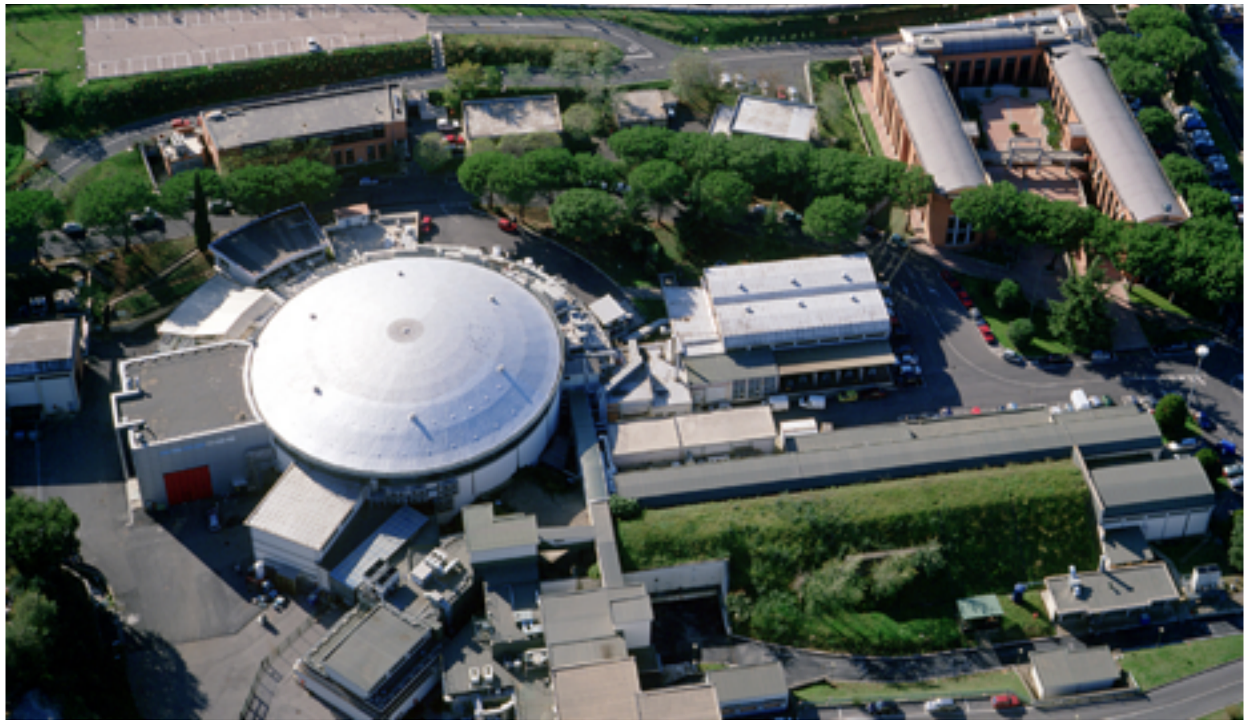
LNF Winter Institute



Searching for New Physics with the NA62 experiment

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Frascati 2017, February 1st

Outline

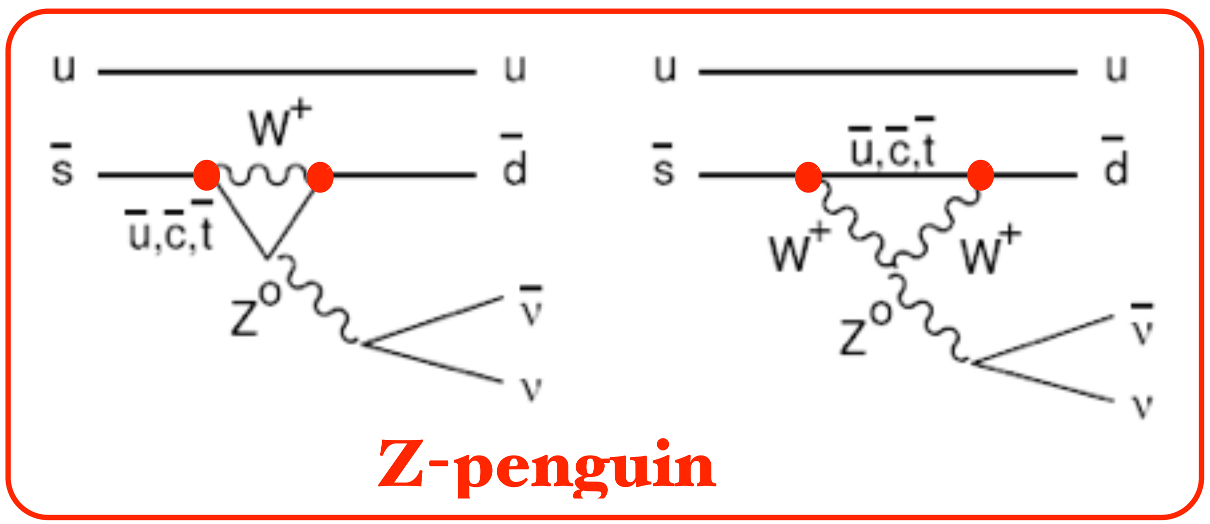
- Theoretical introduction to the $K \to \pi\nu\nu$ rare decays
- NA62 experiment
  - Aim and strategy
  - Results and prospects
- Physics program beyond the main goal

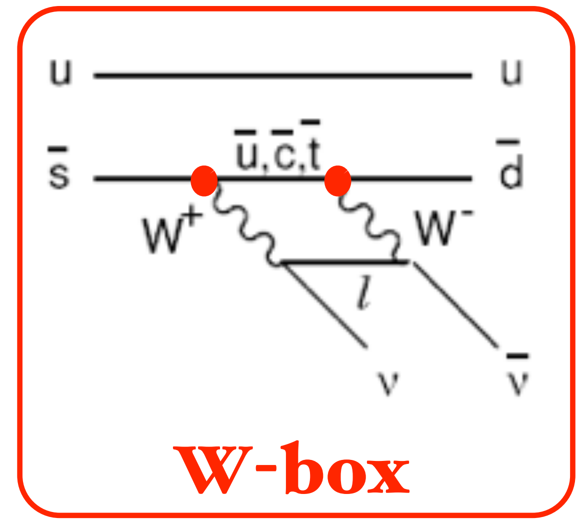
SM theoretical framework

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

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**

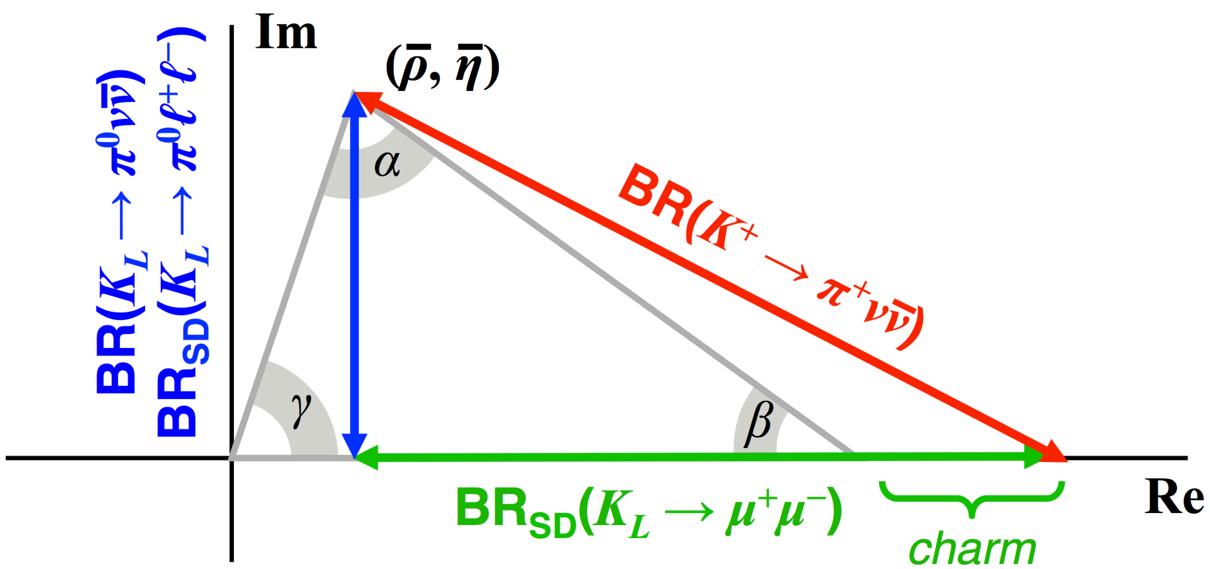
K→πνν and the Unitary Triangle

Dominant uncertainties for SM BRs are from CKM matrix elements

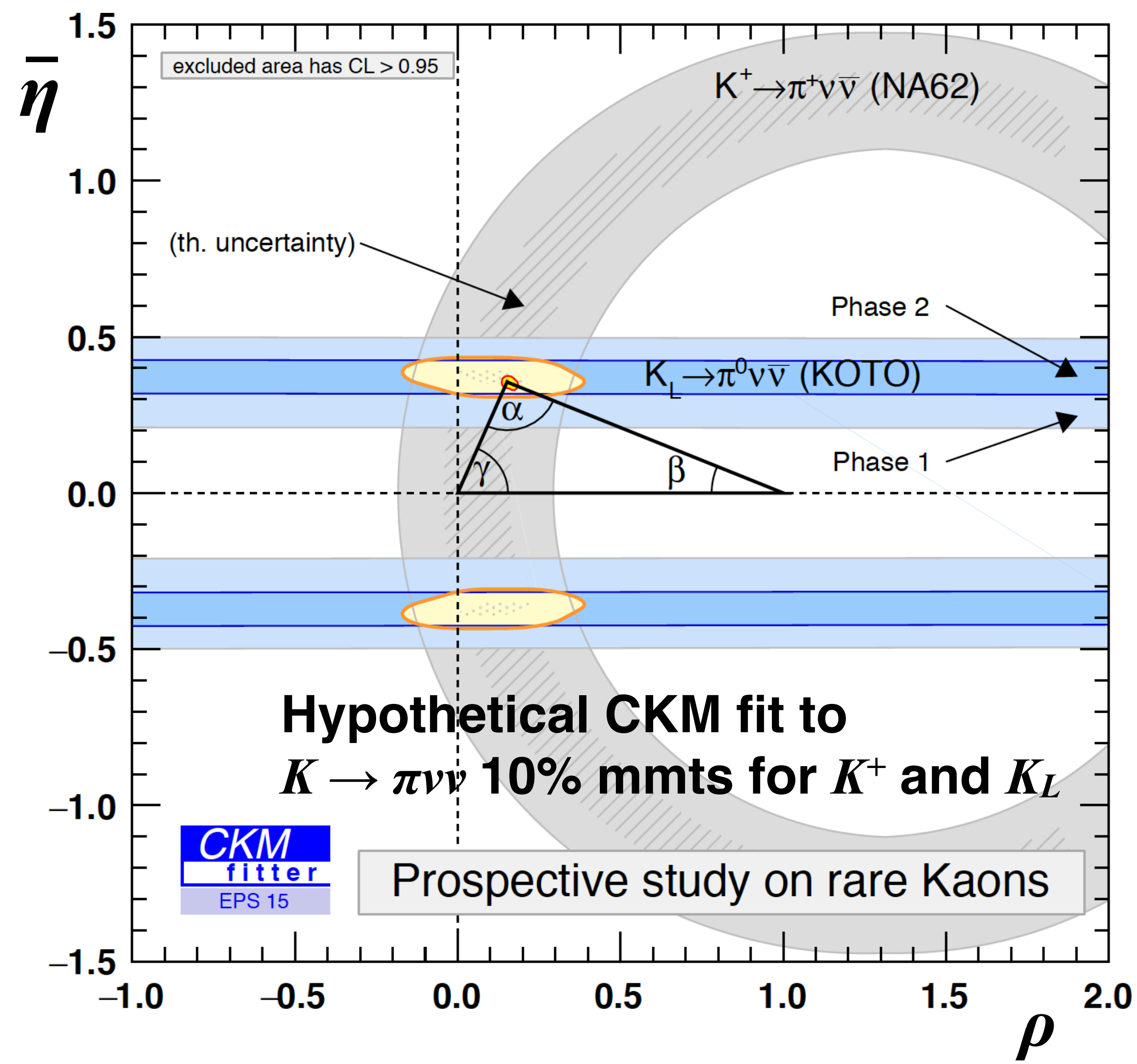
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$

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 of B inputs

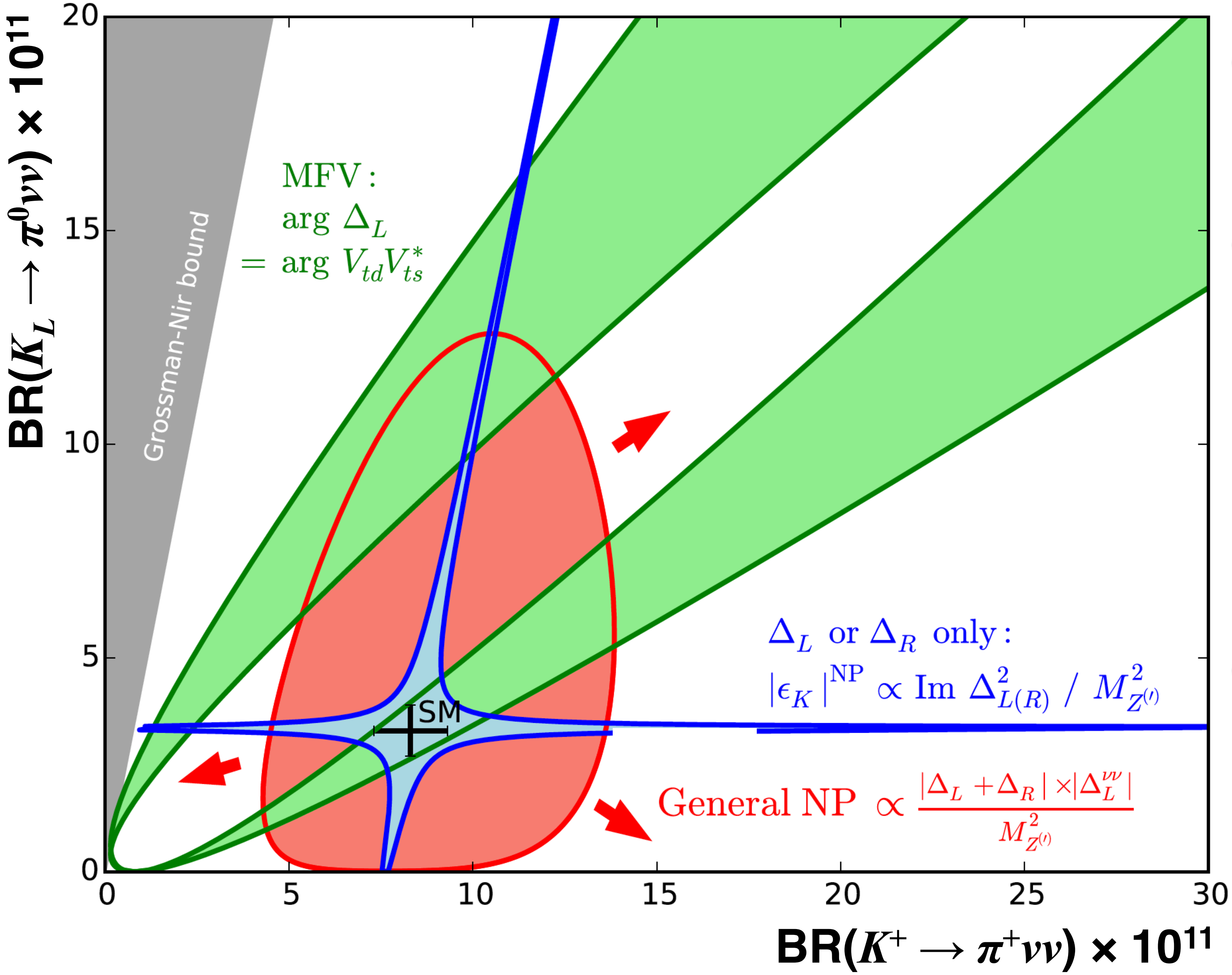


Overconstrain CKM matrix → reveal NP?



New Physics from K⟶πνν decays

New physics affects BRs differently for K^+ and K_L channels
Measurements of both could discriminate among NP scenarios



- **Models with CKM-like flavor structure:**
  - **Models with MFV [4]**
- **Models with new flavor-violating interactions in which either LH or RH couplings dominate:**
  - **Z/Z′ models with pure LH/RH couplings [5]**
  - **Littlest Higgs with T parity [6]**
- **Models without above constraints**
  - **Randall-Sundrum [7]**

Past measurement and prediction

Current SM theoretical prediction [1][2]:

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

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}.$$

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 [3]:

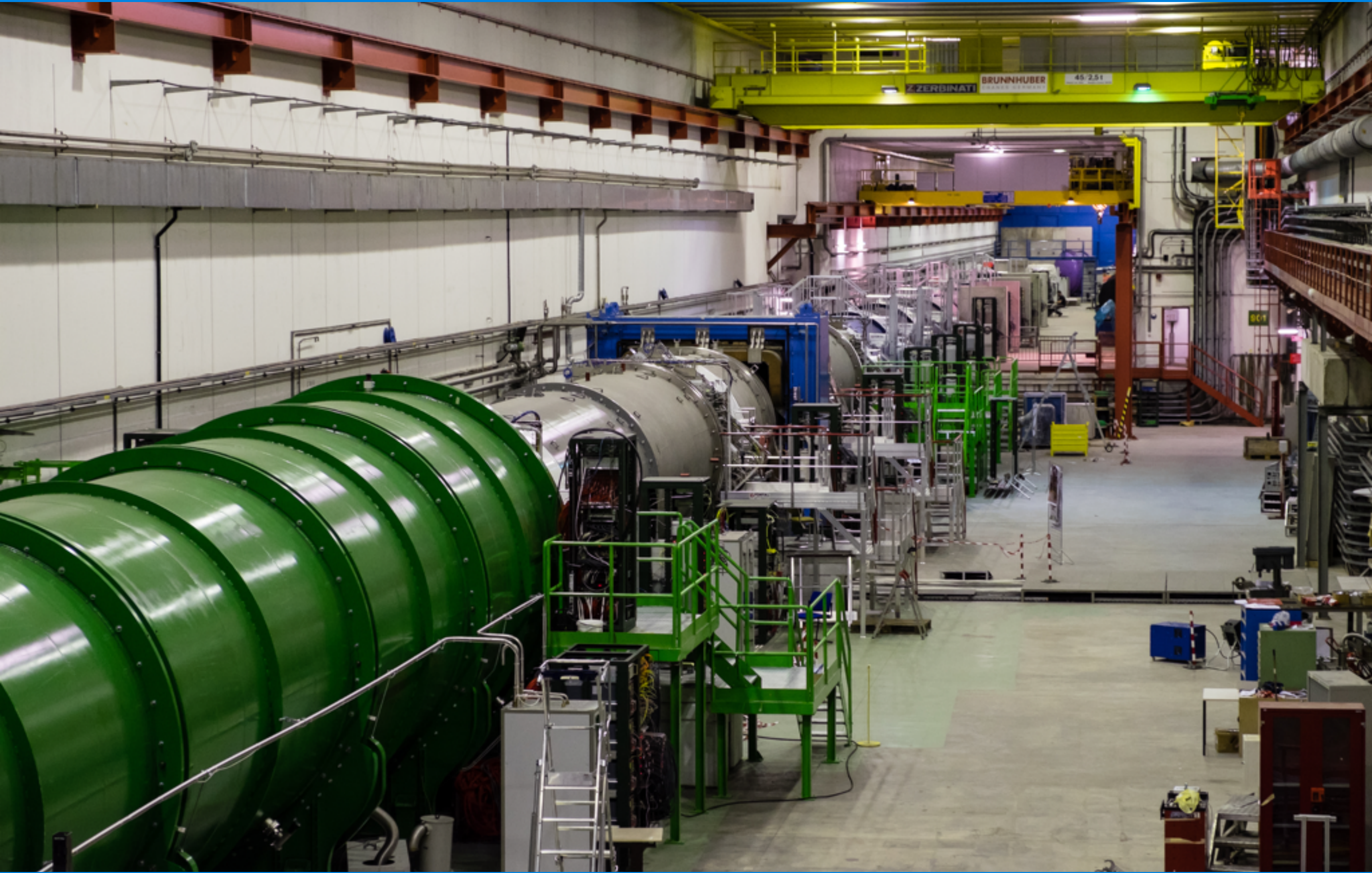
Charged decay: only measurement obtained by E787 and E949 experiments at BNL with stopped kaon decays (7 events):

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

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

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

NA62 Experiment



Experimental requirements

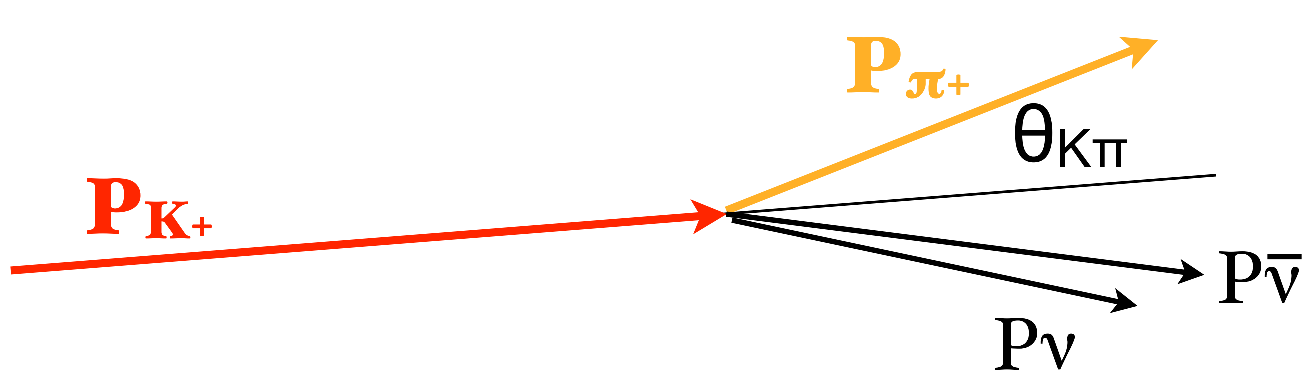
GOAL: measure BR($K^+ \rightarrow \pi^+ \nu\nu$) with 10% accuracy

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

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

Design criteria[8]: **kaon intensity, signal acceptance, background suppression**

Decay in flight technique. Kaons with high momentum

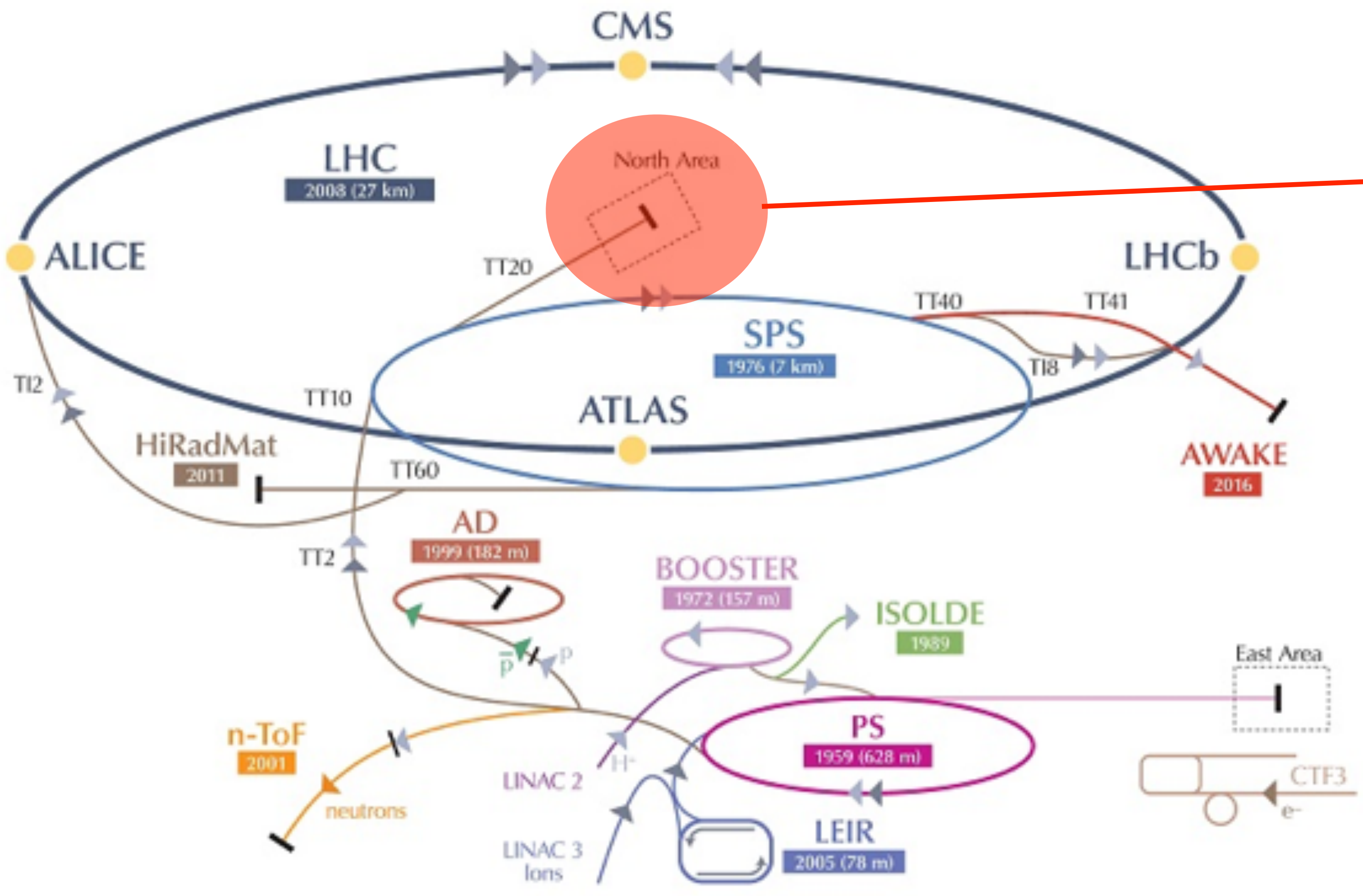


Signal signature:
one **K^+ track** + one **π^+ track**

Basic ingredients:
precise timing, kinematic cuts, particle ID & hermetic photon vetoes

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. A new beam line will provide 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)

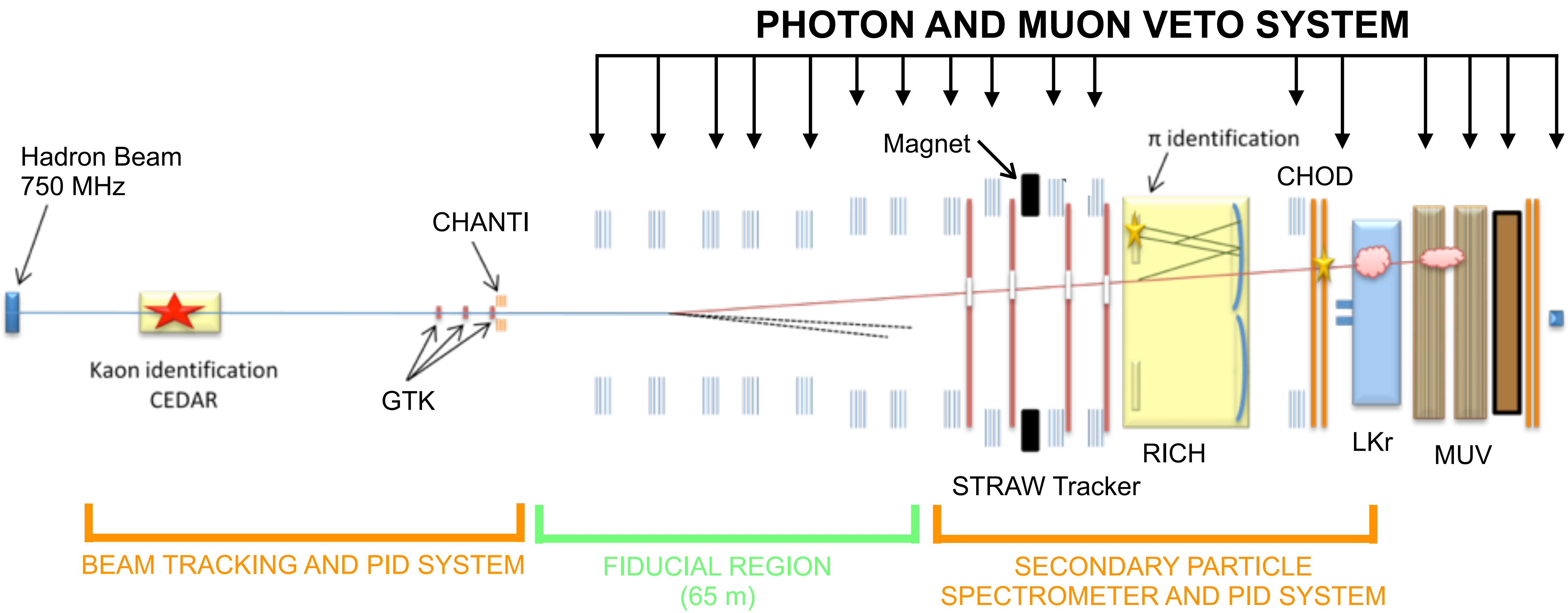
400 GeV/c protons impinge on a beryllium target and produce a secondary charged beam: **6% are K^+** (mixed with π and protons).

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

(1% momentum bite, ~ 100 μrad divergence)

NA62 Apparatus

270 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.

The overall rate integrated over these detectors is ~ 10 MHz.

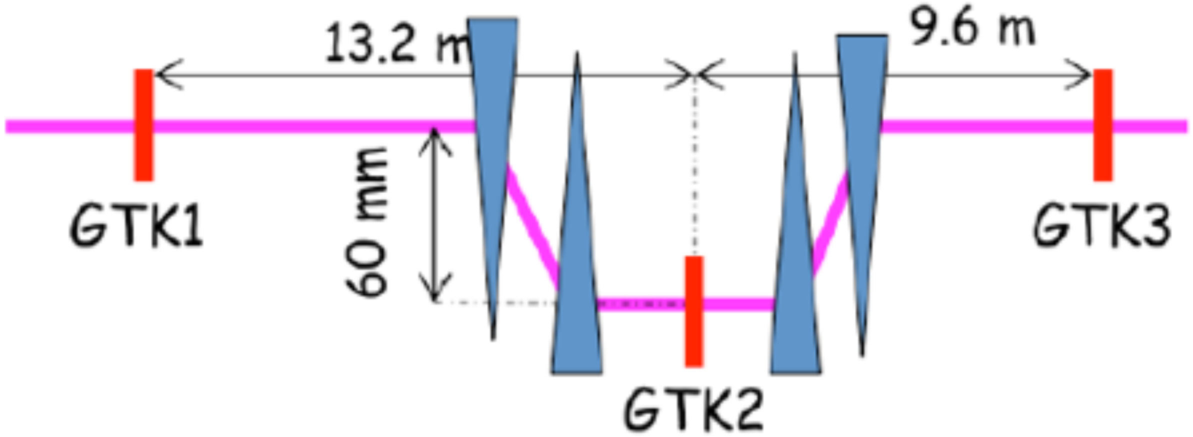
Kaon Identification and Timing

K^+ identification in the hadron beam

KTAG A differential Cerenkov counter is operated being blind to all particles but kaons of appropriate momentum (**75 GeV**).

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

K^+ spectrometer for momentum and timing measurement



3 stations of silicon pixels

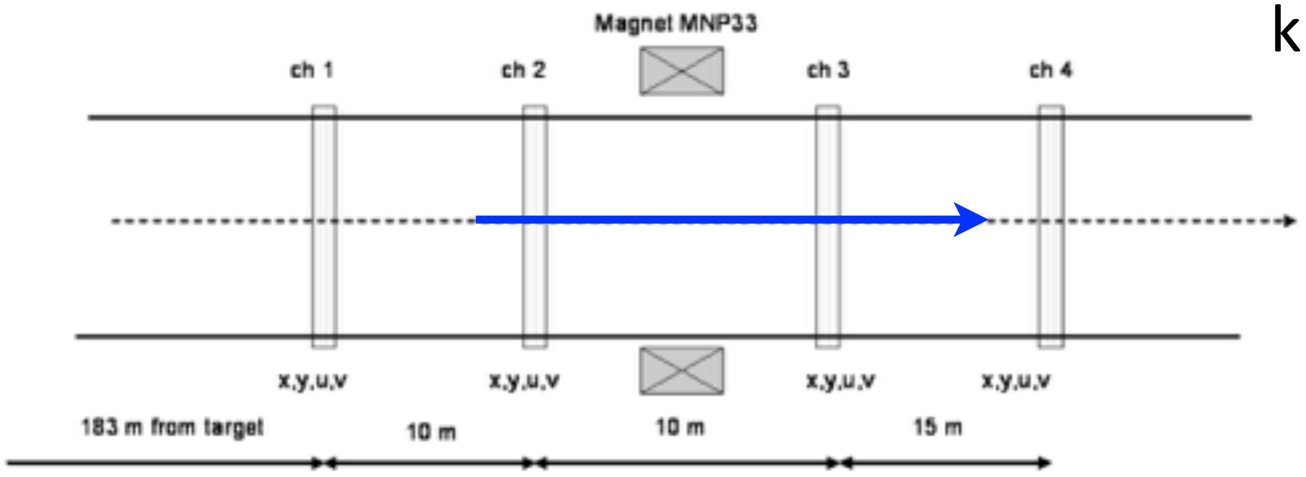
GTK must provide, (in a 750 MHz beam environment) a precise timing of the kaon in coincidence with the particle from the decay detected in downstream detectors.

time resolution ~ 66ps
direction resolution ~16 μrad

Secondary Particle Tracking and ID

Secondary particle momentum measurement

STRAW 4 chambers in vacuum of STRAW tubes. Magnet after the 2nd STRAW chamber provides a 270 MeV/c momentum kick in the horizontal plane.



Spatial resolution:
130 μm
$\sigma(p)/p \sim 0.5\%$

Particle Identification and crossing time

RICH Ring Imaging CHerenkov Detector. 17 m long tank filled with neon gas at atmospheric pressure. Internal Al beam pipe keeps the beam particles in vacuum.

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

Photon Vetoes: Large & Small Angle

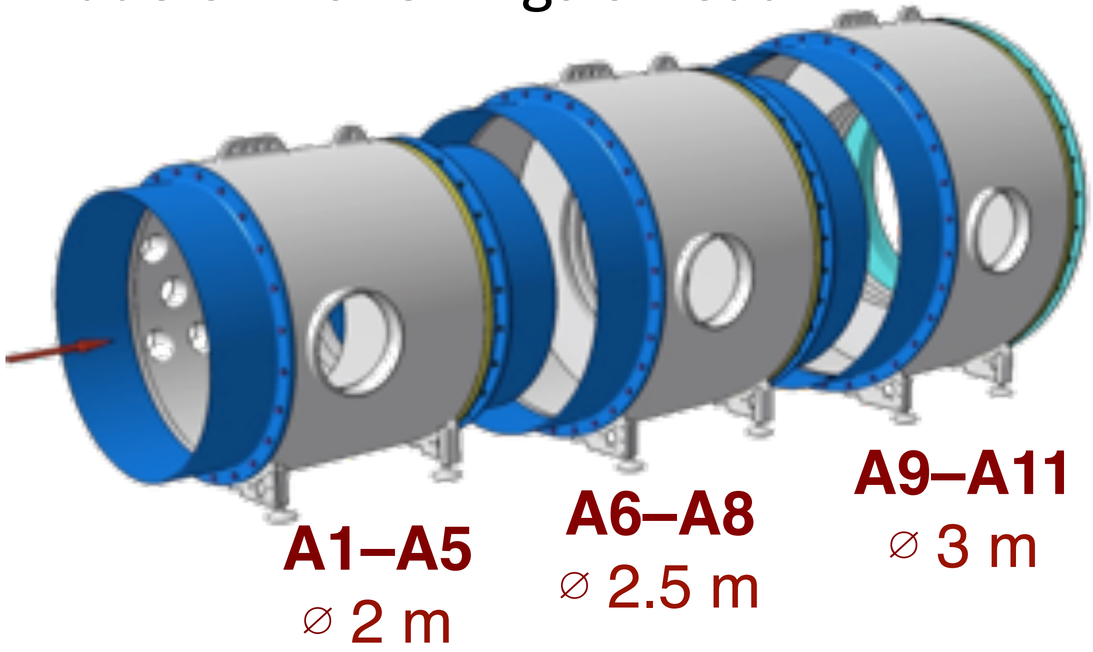
BR($K^+ \rightarrow \pi^+ \pi^0$) = 21%

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

Large Angle Veto: covering $8.5 < \theta\gamma < 50$ mrad

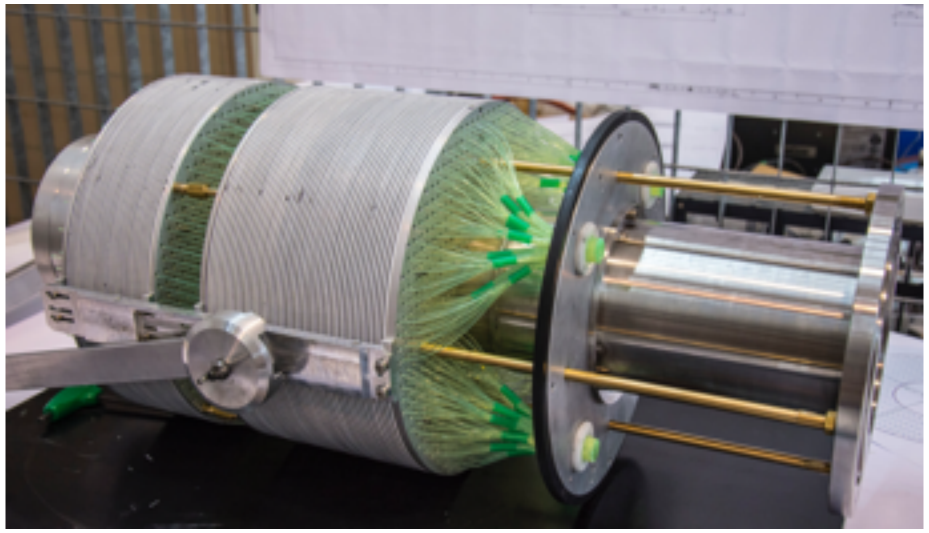
LAV 12 stations (11 in vacuum), placed along 120 m decay region. Each LAV station is made of 4 or 5 rings of lead glass crystals.

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



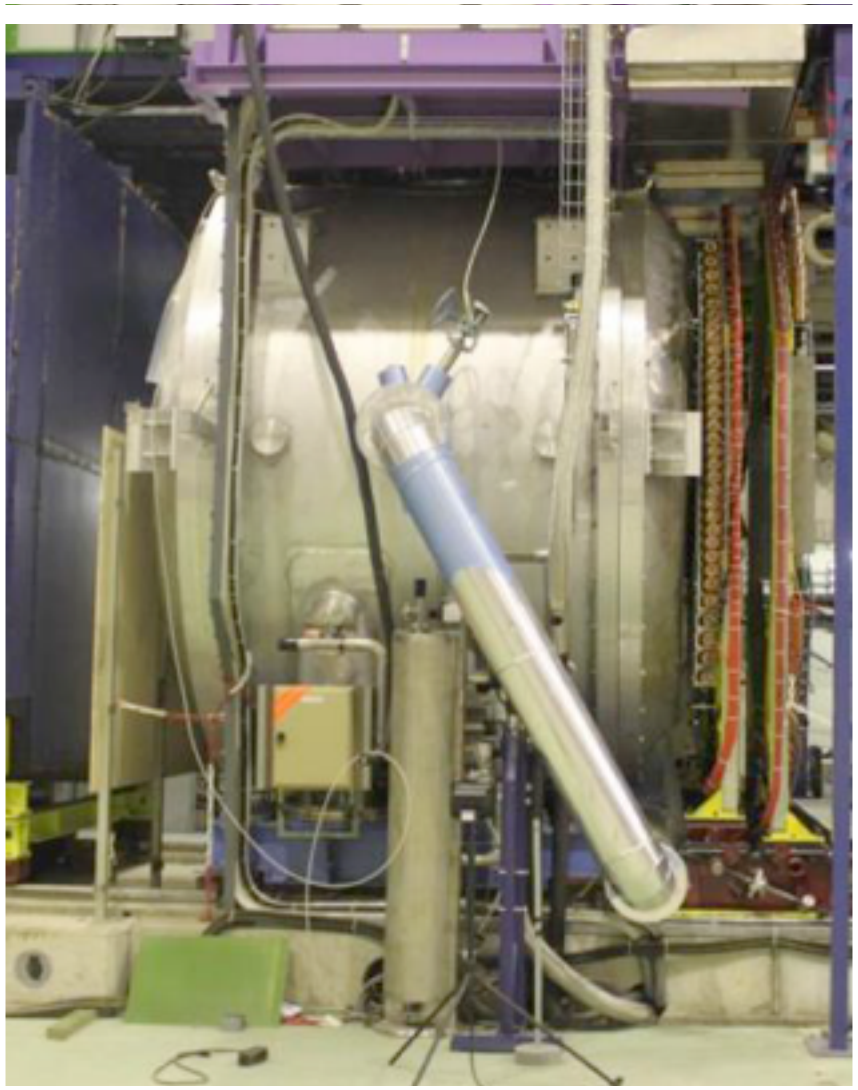
Small Angle Veto:
covering $\theta\gamma < 1$ mrad

SAV Two Shashlik calorimeters. Lead and plastic scintillator plates.



10^{-4} inefficiency (for $E_\gamma > 1$ GeV)
time resolution few ns

LKr Calorimeter & Muon Veto



Electromagnetic calorimeter covering $1 < \theta_\gamma < 8.5$ mrad

LKr Calorimeter (Inherited by NA48). Particle ID from measurement of energy with the shower reconstruction.

energy resolution 3.2%/sqrt(E)
time resolution ~ 2.5 ns/sqrt(E)
space resolution 4.2 mm/sqrt(E)
inefficiency < 10^{-5} for E_γ > 10 GeV

BR($K^+ \to \mu^+ \nu$) = 63%

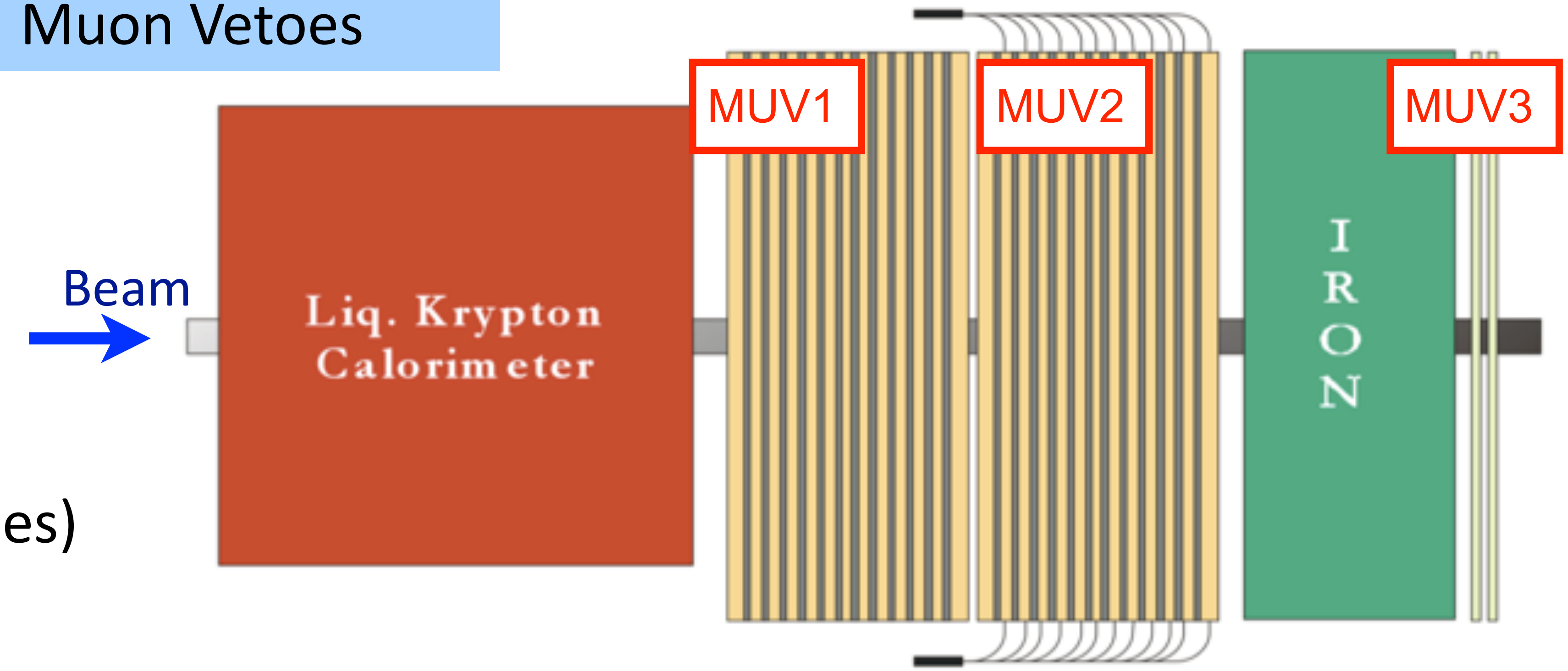
GOAL: $O(10^7)$ rejection power of μ^+ from $K^+ \to \mu^+ \nu$

Muon Vetoes

MUV1, MUV2 hadronic calorimeters (iron-scintillator plate sandwiches)

MUV3 fast μ-veto (scintillator tiles)

time resolution ~ 0.5 ns



NA62 Status

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

2014 Pilot Run

- Detectors only partially installed

2015 Run

- **All detectors installed and active**
- First L1 trigger algorithms tested
- **Beam commissioned up to nominal intensity**

2016 Run

- Readout improvements to enhance stability at high rate
- Tracking included in L1 software trigger
- **Extensive running at 50% intensity for $K^+ \to \pi^+\nu\nu$ and secondary programs**
- **Readout tested up to 80% intensity**

Results timescale:

- 2016 data: reach SM-expectation sensitivity $O(10^{-10})$
- End of 2017 run: improve (by much) on the present state of the art (BNL measurement)
- End of 2018 run: measurement of BR at 10%

Expected performance

Signal Selection:

- 1 track with 15 < p < 35 GeV with π-iD
- No γs in Photon Veto Detectors
- No μs in Muon Veto Detectors
- 1 beam particle in GTK with K-ID in KTAG
- Vertex reconstructed in 60 m fiducial volume

Signal Acceptance ~ 12%

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

Main 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

Rejection factor for the background:

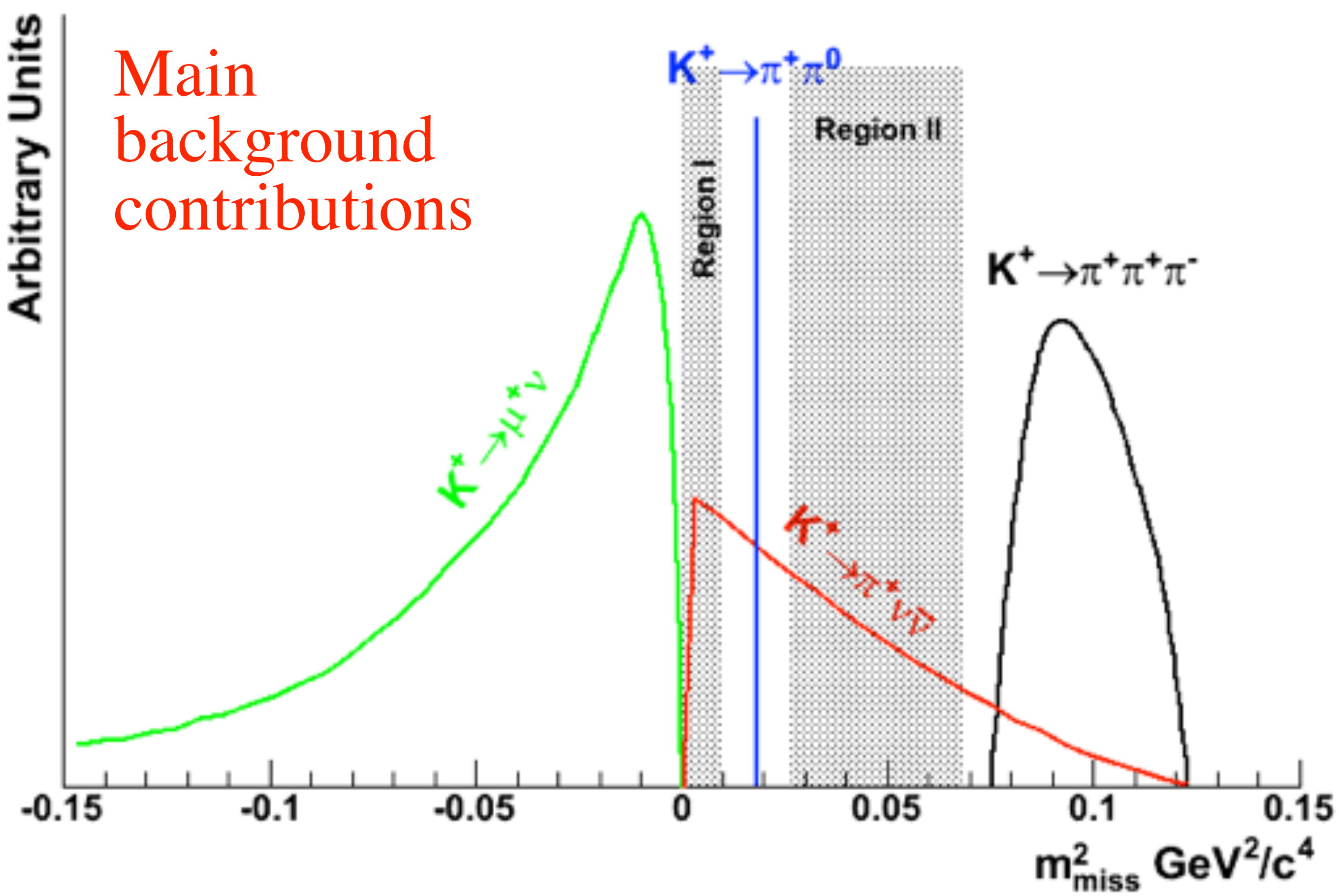
- Kinematics ~ 10^4-10^5
- Charged Particle ID ~ 10^7
- Photon detection ~ 10^8
- Timing ~ 10^2

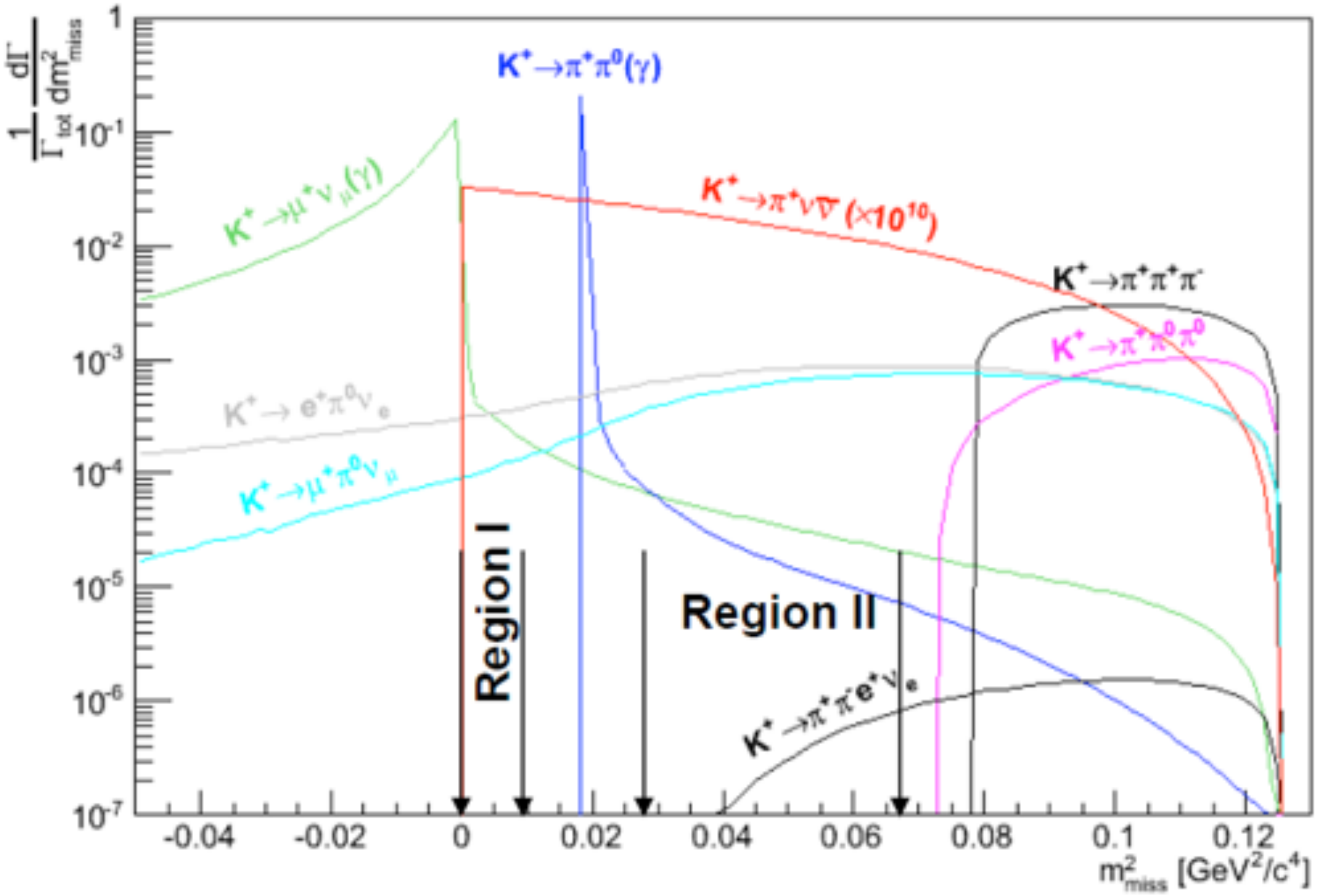
Analysis Strategy

Most discriminating variable:

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

Where the daughter charged particle is assumed to be a pion



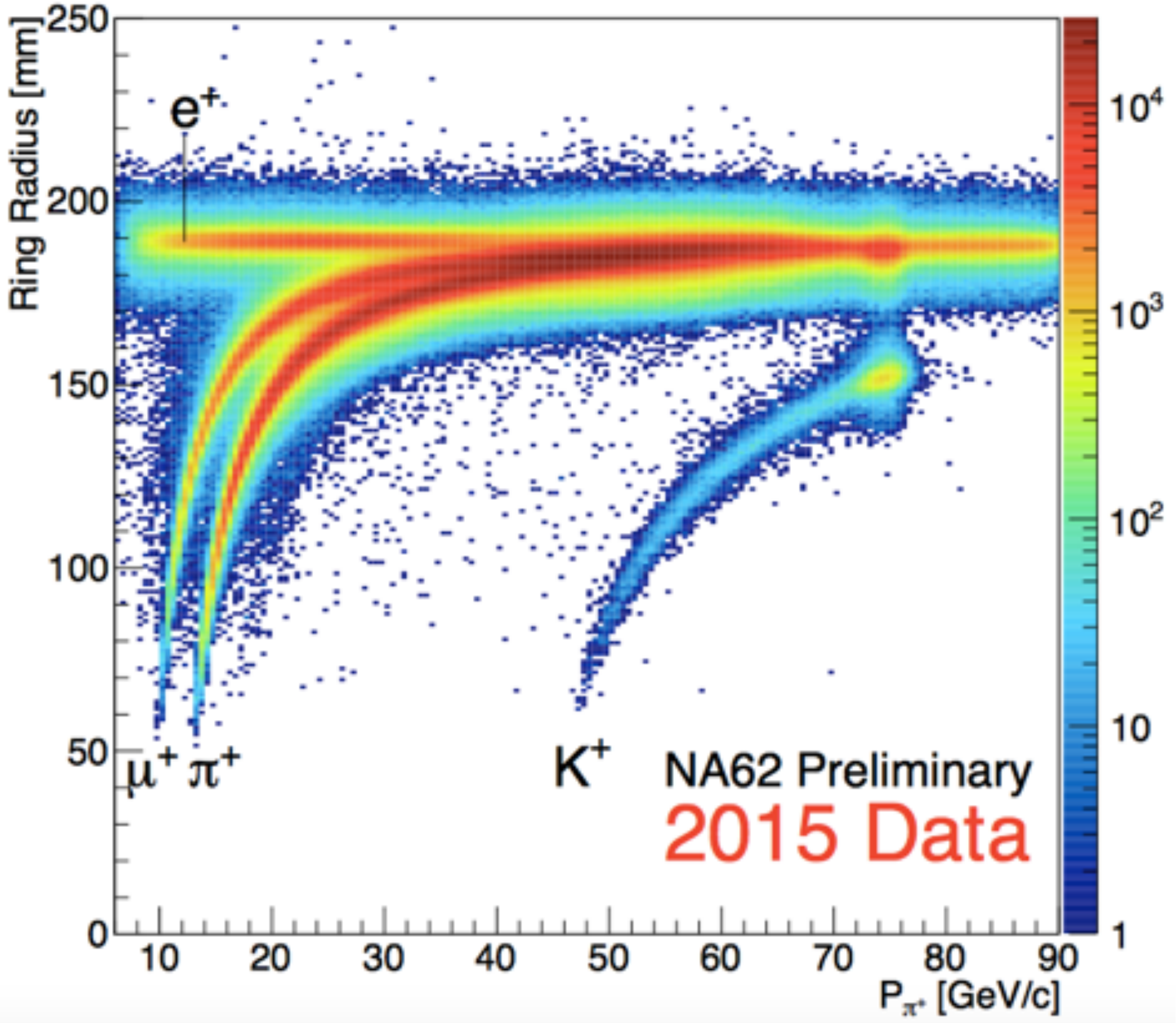


2 signal regions, on each side of the $K^+ \to \pi^+\pi^0$ peak, are chosen to eliminate background from dominant 2-body decays (84% of the K^+ width)

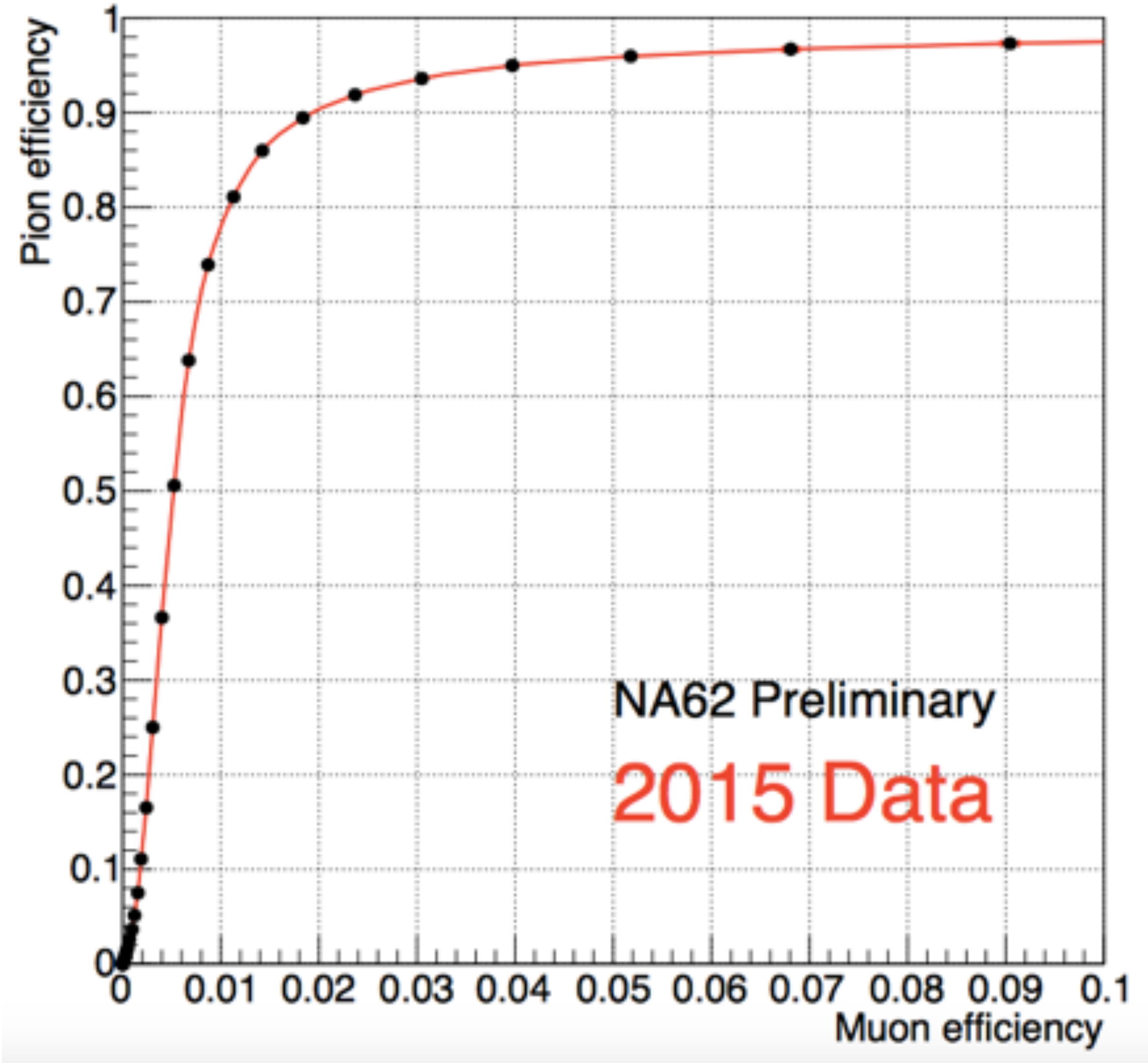
2015 Data: Downstream Particle ID

GOAL: 10^7 π/μ separation with RICH and LKr Calorimeter

RICH Ring Radius Vs Track Momentum:

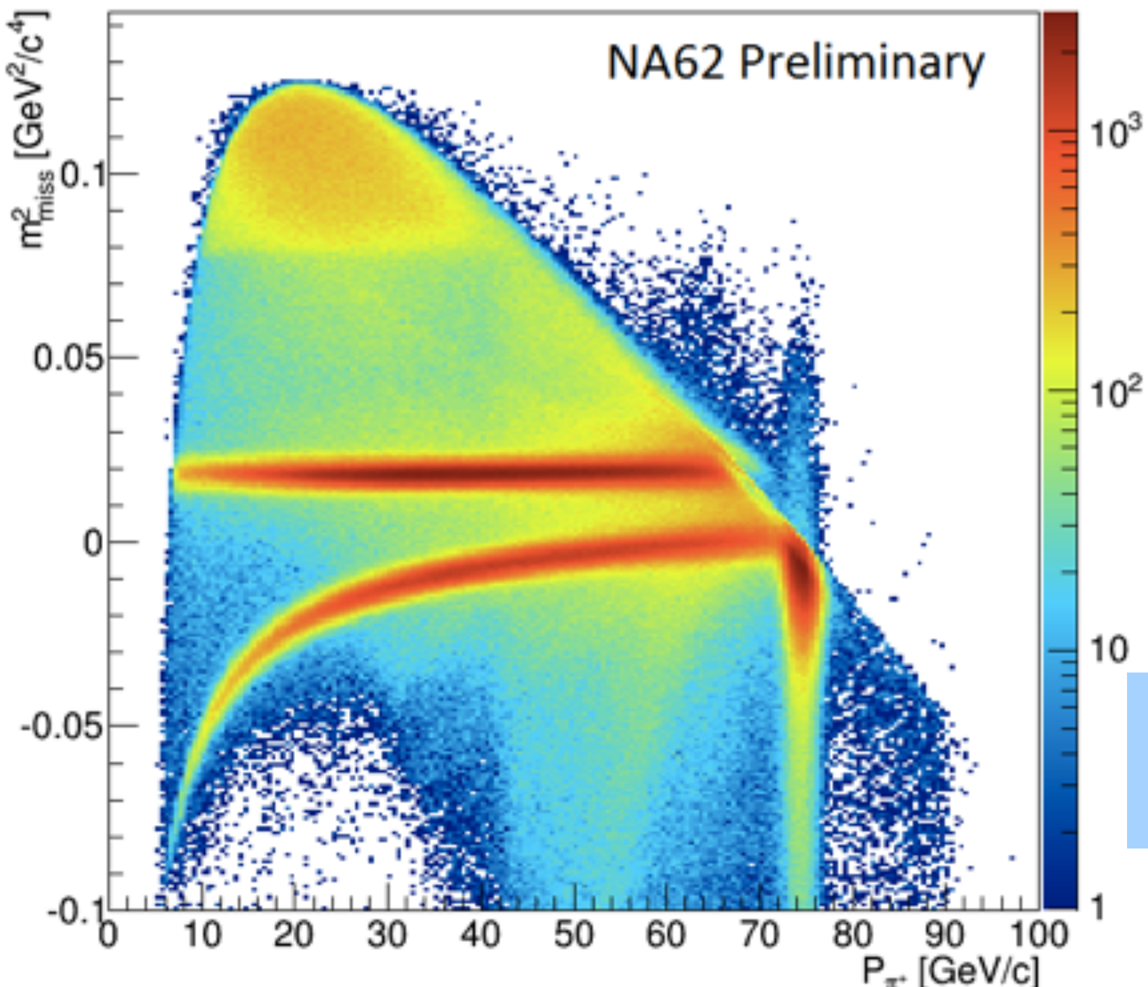


RICH π-ID efficiency Vs μ-ID efficiency:



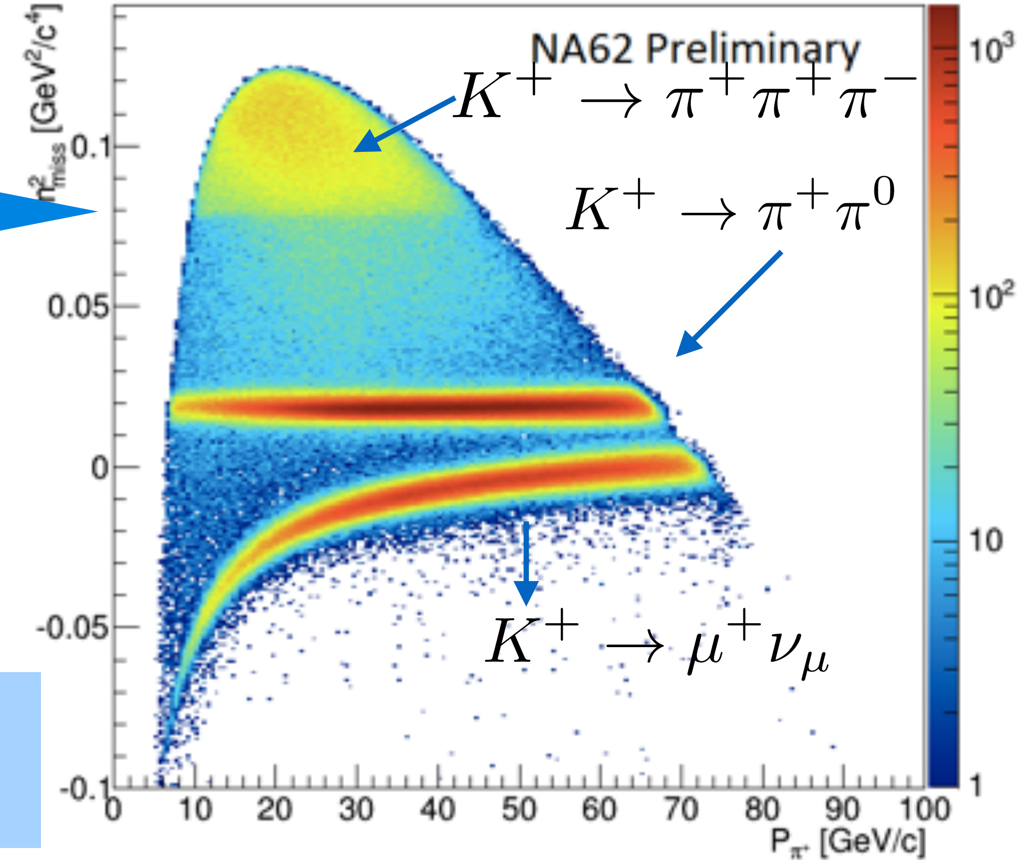
- RICH: $O(10^2)$ π/μ separation, 90% π+ efficiency in 2016
- Calorimeters: 10^4 - 10^6 μ suppression, 90% - 40% π efficiency in 2015 using a cut analysis. Room for improvements

2015 Data: Signal selection and Kaon ID

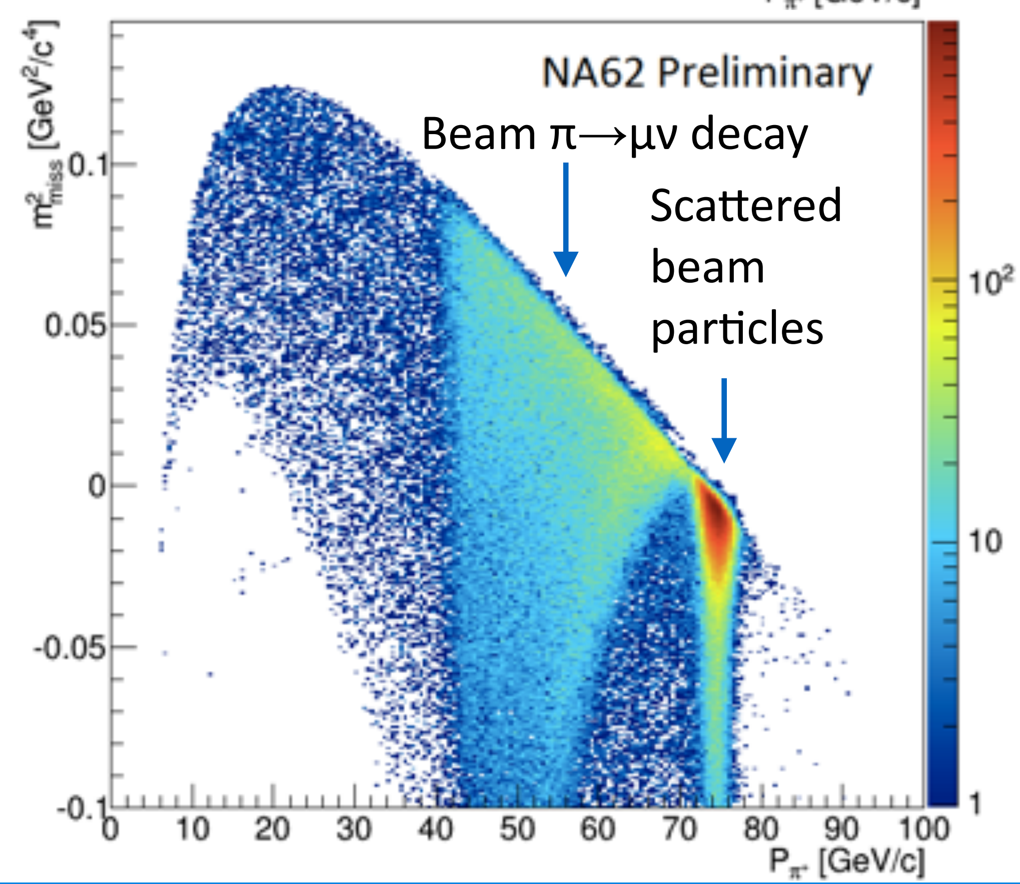


With Kaon ID matching

Track origin in the fiducial region



Anti-coincidence with a Kaon track



One track selection

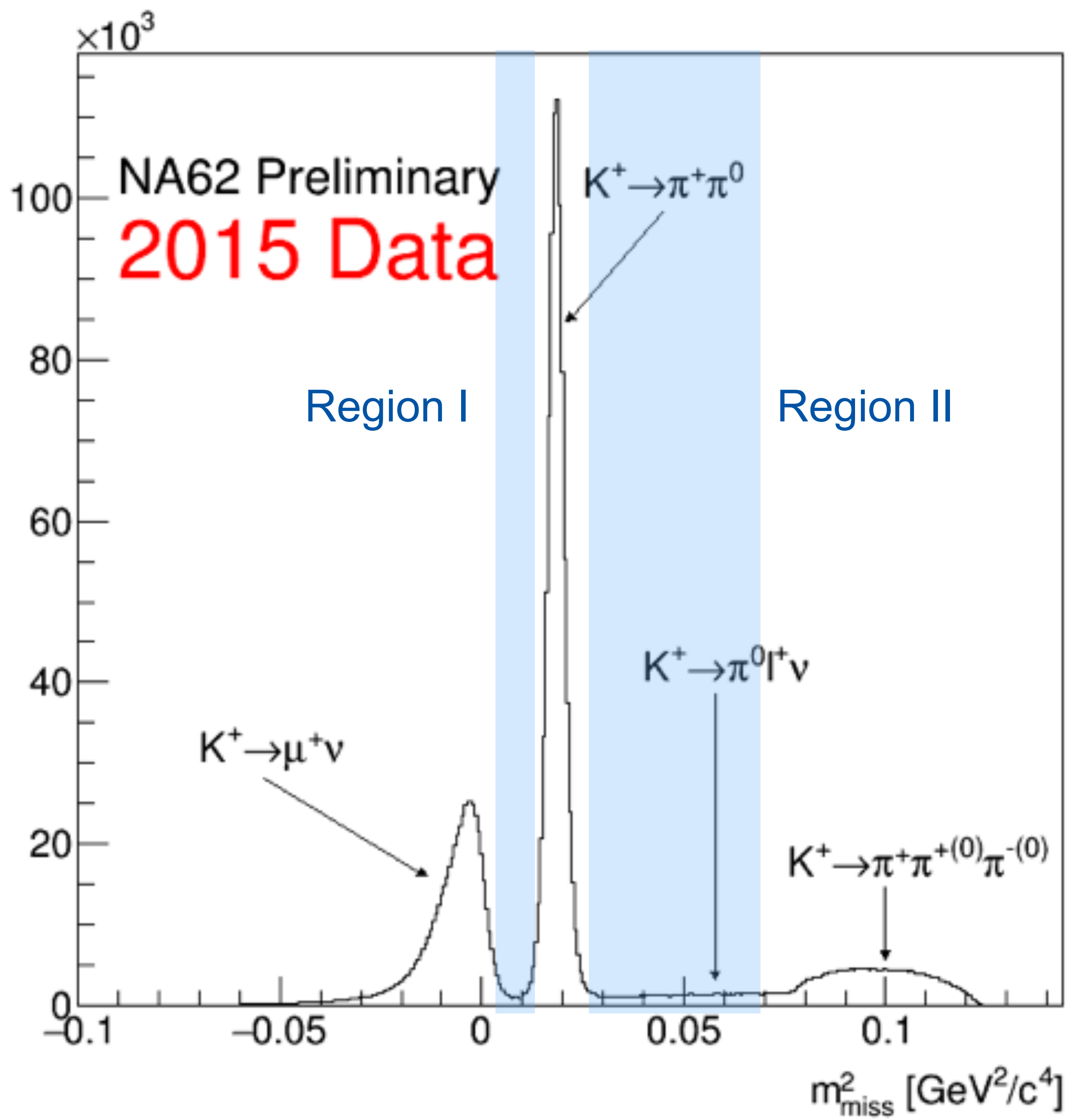
- Single downstream track
- Beam track matching the downstream track
- Beam track matching a K^+ signal in Kaon ID
- Downstream track matching energy in calorimeters

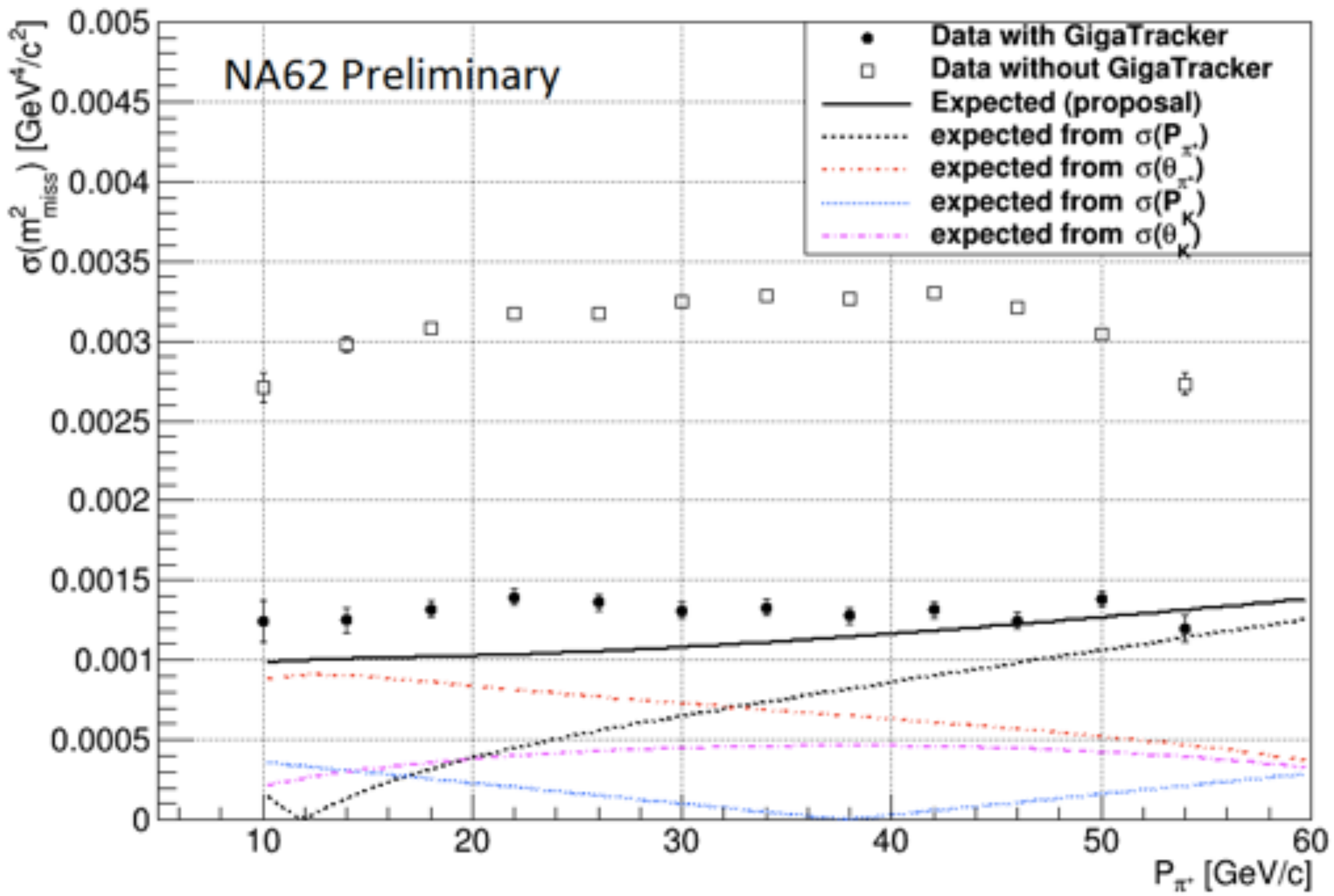
Time resolutions

- Kaon ID < 100 ps, downstream track < 200 ps
- Calorimeters < 1-2 ns

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

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





Resolution near to design value

2016 Data Analysis coming soon

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

- $K^+\to \pi^+\mu^\pm e^\mp$, $K^+\to \pi^-\mu^+e^+$, $K^+\to \pi^-e^+e^+$, $K^+\to \pi^-\mu^+\mu^+$ (+ 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

- π^0 form factor
- Ultra-rare/forbidden decays

Additional triggers needed

NA62 Trigger →

Level 0 (L0) (FPGA): from 10 MHz to **1 MHz**

Level 1 & **Level 2** (software): from 1 MHz to **10 kHz**

At L0 "πνν" trigger requires: 1 track, no muon, E_{miss} (Photon Vetoes)

"πνν" + control trigger + calibration trigger + little free bandwidth: max 1 MHz

Trigger bandwidth for final states other than "πνν" is limited

< 100 kHz for additional triggers

- Some LFV/LNV studies can be performed because involve low-bandwidth triggers (3 daughter tracks)

$$K^+ \to \pi^+\mu^\pm e^\mp,\ K^+ \to \pi^-\mu^+e^+,\ K^+ \to \pi^-e^+e^+,\ K^+ \to \pi^-\mu^+\mu^+$$

- Others searches can be made in parasitic mode with the main trigger. Heavy neutrino lepton produced in K decays:

$$K^+ \to \mu^+\nu_h,\ K^+ \to e^+\nu_h$$

Neutral pion decays

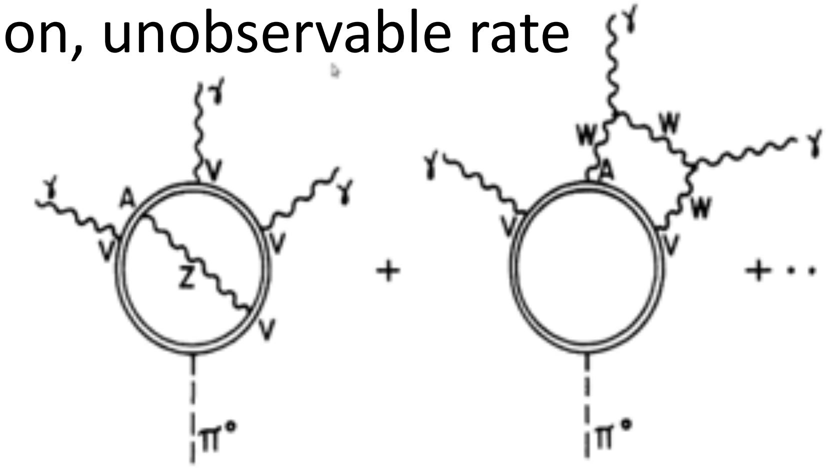
$\pi^0 \to \gamma\gamma\gamma$

Violates charge conjugation invariance: week interaction, unobservable rate

Non-commutative quantum electrodynamics: anomalous interaction between π^0 and two γs can induce the C-violating decay

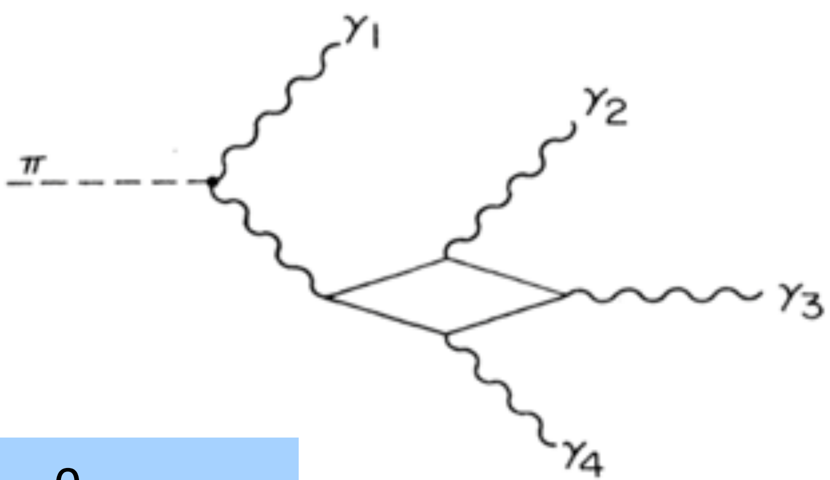
$BR(\pi^0 \to 3\gamma)_{NCQED} = 6.4 \times 10^{-21}$ [9]

$BR(\pi^0 \to 3\gamma)_{exp} = 3.1 \times 10^{-8}$ (90 % C.L.) [10]



$\pi^0 \to \gamma\gamma\gamma\gamma$

The main contribution arises from the QED mechanism $\pi^0 \to \gamma(\gamma*) \to \gamma(3\gamma)$.



$BR(\pi^0 \to 4\gamma)_{SM} \simeq (2.6 \pm 0.1) \times 10^{-11}$ [11]

Possible deviation given by light scalar S weakly coupled to the electromagnetic current: $\pi^0 \to SS$ with $S \to \gamma\gamma$.

$BR(\pi^0 \to 4\gamma)_{exp} = 2 \times 10^{-8}$ (90% C.L.) [10]

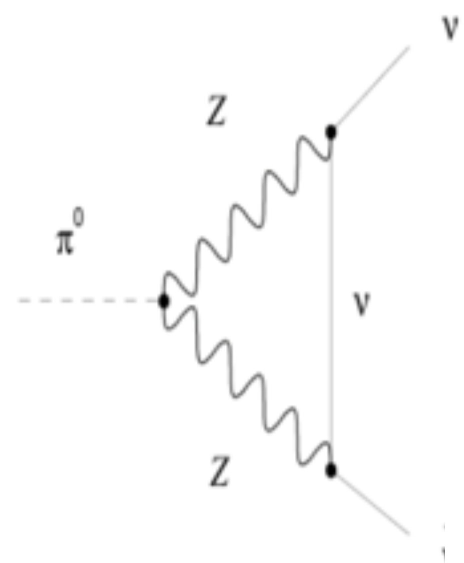
$\pi^0 \to \nu\nu$

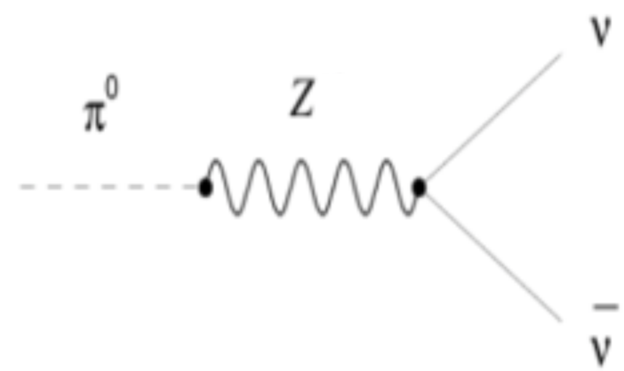
$$BR(\pi^0 \to \nu\bar{\nu}) = 3.8 \times 10^{-8} \left(\frac{m_\nu}{m_{\pi^0}}\right)^2 \sqrt{1 - 4\left(\frac{m_\nu}{m_{\pi^0}}\right)^2}$$

$BR(\pi^0 \to \nu\nu)_{SM} \sim 10^{-24}$ with $M_\nu = 1$ MeV [12]

$BR(\pi^0 \to \nu_1\nu_2)_{NP} \sim 10^{-8}$ [13]

$BR(\pi^0 \to \nu\nu)_{exp} < 2.7 \times 10^{-7}$ (90% C.L.) [14]

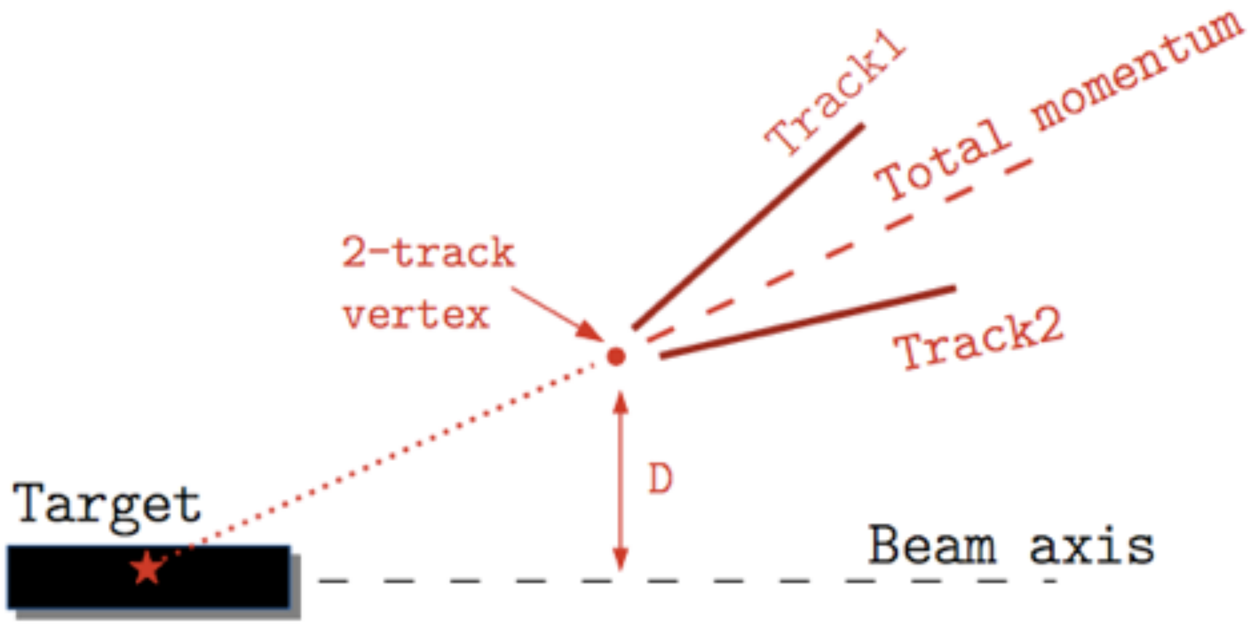




Exotic searches at NA62

Searches for long-lived dark sector particles

Long-lived exotic particles from Hidden Sector (DM candidates) may be created in the proton-target interaction and reach the NA62 decay volume



The possible presence of a sector with vector particles of mass below 1 GeV is one of the possibilities ("portals") for new-physics from a dark sector of fleebly interacting new degrees of freedom.

Assuming DM decays to SM particles with universal coupling, we can be sensitive to possible mediator-SM interactions

- Heavy Neutrino HNL from upstream D decays with $\nu_h \to \pi l$
- Dark photon A' produced in π/ρ decays in target, with $A' \to \ell^+\ell^-$
- Axion-like particle A^0 produced in target/beam dump, with $A^0 \to \gamma\gamma$

Long-lived Dark Photon Searches

The A’ boson is expected to interact with the electromagnetic field.

A’ can be produced by modified electromagnetic two-body decays of π^0, η, η’, Φ, ρ, and ω mesons or by proton bremstrahlung.

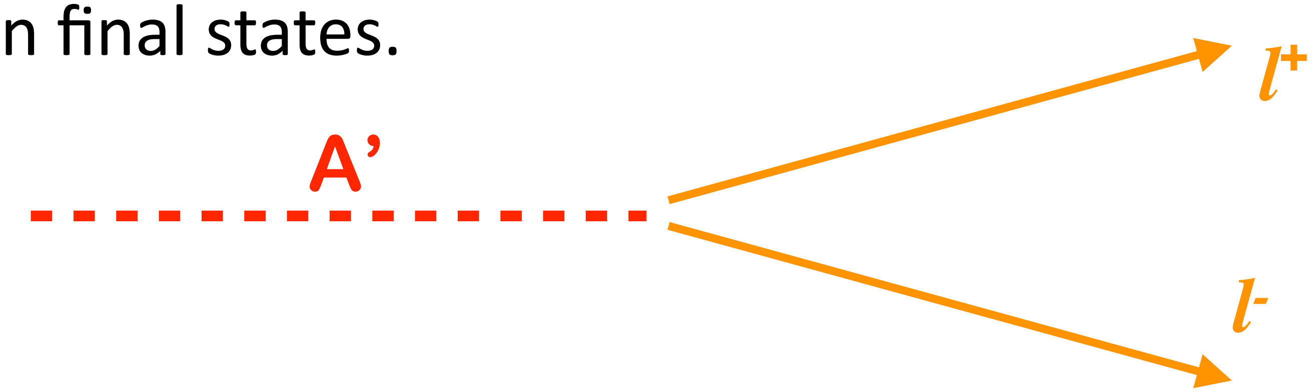
Model dependence: experimentally driven approach.

Long-lived dark photon traverses much of the experimental apparatus before decaying to a visible final state

Limit on a specific coupling: searching for a given decay mode.

Dark Photon (Vector Mediator A’) with mass below 600 MeV

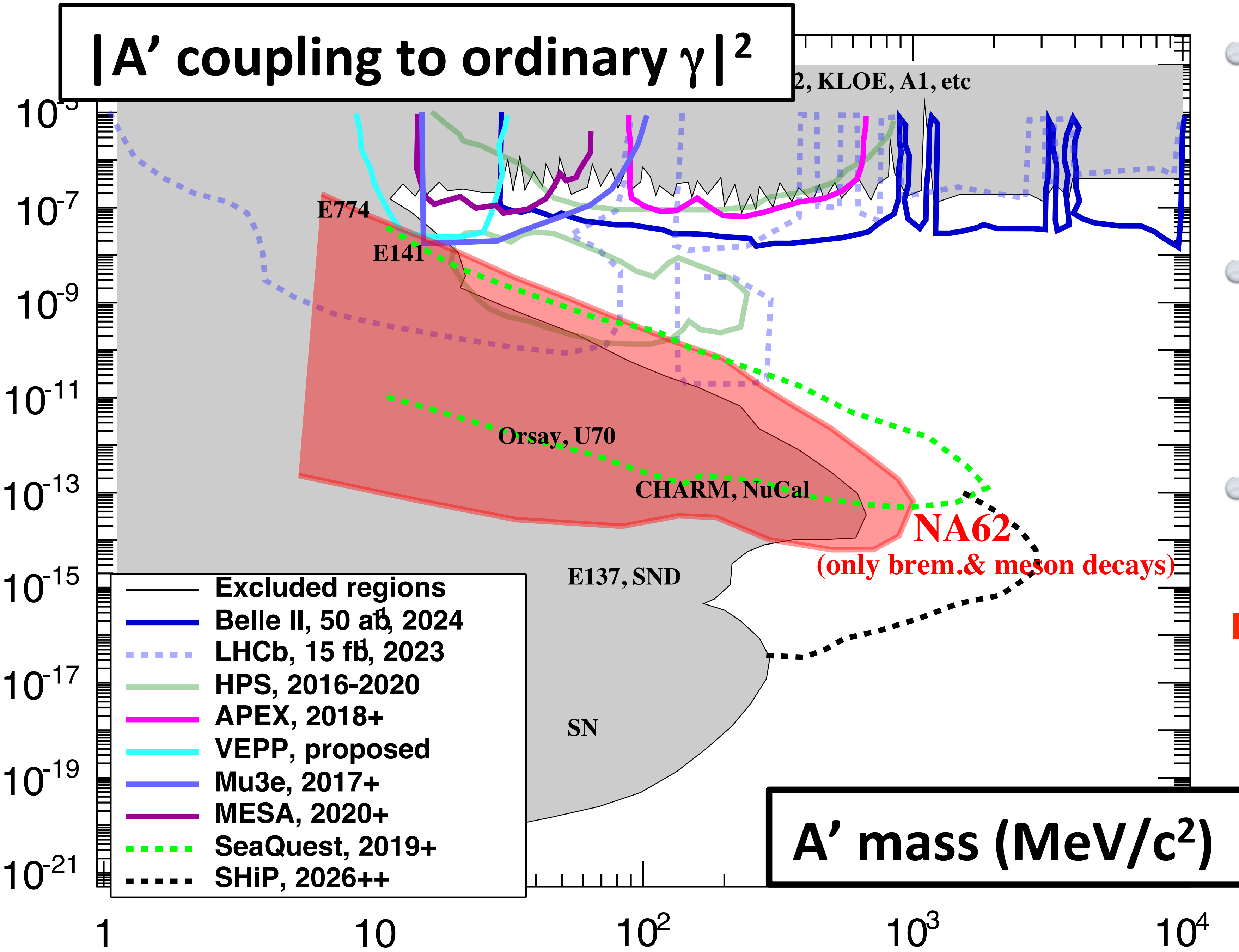
- **A’→ e^+e^-, A’→$\mu^+\mu^-$**: two, oppositely-charged, in-time, tracks reconstructed as originating from the 60-m long fiducial volume, two lepton final states.



invariant mass should reconstruct A’ mass

Long-lived Dark Photon Searches

Sensitivity studies assuming 2×10^{18} POT (2 years of data taking)



- search for displaced, dilepton decays of dark photons, A'→ μμ
- include trigger/ acceptance/selection efficiency
- assume zero-background,

➡ expected 90%-CL exclusion plot

MC demonstrates that NA62 can achieve interesting results

Heavy Neutrino searches

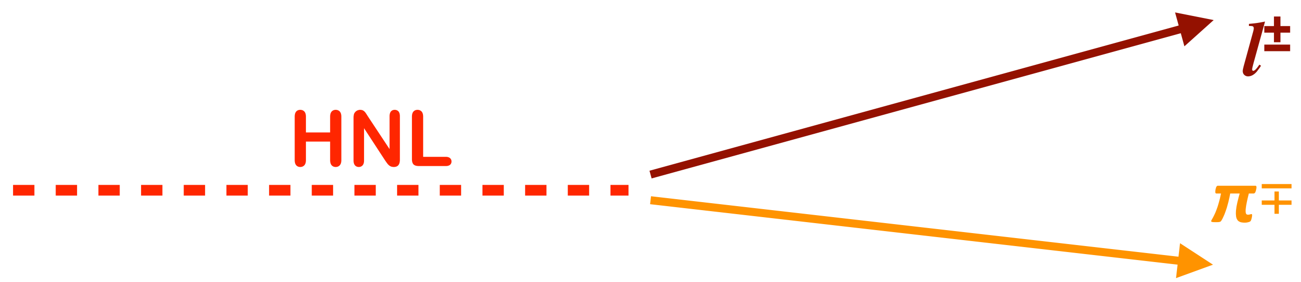
Existence of neutrino oscillations and baryon asymmetry of the universe (BAU), may be explained by adding three massive right-handed (sterile) neutrinos to the SM

The HNLs are expected to be produced:

- From leptonic decays of **$K^+ \rightarrow$ HNL l^+** before KTag system (range mass from π-mass to K-mass)
- From leptonic decays **$D(D_s) \rightarrow$ HNL l^+** soon after production in the target, with l = e,μ. (mass up to ~ 1.7 GeV)

Heavy Neutrinos (Neutrino portal HN') with mass up to the D meson

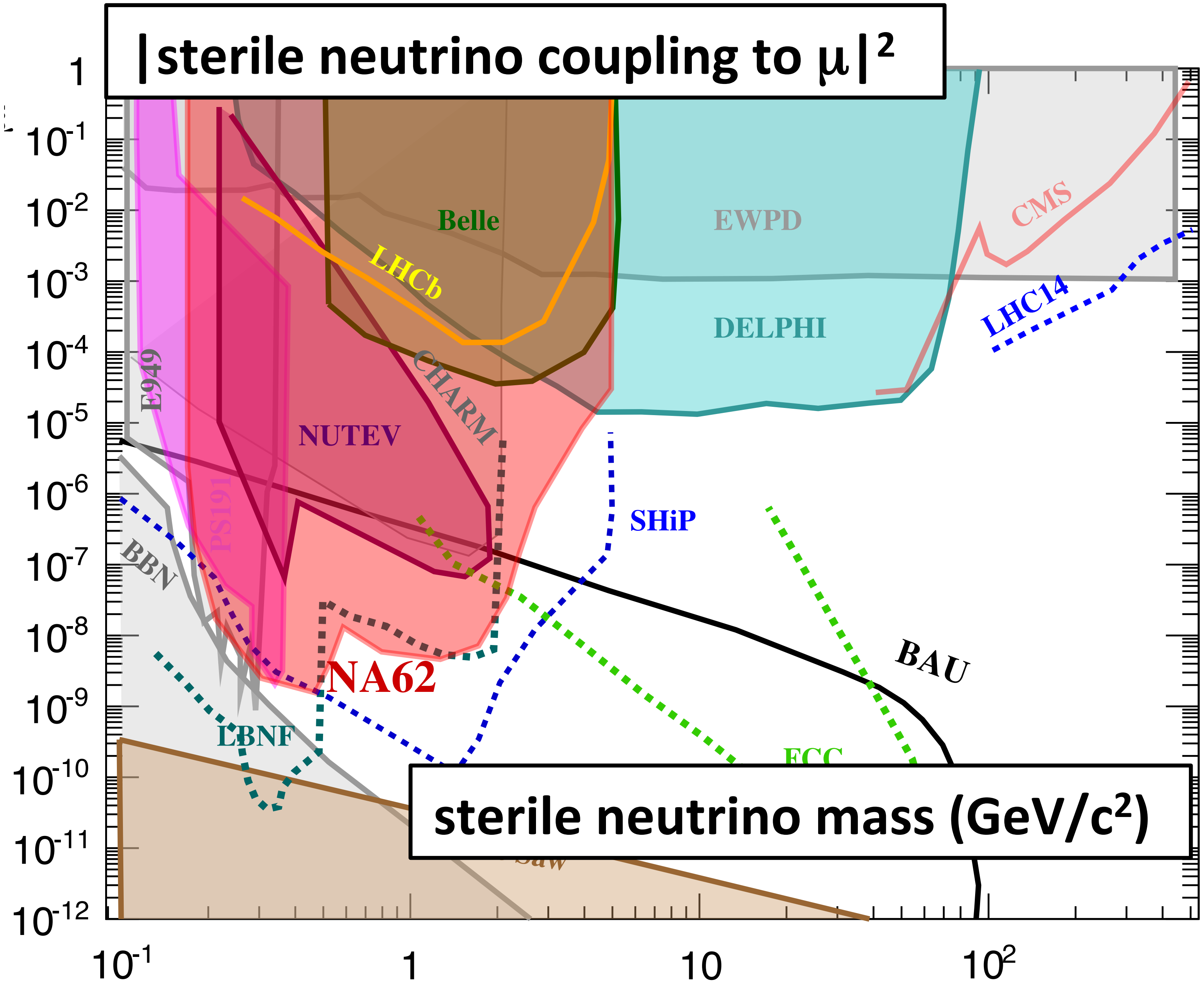
- **HNL → πe, HNL → πμ**: two, oppositely-charged, in-time, tracks reconstructed as originating from the 60-m long fiducial volume, one-lepton final states.



invariant mass should reconstruct HNL mass

Heavy Neutrino searches

NA62 expected sensitivity with respect to that of the existing experimental results and to the theoretical limit imposed by the observed BAU.



Sensitivity studies assuming
2×10^{18} POT
(2 years of data taking)

- search for displaced, leptonic decays HNL⟶ πμ
- include trigger/acceptance/ selection efficiency
- assume zero-background,

➡ expected 90%-CL exclusion plot

Exotic searches at NA62

MC Study for the expected backgrounds evaluation are currently underway

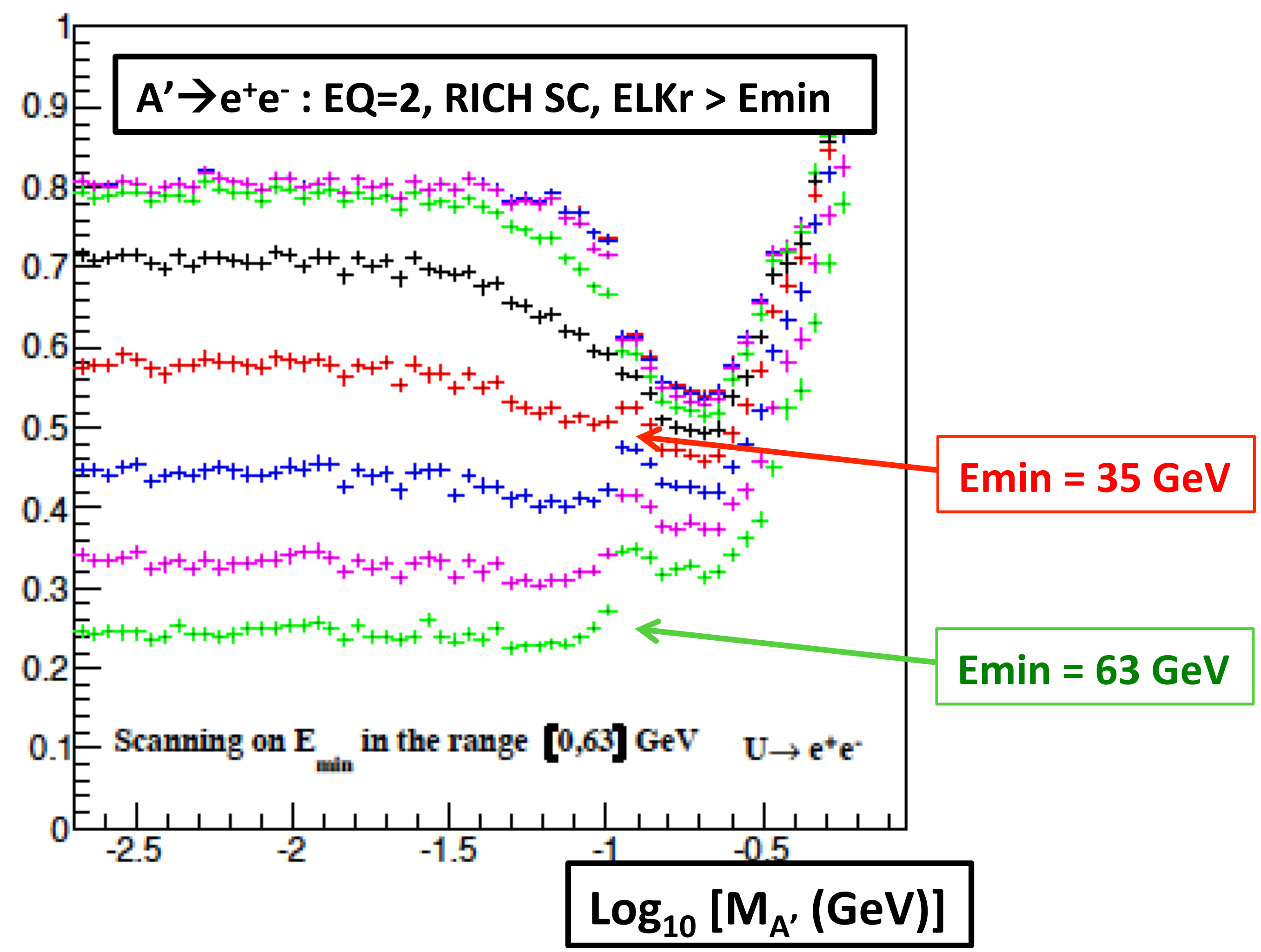
- Expected background from K^+ and K_S, K_L decays
- Combinatorial background from beam muon HALO

Parallel triggers to detect the possible dark-matter-decay final states have been developed: high efficiency, negligible efficiency reduction for the main stream

Various additional trigger streams have been tested and are under study. Conditions suited for:

A'→μ+μ-, A'→e+e-, HNL→eπ, HNL→μπ

A'→e+e- Trigger efficiency for different LKr Calorimeter energy thresholds:



Physics at NA62 after LHC LS2 (end 2018)

Physics program after LS2

(1) Present K^+ beam and dedicated triggers

- LFV and LNV to expected sensitivity ~ 10^{-12} from K
- Ultra-rare/forbidden π^0 decays

(2) Data-taking with beam dumped on collimator in experimental area

- Dark photons, Heavy Neutral Leptons, Axion-like particles

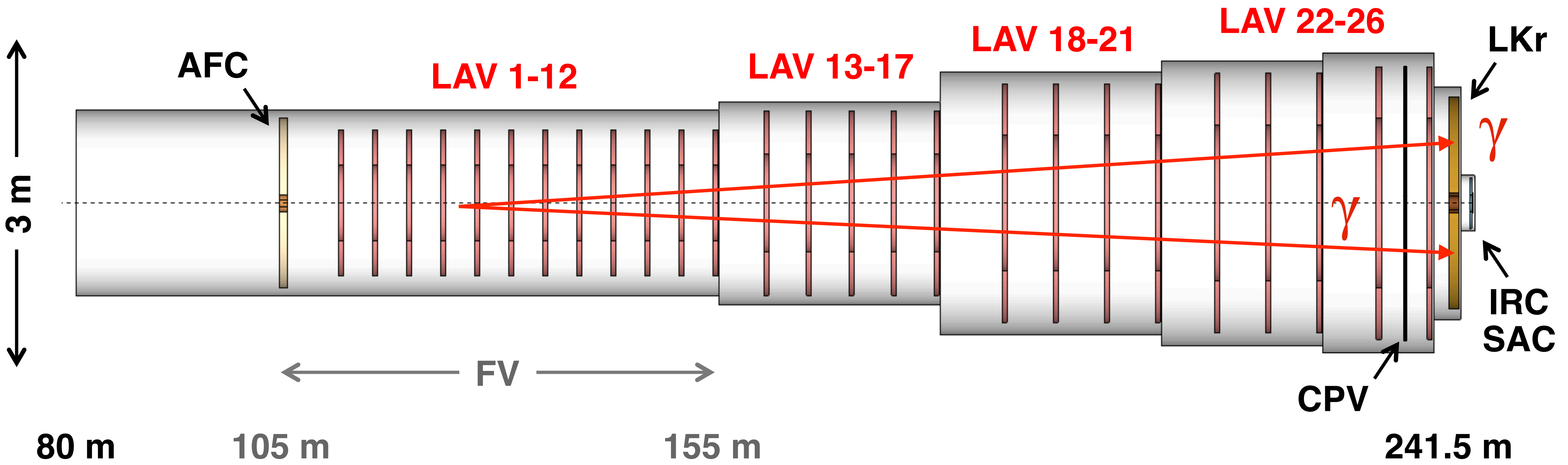
The current NA62 data will be exploited to future sensitivity studies:

- Evaluate background rejection capability
- Understand how to optimize design for future beam-dump mode

  - With a minimally-modified beam line
  - With a minimally-upgraded detector

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 in NA62 site



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 2×10^{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

Conclusions

- NA62 is running and collecting data. About 10^{12} K^+ decays collected in 2016.
  - Physics sensitivity for $K^+ \to \pi^+ \nu\nu$ measurement in line with the design.
  - Analysis of 2016 data at high intensity is on going.
  - A further compelling physics program is going to be addressed.
- Interesting future plans beyond NA62

Thank you for the attention!!
On behalf of NA62 Collaboration

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