K^+ \to \pi^+\pi^0$ mass region):

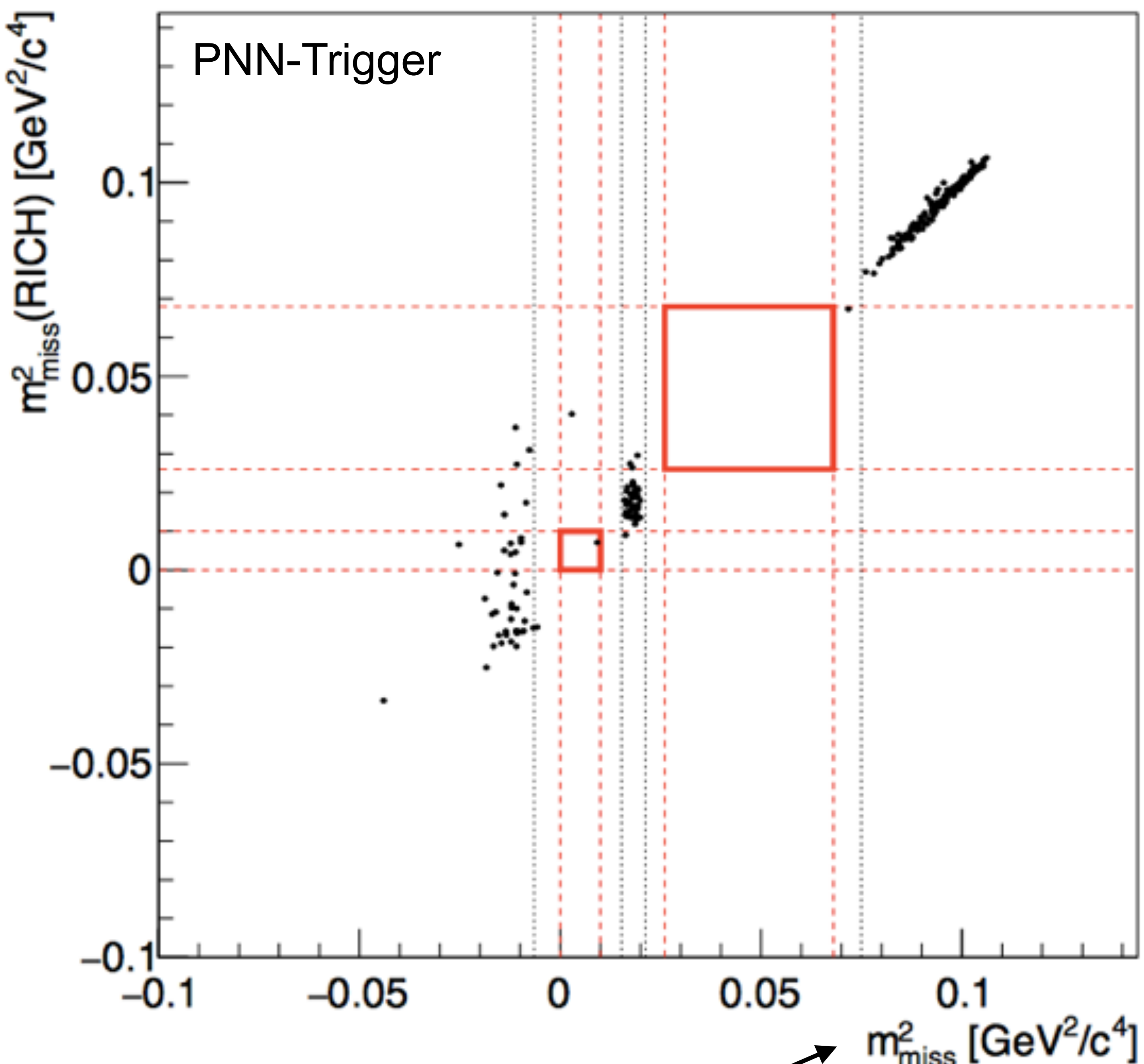
  $\boldsymbol{\varepsilon(\pi^0) = (1.2 \pm 0.2) \times 10^{-7}}$
- 15−16% $K^+ \to \pi^+\nu\nu$ accidental losses (measured with data)

Hermetic $\gamma$ veto suppression of $\pi^0 \to \gamma\gamma$ decays $< 10^{-7}$

# Preliminary Result

$P_\pi$ estimated with RICH

From $2.3 \times 10^{10}$ $K^+$ decays in fiducial volume




$P_\pi$ estimated with Spectrometer

**Expected signal:**

- $K^+ \rightarrow \pi^+\nu\nu \simeq 0.064$

(normalization $K^+ \rightarrow \pi^+\pi^0$)

**Expected background:**

- $K^+ \rightarrow \pi^+\pi^0 \simeq 0.024$
- $K^+ \rightarrow \mu^+\nu \simeq 0.011$
- $K^+ \rightarrow \pi^+ \pi^+ \pi^- \simeq 0.017$
- Beam-induced < 0.005

(estimated with data-driven method)

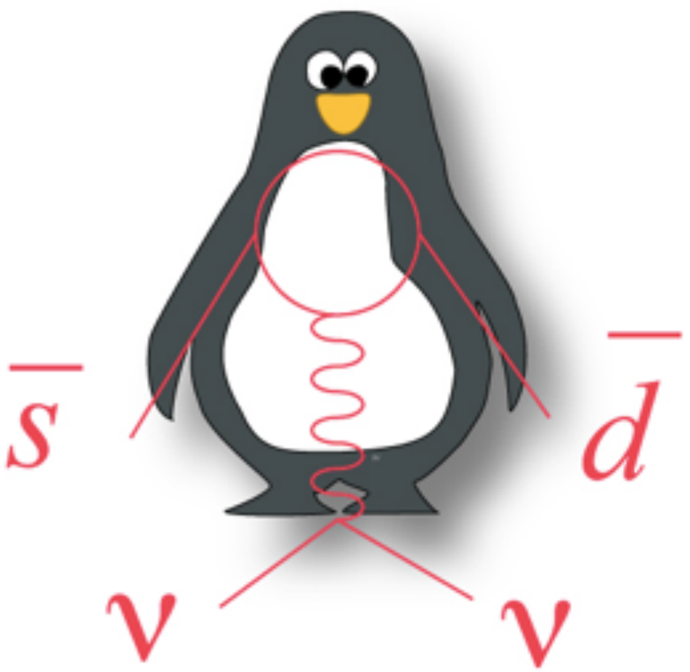
No event in signal region*

*Event in box has $m^2_{miss}$(NoGTK) - i.e. with nominal $P_k$ - outside the signal region

....analysis optimization in progress!

# Conclusion

- NA62 experiment is running and collecting data
  - Results from 5% of 2016 data presented, $2.3\times10^{10}$ kaon decays
  - No signal observed compared to expectation of 0.064 events
  - Data taking to continue through 2018
  - Analysis in progress
- Future programs after 2018 under discussion




Thank you for the attention from the NA62 Collaboration*!

*~200 participants, ~30 institutions

# Backup

# Broader NA62 Physics Program

The high-intensity, high-performance NA62 setup is ideal for many other measurements

**Standard Kaon Physics**

- Measurements of the BR of all the main $K^+$ decay modes
- Chiral perturbation theory studies: $K^+\to \pi^+\gamma\gamma$, $K^+\to \pi^+\pi^0 e^+e^-$, $K^+\to \pi^{0(+)}\pi^{0(-)}l^+\nu$
- Precision measurement of $R_K = \Gamma(K^+\to e^+\nu_e)/(K^+\to \mu^+\nu_\mu)$

…and other new physics searches

**Searches for lepton-flavour or lepton-number violating decays**

- $K^+\to \pi^+\mu^\pm e^\mp$, $K^+\to \pi^-\mu^+e^+$, $K^+\to \pi^-e^+e^+$, $K^+\to e^+\nu\gamma$, $K^+\to \pi^-\mu^+\mu^+$ (+ radiative modes)

$10^{13}$ $K^+$: expected sensitivity $10^{-12}$. Improve by ~x100 the past results.

**Searches for exotic particles**

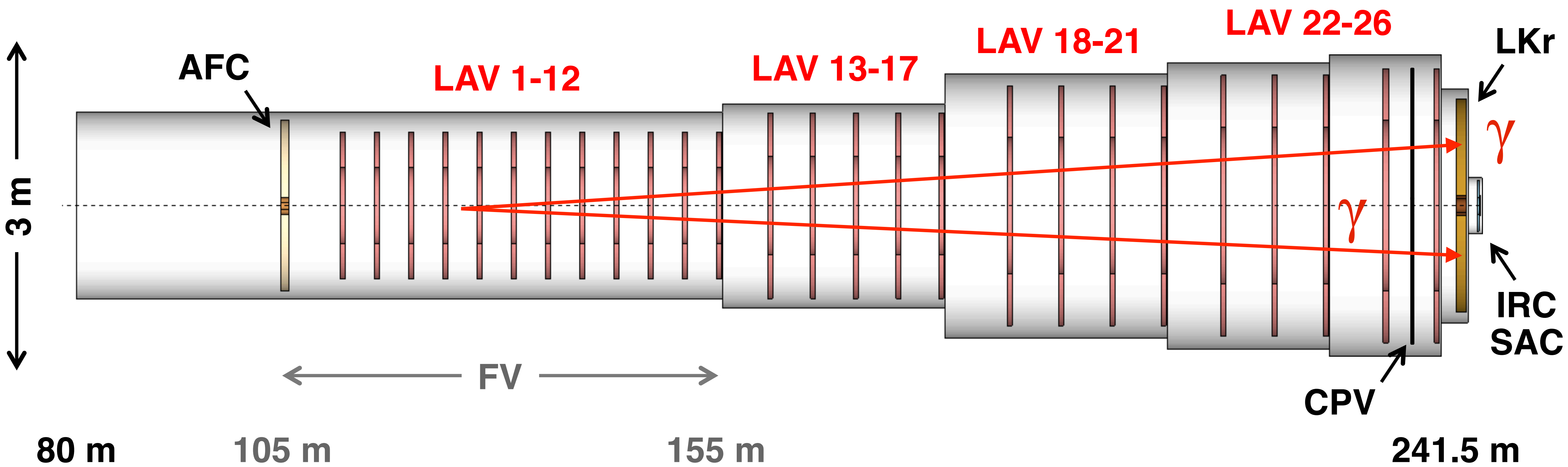
- Heavy neutral leptons, axion-like particles, dark photons

**Neutral pion**

- $\pi^0$ form factor
- Ultra-rare/forbidden decays ($\pi^0 \to \gamma\gamma\gamma$, $\pi^0 \to \gamma\gamma\gamma\gamma$, $\pi^0 \to \nu\nu$)

# KLEVER project: $K_L \rightarrow \pi^0 \nu\nu$ at the SPS

Estimate cost, timescale, and performance for a future experiment to measure BR($K_L \rightarrow \pi^0 \nu\nu$) at the SPS




**Main detector/veto systems:**

| | |
|---|---|
| AFC | Active final collimator/upstream veto |
| LAV1-26 | Large-angle vetoes (26 stations) |
| LKr | NA48 LKr calorimeter |
| IRC/SAC | Small-angle vetoes (SAC in neutral beam) |
| CPV | Charged-particle veto |

Operate in ECN3 and make use of the NA48 LKr calorimeter as primary veto.
In 5 years of running ($10^7$ s/yr) at a beam intensity of $2 \times 10^{13}$ pot/16.8 s
(6x of NA62, Target area and transfer lines would require upgrades):

**65 $K_L \rightarrow \pi^0 \nu\nu$ events are expected with S/B ~ 1**