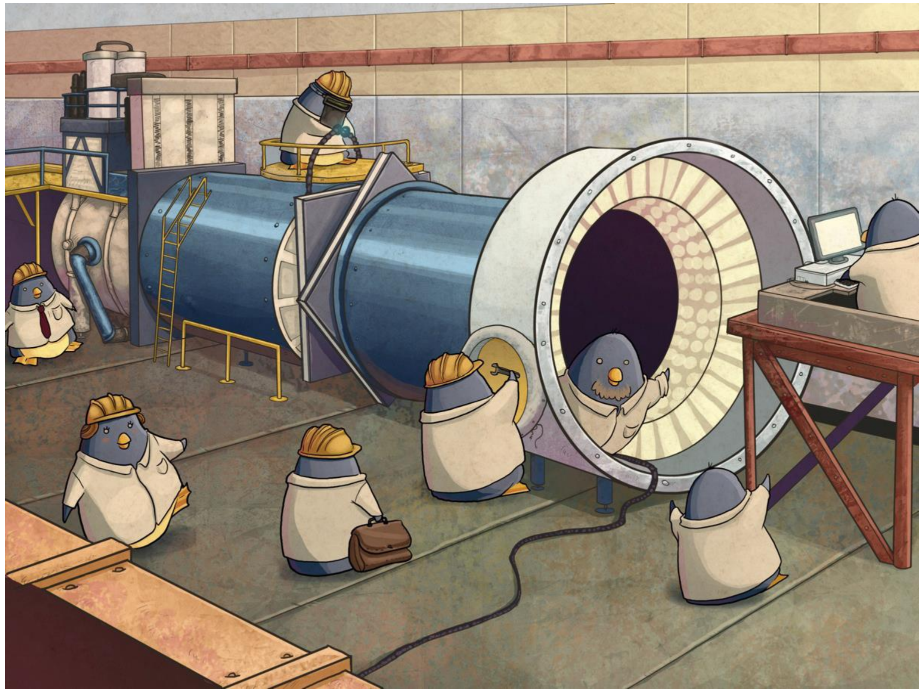
Search for $K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$ at NA62

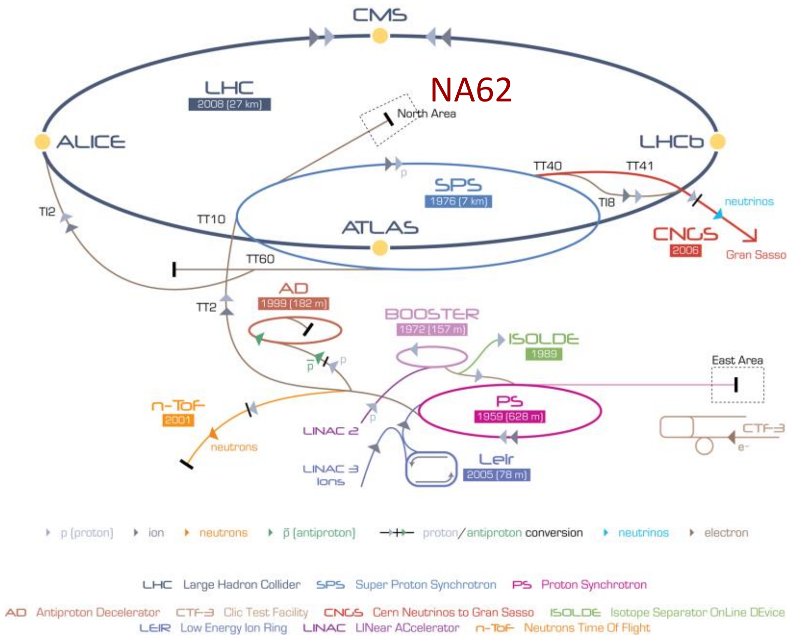


Jacopo Pinzino
INFN Pisa

New Trends in High-energy physics
04/10/2016

The NA62 Experiment

- NA62: High precision fixed-target Kaon experiment at CERN SPS
- Main goal: precise measurement of BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) with 10% accuracy
- Broader physics program: LFV / LNV in K^+ decays, hidden sector particles searches.

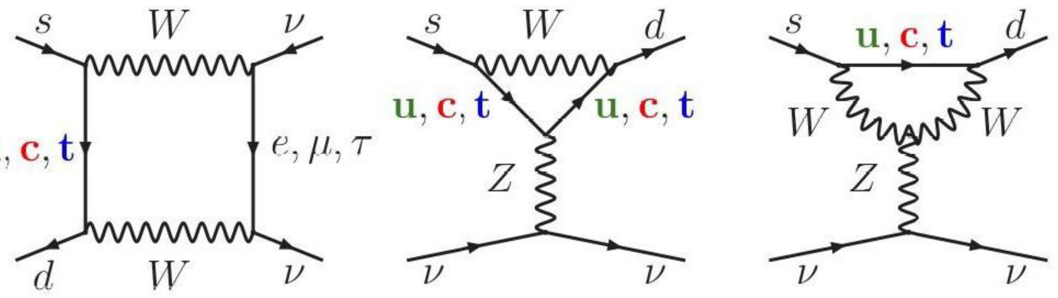


NA62 Timeline

- December 2008: NA62 Approval
- 2009 – 2012: detector R&D
- Oct 2012: NA62 Technical Run (partial layout)
- 2013 - 2014: Installation/Commissioning
- Oct 2014: NA62 Pilot Run (partial layout)
- 2015 - 2018: Physics Runs
- Proposed runs after LS2 under discussion

Accelerator schedule	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
LHC		Run 2			LS2			Run 3			LS3		Run 4
SPS										NA stop	SPS stop		

The $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ Decay



- 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 %) uncertainty

- Very clean theoretically:

  Short distance contribution; hadronic matrix element extracted from precisely measured BR($K^+ \rightarrow \pi^0 e^+ \nu$)).
- SM predictions:

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

  $BR(K_L \rightarrow \pi^0 \nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$

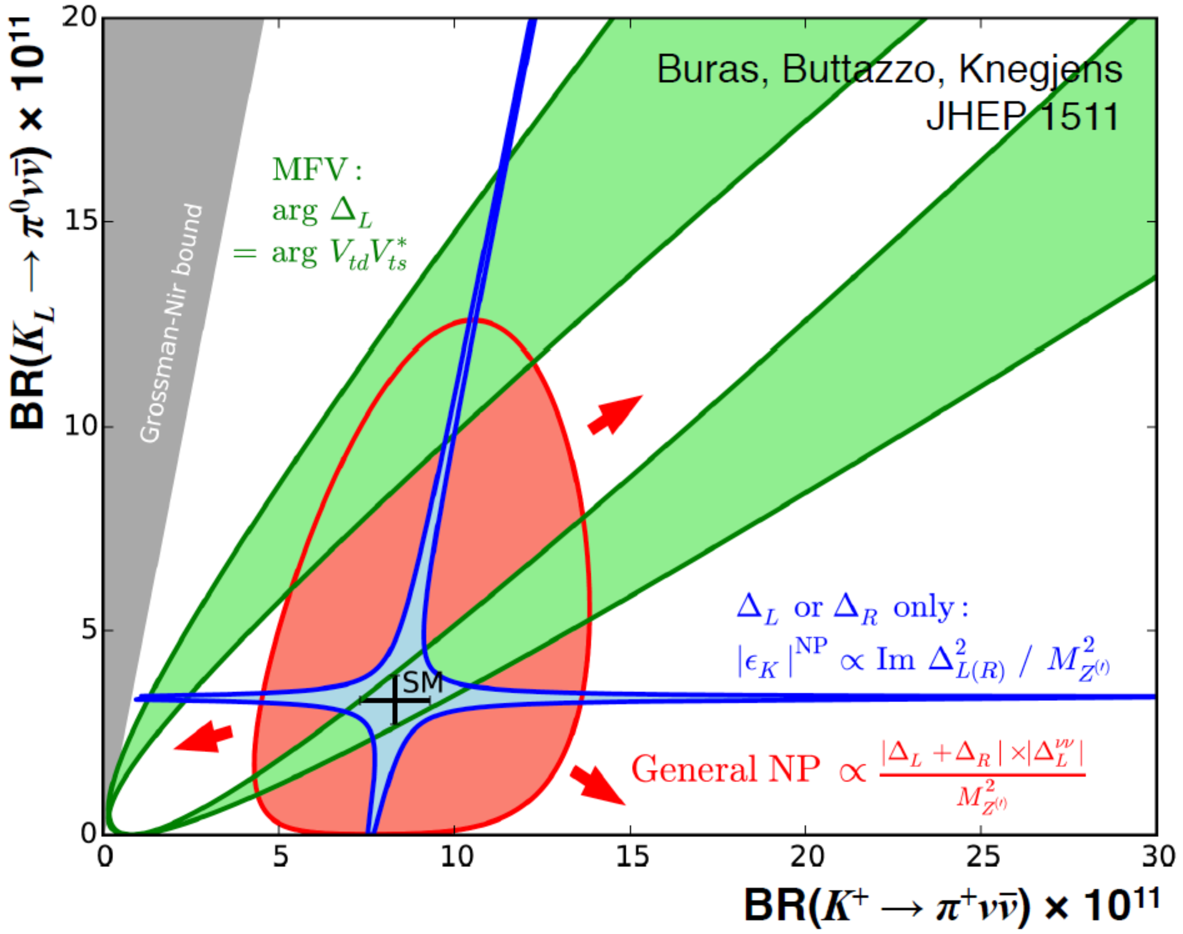
  [Buras et al. JHEP 1511 (2015) 33]
- Experimental Result:

  $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ [Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)]

  $BR(K_L \rightarrow \pi^0 \nu\bar{\nu}) < 2.6 \times 10^{-8}$ (90% C.L) [Phys. Rev. D 81, 072004 (2010)]

$K \rightarrow \pi\nu\bar{\nu}$ and New Physics

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

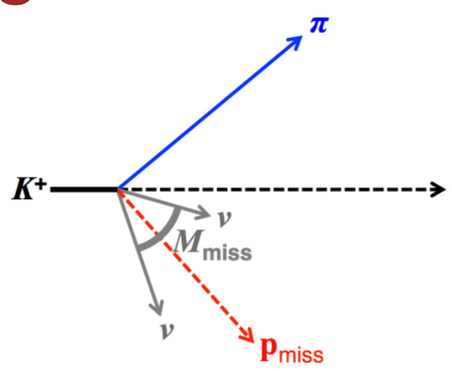


- Models with CKM-like flavor structure:
  - Models with MFV
- Models with new flavour-violating interactions in which either LH or RH currents dominate:
  - *Z/Z'* models with pure LH/RH couplings
  - Little Higgs with *T* parity
- Models without above constraints:
  - Randall-Sundrum

Signal and Backgrounds

Signal:

K track in, π track out and no other particles in final state



NA62 goal: measure BR to 10% precision

100 signal event and background < 20%

- K decays 10^{13}
- Signal acceptance ~10%
- <10% precision background measurement
- More than 10^{12} background rejection

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%
$\pi^+\pi^- e^+\nu$	4.3×10^{-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}

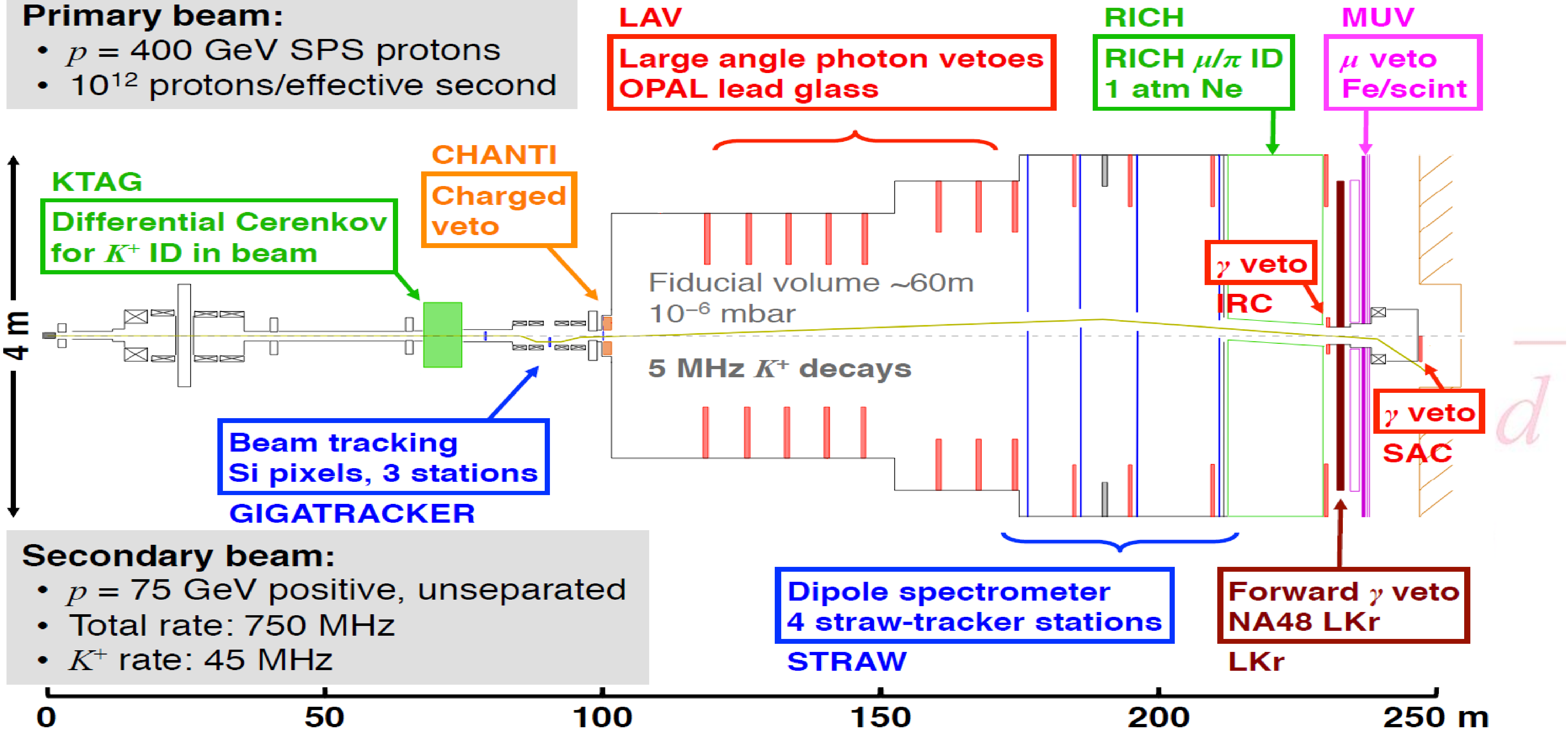
Other backgrounds

Beam-gas interactions

Upstream interactions

NA62 Layout

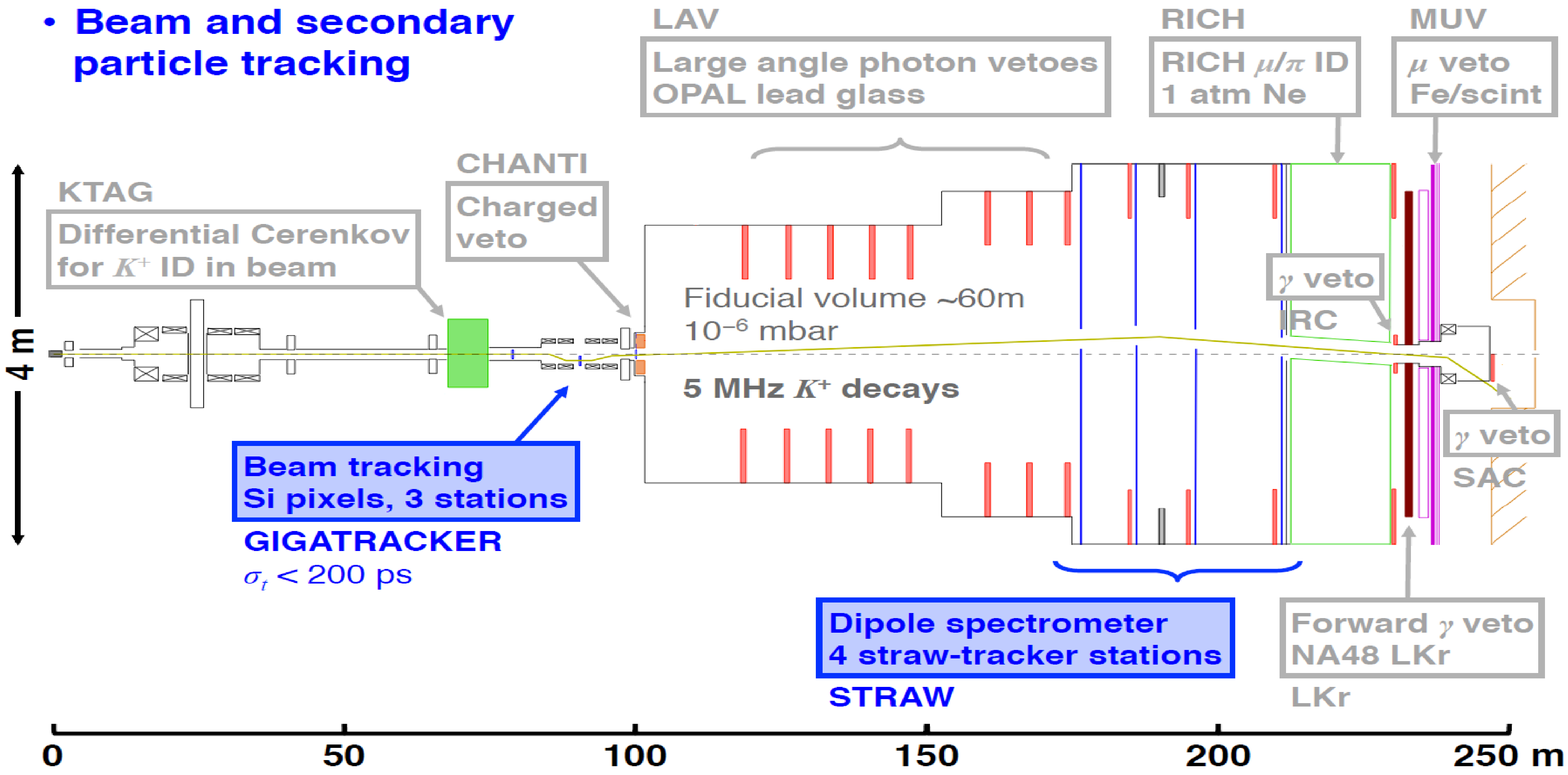
Primary beam:
- p = 400 GeV SPS protons
- 10^{12} protons/effective second



Secondary beam:
- p = 75 GeV positive, unseparated
- Total rate: 750 MHz
- K^+ rate: 45 MHz

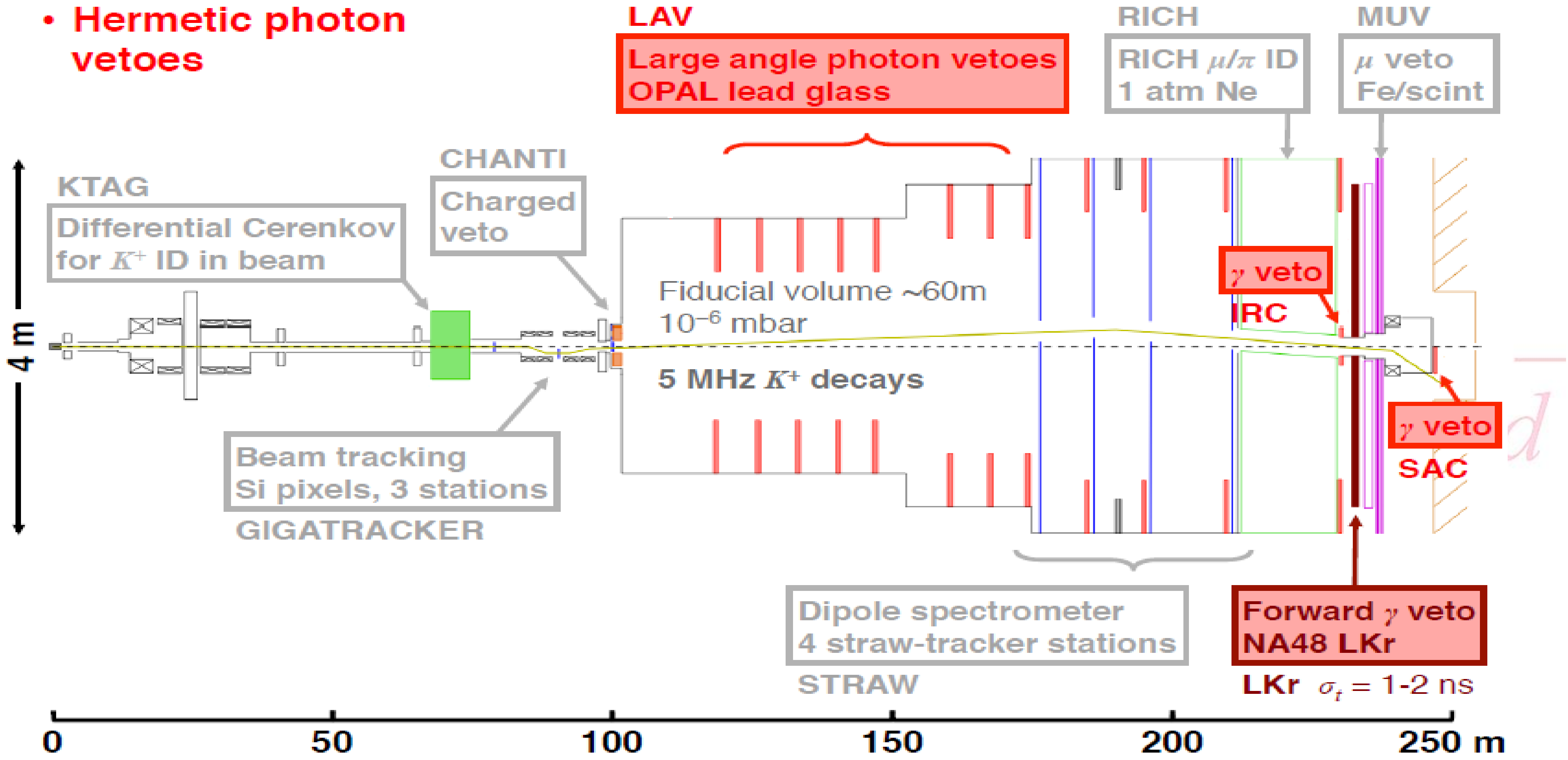
NA62 Layout

- **Beam and secondary particle tracking**

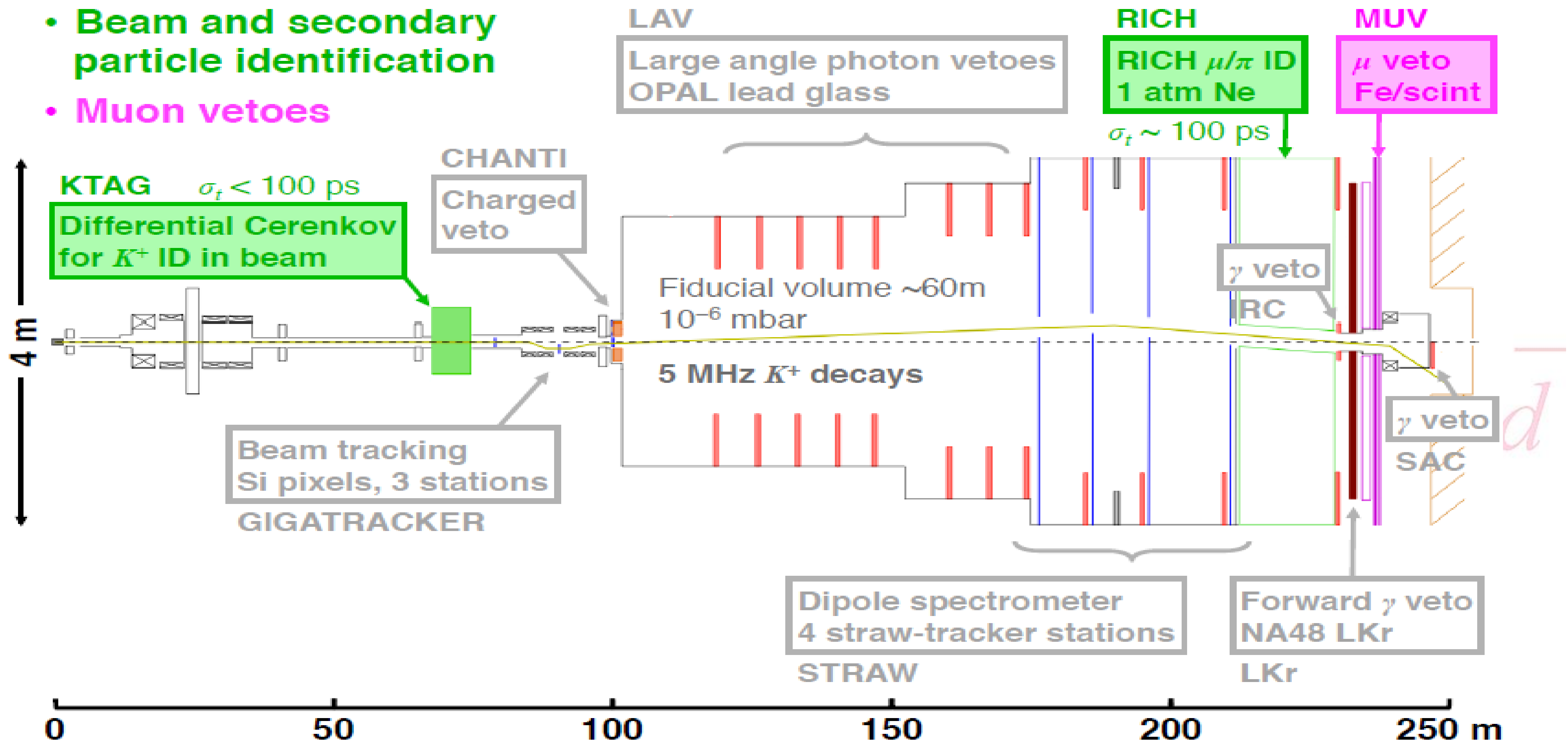


NA62 Layout

- **Hermetic photon vetoes**



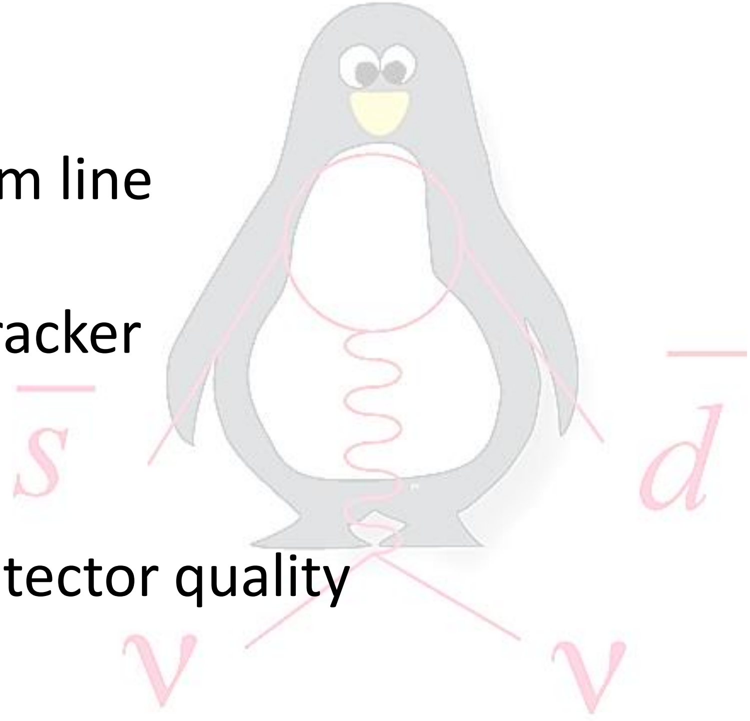
NA62 Layout



• Beam and secondary particle identification
• Muon vetoes
LAV
Large angle photon vetoes
OPAL lead glass
RICH
RICH μ/π ID
1 atm Ne
$\sigma_t \sim 100$ ps
MUV
μ veto
Fe/scint
KTAG
$\sigma_t < 100$ ps
Differential Cerenkov
for K^+ ID in beam
CHANTI
Charged
veto
4 m
Fiducial volume ~60m
10^{-6} mbar
5 MHz K^+ decays
γ veto
IRC
γ veto
SAC
Beam tracking
Si pixels, 3 stations
GIGATRACKER
Dipole spectrometer
4 straw-tracker stations
STRAW
Forward γ veto
NA48 LKr
LKr
0
50
100
150
200
250 m

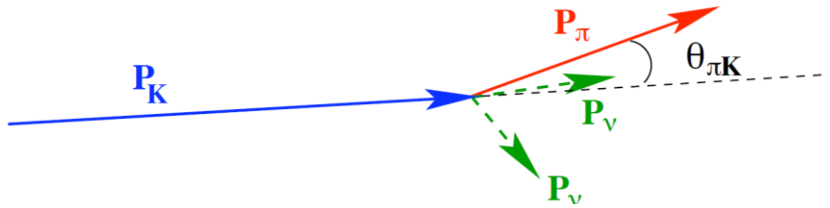
Status and Data Taking

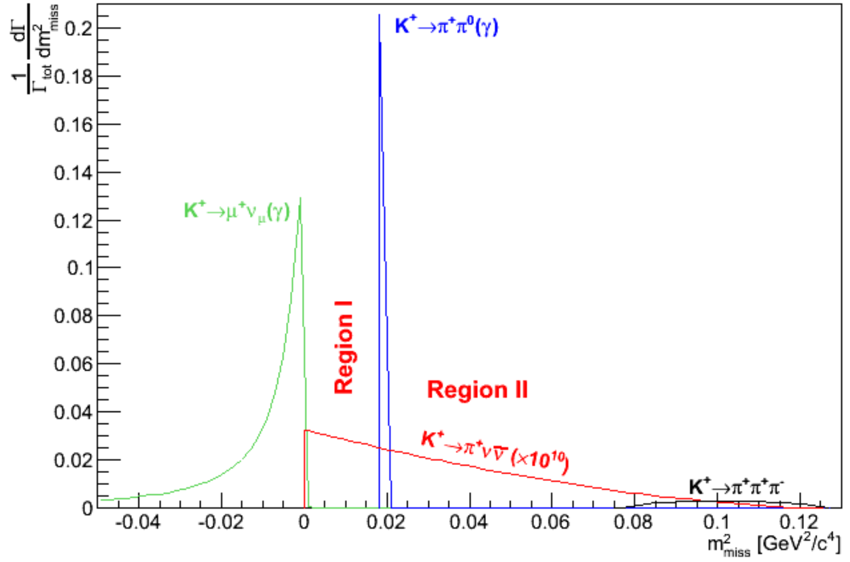
- Beam line, detectors, trigger and DAQ fully commissioned
- NA62 data taking periods
  - 2014: detector commissioning
  - 2015: trigger commissioning, detector quality studies, beam line commissioning up to nominal intensity
  - 2016: high level trigger commissioning (done), full beam tracker commissioning (done), physics (on-going)
- Data samples for analysis:
  - 2015: Low intensity data with minimum bias trigger for detector quality studies (this talk)
  - 2016: $\pi\nu\bar{\nu}$ data (up to 30% of nominal intensity) and not $\pi\nu\bar{\nu}$ data (up to 30% of nominal intensity)

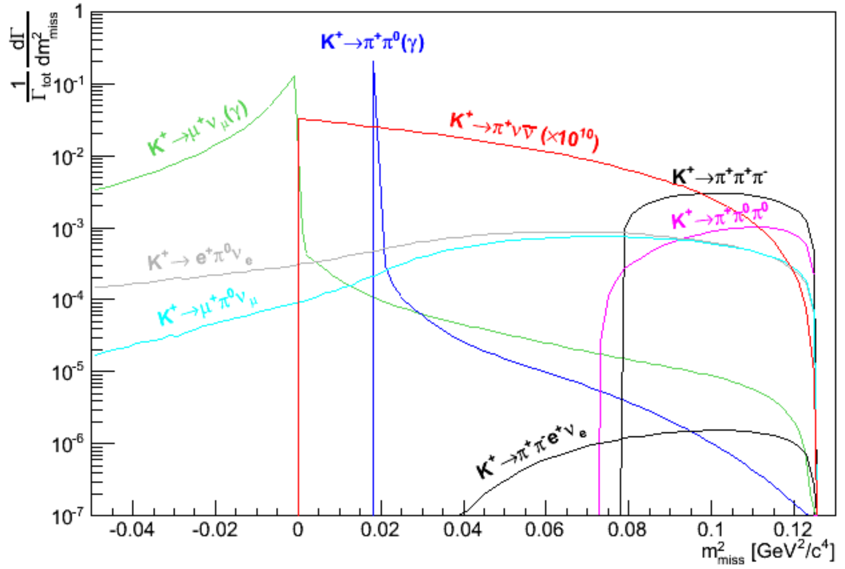


Analysis Strategy

- Signal: 1 beam track, 1 charged track, nothing else
- Background: K^+ decay modes; beam activity
- Kinematics: $m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$







Experimental principles:

1. Precise kinematic reconstruction
2. PID: K upstream, e / μ / π downstream
3. Hermetic γ detection
4. Sub-ns timing

Key analysis requirements:

- 2 signal regions in m^2_{miss}
- 15 < P_{π^+} < 35 GeV/c
- 65 m long decay region

Expected Performances and Sensitivity

Required background suppression

Kinematics	$O(10^4\text{-}10^5)$
Charged Particle ID	$O(10^7)$
γ detection	$O(10^8)$
Timing	$O(10^2)$

Sensitivity

Decay	ev/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
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	< 1
Total background	< 10

Signal Selection

One – track selection (OTS):

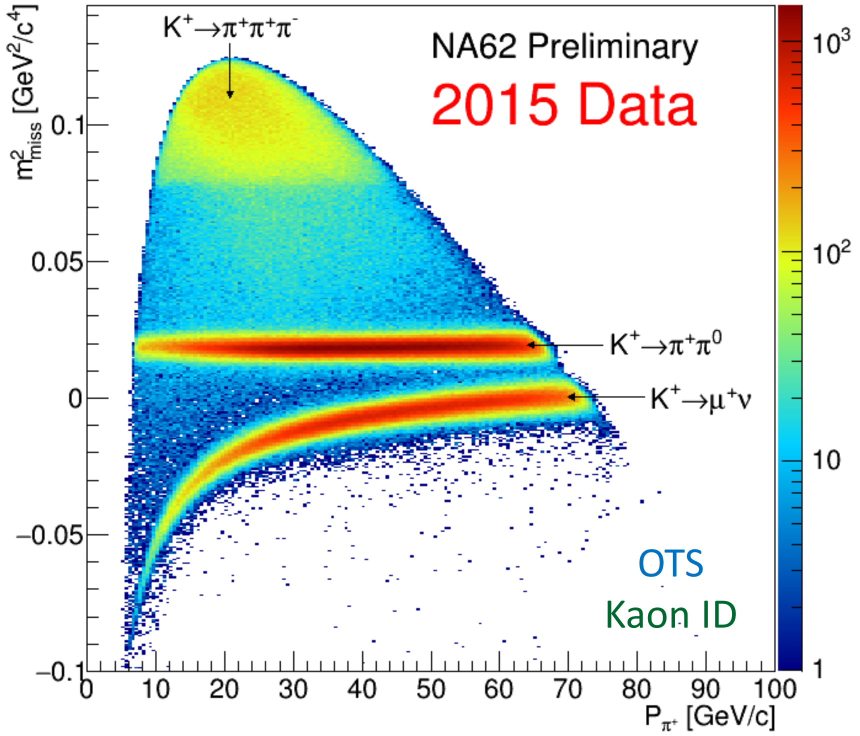
- 1 positive track
- Acceptance/quality cuts
- Matched to hit on CHOD (σ_t ~ 200 ps)
- Downstream track matching energy in calorimeters
- Further associated to hits on RICH, muon vetoes
- Beam track matching the downstream track

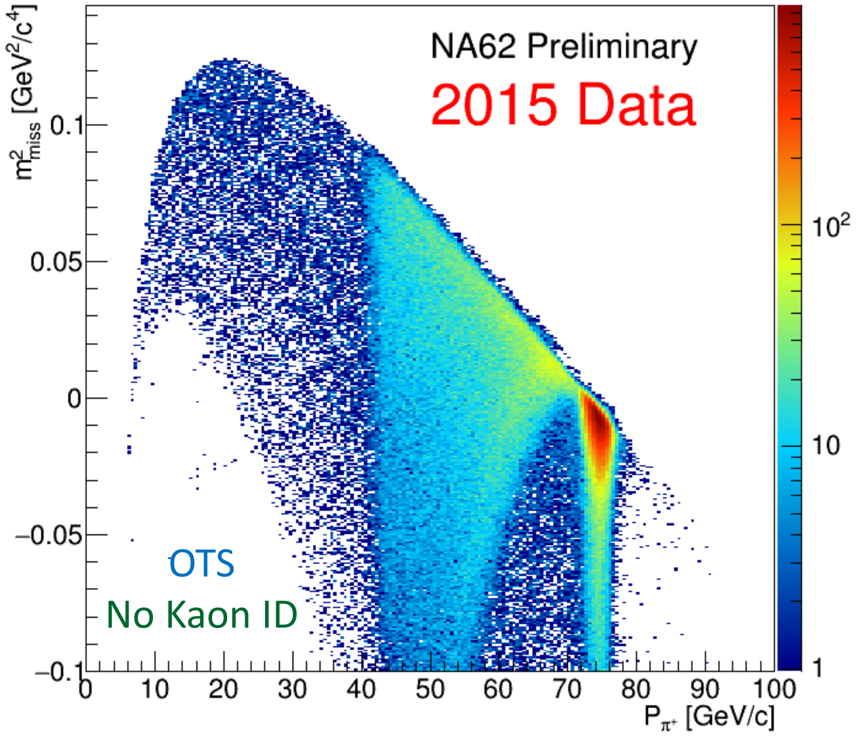
Kaon ID:

- Beam track matching a K signal in Kaon ID (σ_t ~ 100 ps)
- Decay vertex in the fiducial region (65 m)

Time resolutions:

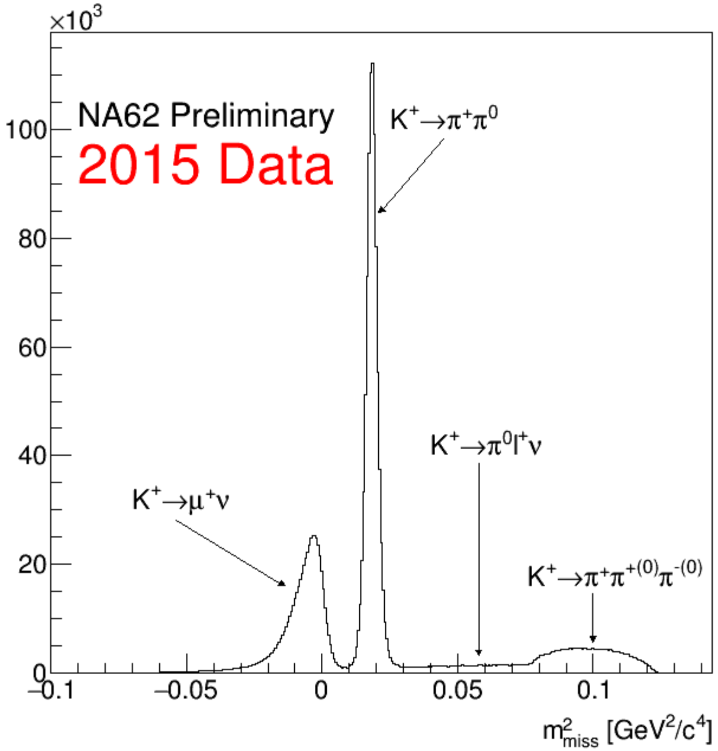
- Kaon ID < 100 ps
- Beam track < 200 ps
- Downstream track < 200 ps
- Calorimeters 1-2 ns

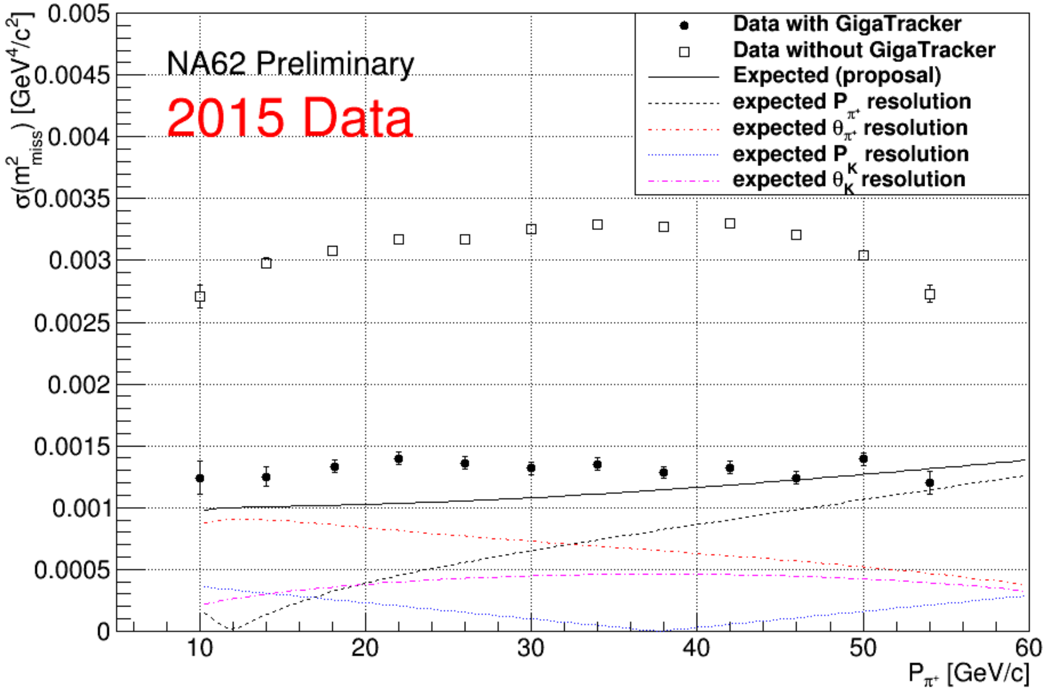




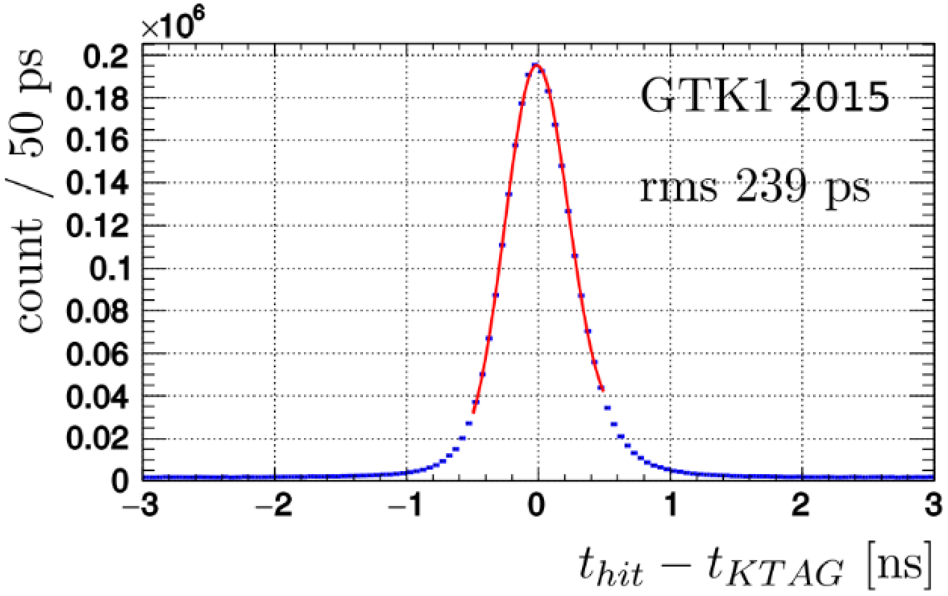
Kinematics

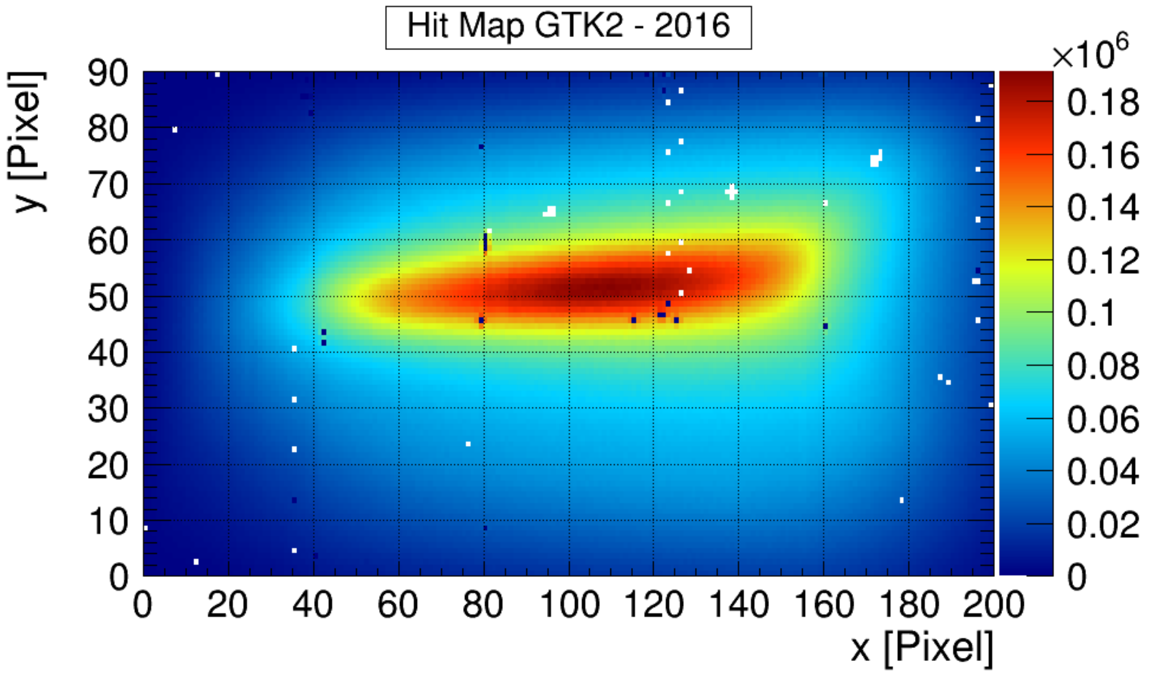
- Tracking Techniques: Si -pixel tracker (beam); Straw tube tracker in vacuum (downstream)
- Goal: $O(10^4 \div 10^5)$ suppression factor of the main kaon decay modes
- P_{π^+}<35GeV/c: best $K^+ \rightarrow \mu^+\upsilon$ suppression.
- Kinematics studied on $K^+ \rightarrow \pi^+\pi^0$ selected using LKr calorimeter.
- Resolutions close to the design.
- $O(10^3)$ kinematic suppression factor measured.



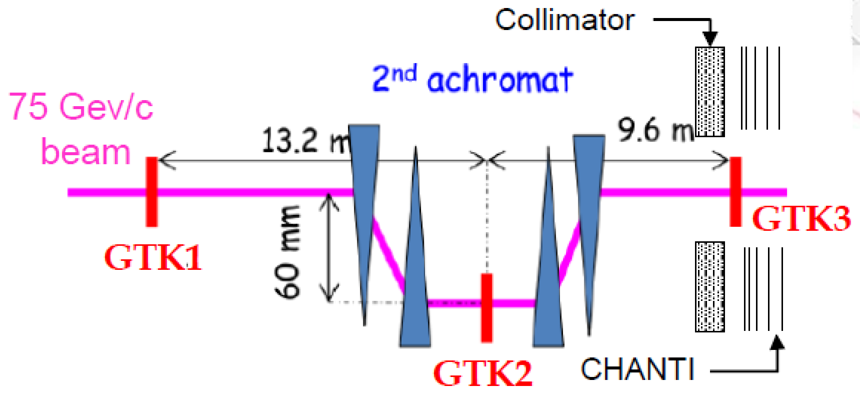


Beam Tracker (Gigatracker)

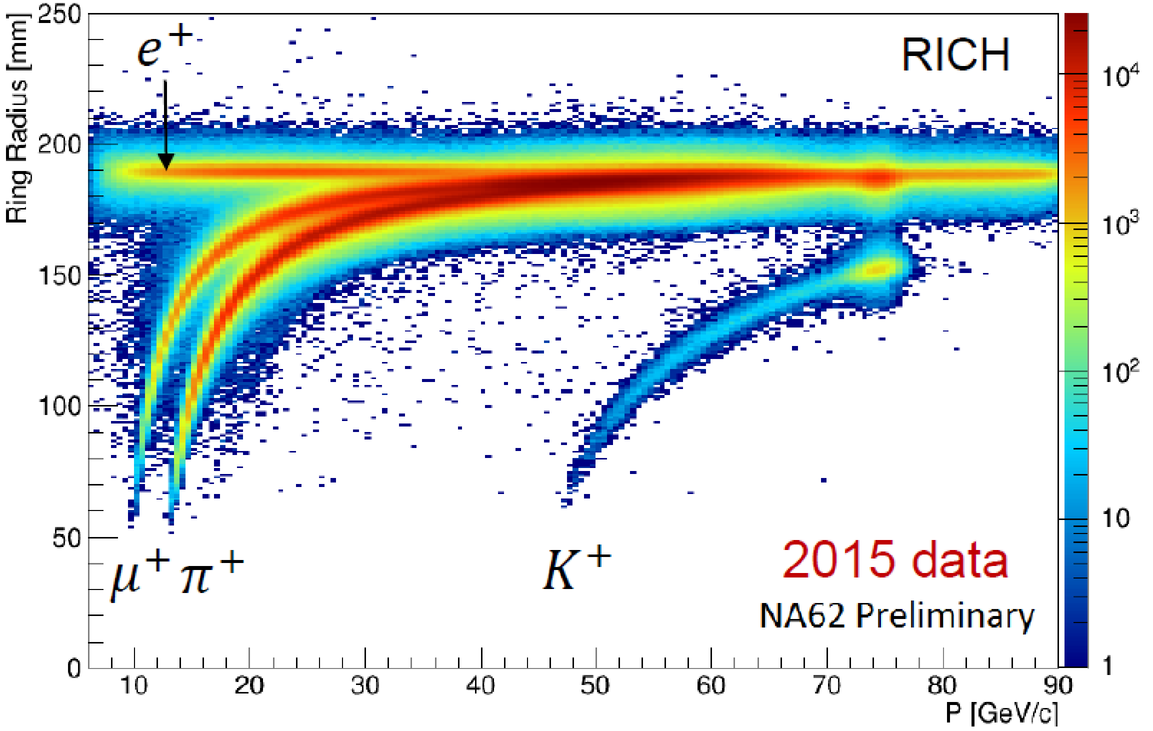


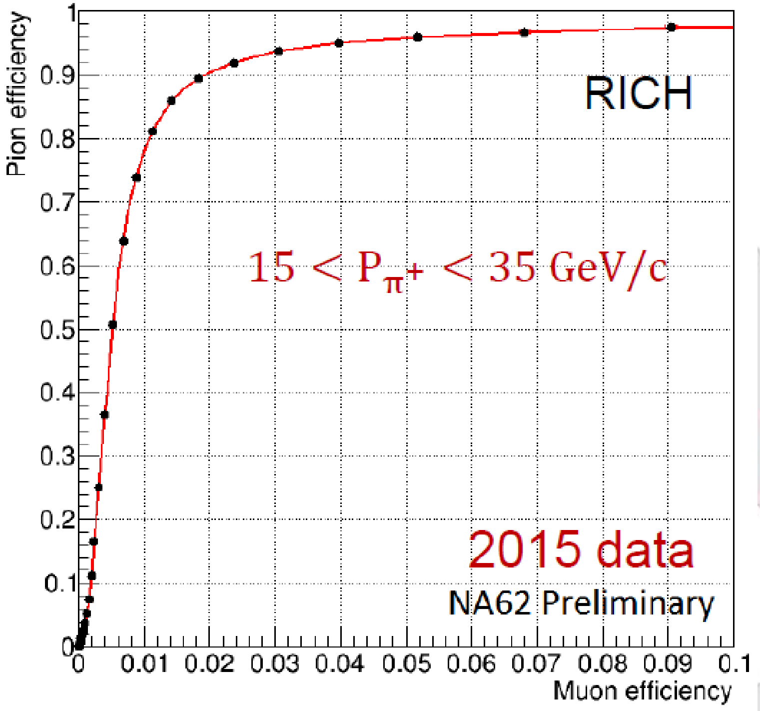


- 3 Si pixel station on the beam
- $X/X_0 < 0.5\%$ / station
- Cooling using microchannel technique
- $300 \times 300\ \mu m^2$ pixels, ~54000 pixels
- On-sensor TDC readout chip
- Commissioned in 2015-2016
- Measured performances match the design
  - $\sigma(t_{beam\ track}) \sim 200$ ps



Downstream Particle Identification





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

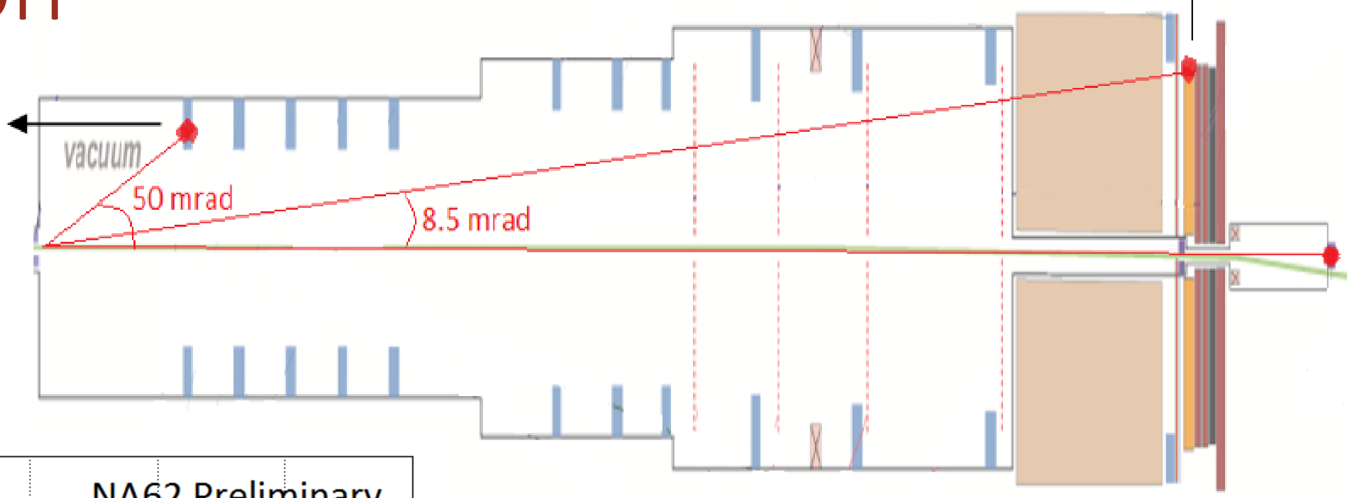
RICH

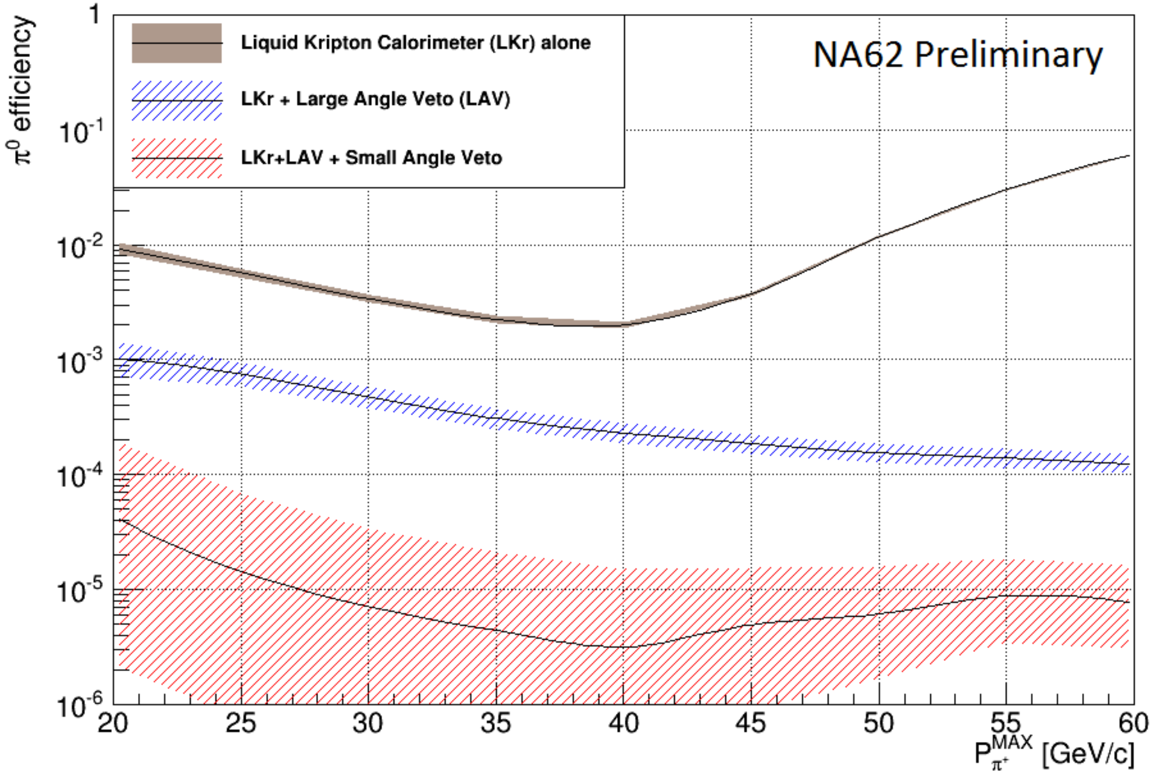
- 15 < P_{π^+} < 35 GeV/c (best π/μ separation)
- O(10^2) π/μ separation
- 80% (90%) π^+ efficiency in 2015 (2016)

Calorimeter (LKr)

- O($10^4 \div 10^6$) μ suppression
- 90% ÷ 40% π^+ efficiency in 2015 using a cut analysis
- Room for improvements

Photon rejection





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

⇩

- P_{π^+} < 35 GeV/c → E_{π^0} > 40 GeV/c
- Measured on data using $K^+ \rightarrow \pi^+ \pi^0$ selected kinematically

O(10^6) π^0 rejection obtained in 2015

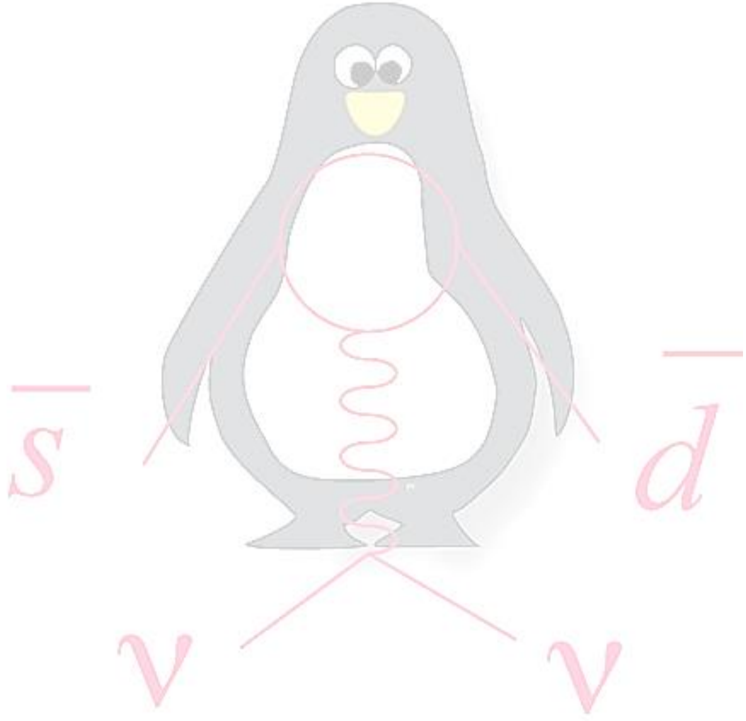
Need more stats to reach design sensitivity

Summary from data quality studies

1. Time resolution → Close to the design.
2. Kinematics → Resolution close to the design.
   Prospects to reach the designed signal –background separation.
3. Pion –muon ID → Separation with RICH close to expectations.
   Study of the separation with calorimeters on going.
   Results from simple cut analysis promising.
4. Photon veto → O(10^6) π^0 rejection already obtained.
   Statistically limited.
   2016 already enough statistic to address the 10^8 rejection level (analysis on -going).

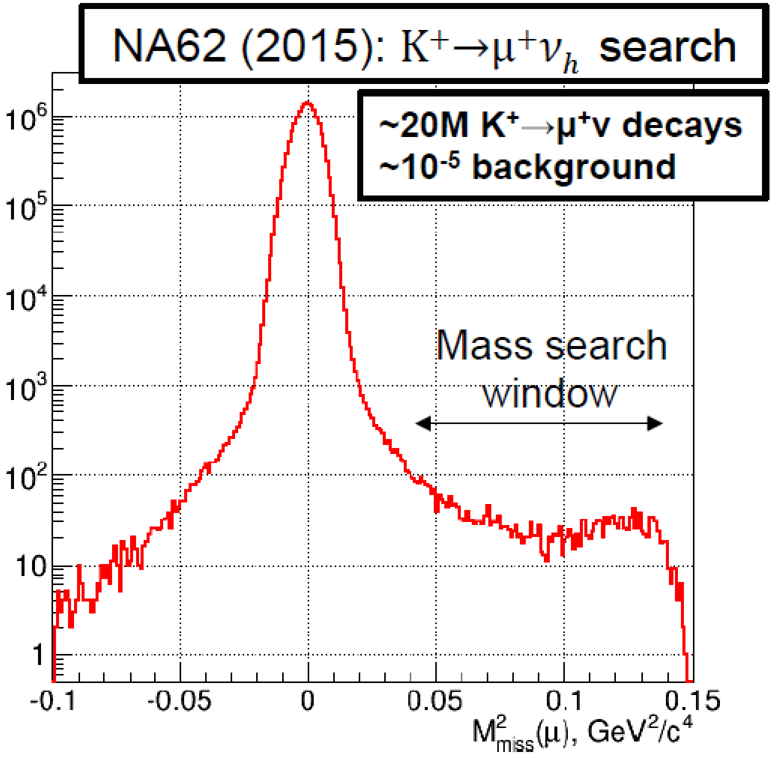
NA62 physics besides $K^+ \rightarrow \pi^+\nu\bar{\nu}$

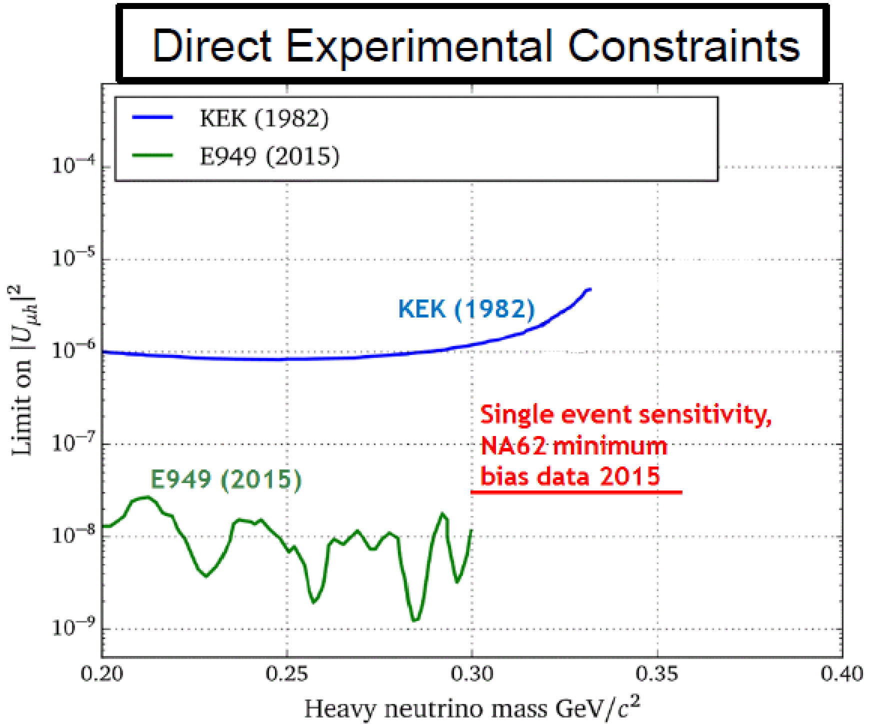
- Standard kaon physics:
  - ChPT studies: $K^+ \rightarrow \pi^+\gamma\gamma$, $K^+ \rightarrow \pi^+\pi^0 e^+e^-$, $K^+ \rightarrow \pi^+\ell^+\ell^-$
- Searches for lepton-flavor or -number violating decays
  - $K^+ \rightarrow \pi^+\mu^\pm e^\mp$, $K^+ \rightarrow \pi^-\mu^+e^+$, $K^+ \rightarrow \pi^-\ell^+\ell^+$
- Heavy neutral lepton production searches
  - $K^+ \rightarrow l^+\nu_h$ (already under analysis with 2015 data)
  - ν_h from upstream *K, D* decays with $\nu_h \rightarrow \pi\ell$
- Searches for long-lived dark sector particles
  - Dark photon γ' produced in π/ρ decays in target, with $\gamma' \rightarrow \ell^+\ell^-$
  - Axion-like particle A^0 produced in target/beam dump, with $A^0 \rightarrow \gamma\gamma$
- π^0 decays rare and forbidden/LFV, dark photon production:
  - $\pi^0 \rightarrow$ invisible, $\pi^0 \rightarrow 3/4\gamma$, $\pi^0 \rightarrow ee, eee$, $\pi^0 \rightarrow \mu e$, $\pi^0 \rightarrow \gamma'\gamma$



An Example: Heavy Neutrino Searches

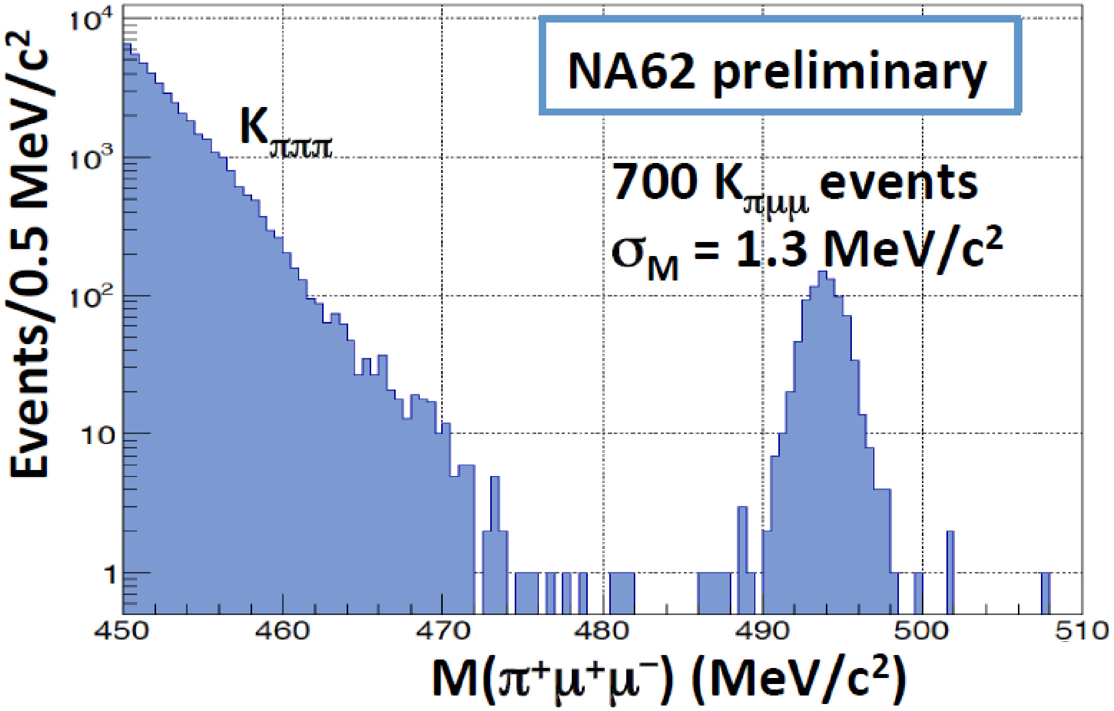
- Search for heavy neutrinos (HNL) produced in $K^+ \rightarrow e^+ \upsilon_h$ and $K^+ \rightarrow \mu^+ \upsilon_h$
- NA62 perfectly suited to search for ***v_h*** in (100 –380) MeV/c^2 mass range
- Background in the mass search region ~5 order of magnitude below the $K^+ \rightarrow \mu^+ \upsilon$ peak
- $M^2_{miss}(\mu) = (P_K - P_\mu)^2$

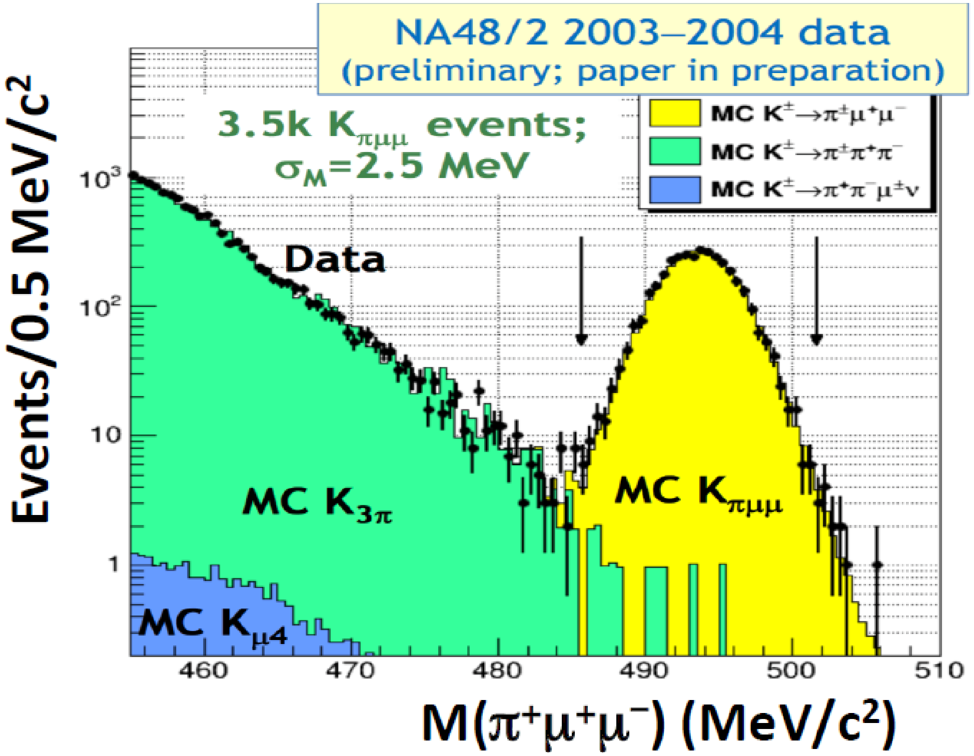




An Example: $K^+ \to \pi^+\mu^+\mu^-$

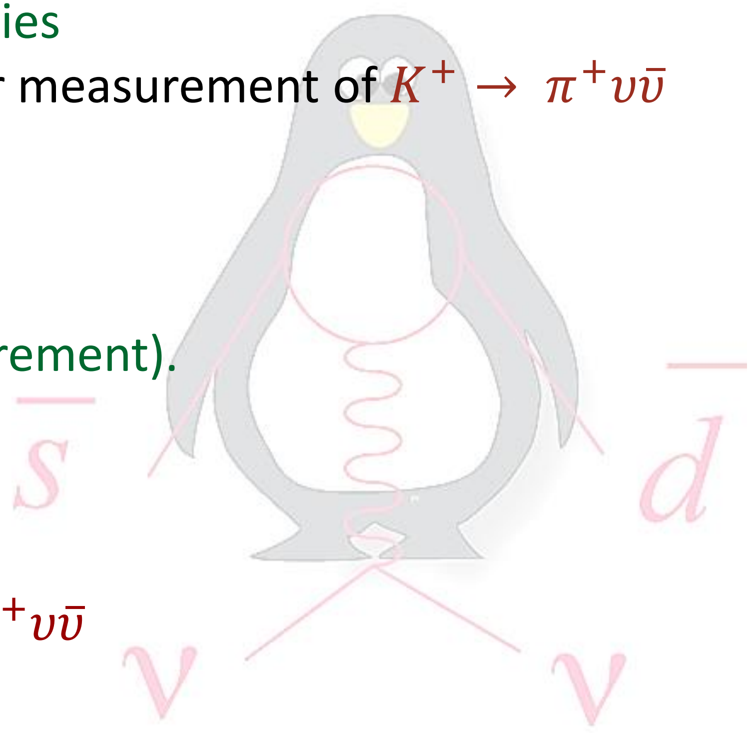
- A dedicated trigger in 2016 Run
- Sample from 2016 data: ~60k bursts (~2 week-equivalent) at ~18% intensity
- Improvements on NA48/2: mass resolution better by ~ a factor of 2
- BR is O(10^{-7}), expects improved sensitivity on hidden sector search, $K^+ \to \pi^+\chi, \chi \to \mu^+\mu^-$
- Basis for the search for LNV decay $K^+ \to \pi^-\mu^+\mu^+$





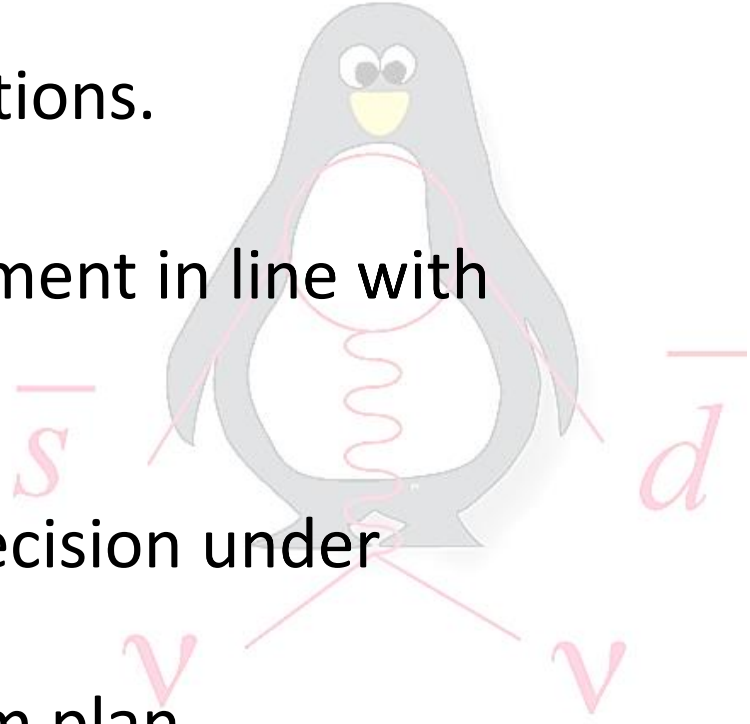
Timescale

- First physics run in 2015:
  - Minimum bias data collected at low intensity used for data quality studies
  - Data and reconstruction quality consistent with design expectations for measurement of $K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$
- $K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$ program until LS2 (2016-2018):
  - Currently running at 38% intensity
  - End 2016: reach the SM sensitivity for $K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$
  - End 2017: improve (by much) the present status of the art (BNL measurement).
  - End 2018: reach the 10% precision.
- Broader physics program until LS2 (2016-2018):
  - LFV / LNV decays, heavy neutrinos, π^0 rare decays, ...
  - as many decay modes as possible to take simultaneously with $K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$
- Broader physics program beyond LS2 (after 2020)
  - LFV / LNV decays, heavy neutrinos, π^0rare decays, hidden sector particles searches

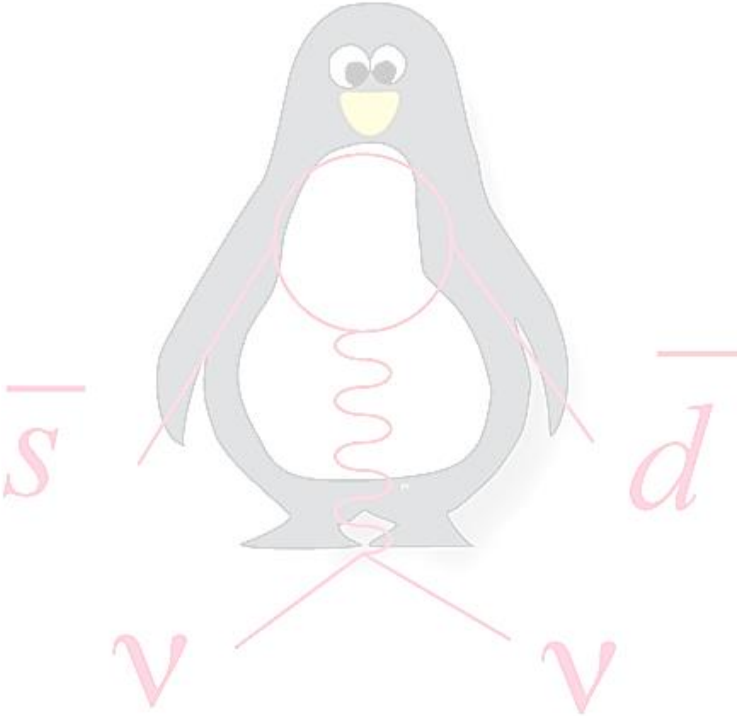


Conclusions

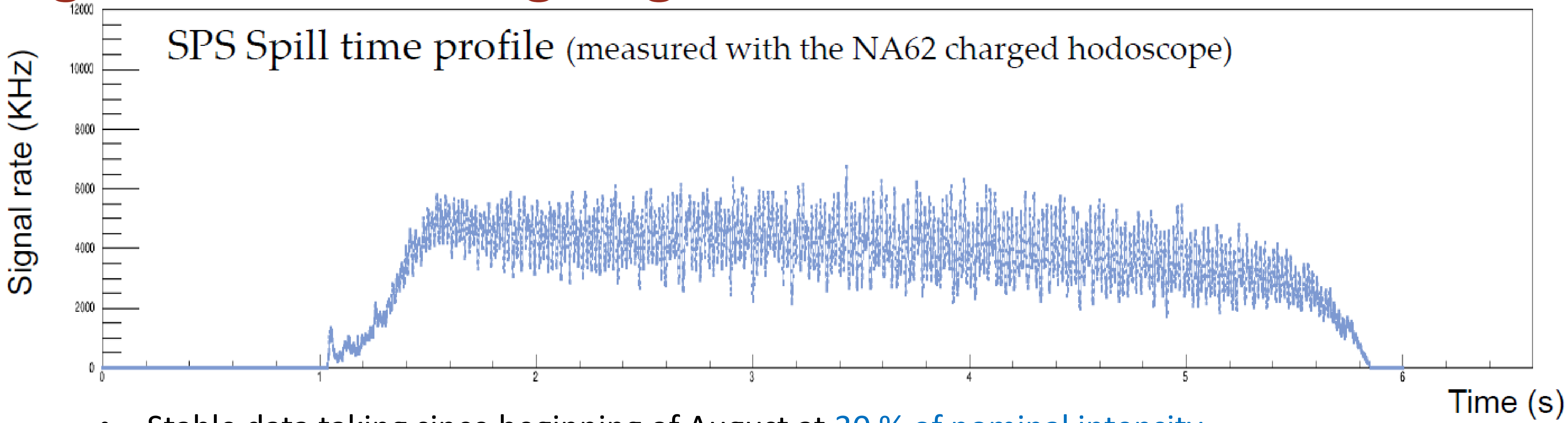
- NA62 Beam line and Detector commissioned up to nominal intensity
- The NA62 experiment is running in stable conditions.
- Data quality studies:
  - Physics sensitivity for $K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$ measurement in line with the design.
- Analysis of the 2016 data on-going.
- $K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$ program to get the 10% design precision under way.
- Broader physics program for short/medium term plan established



Spares



A glance to the on-going 2016 run



- Stable data taking since beginning of August at 30 % of nominal intensity
- L0 $\pi\nu\bar{\nu}$ trigger: hits in RICH & CHOD, !muons, E(LKr) < 20 GeV
- L1 $\pi\nu\bar{\nu}$ trigger: KTAG, LAV, Straw (P < 50 GeV/c)
- Data type (simultaneously): $\pi\nu\bar{\nu}$ (no downscaling), di-lepton, minimum bias
- Average rate at L0 (38% of nominal beam intensity): 350 KHz
- Average rate after L1 (38% of nominal beam intensity): 60 KHz
- On – line $\pi^+\pi^0$ reduction factor ($\pi\nu\bar{\nu}$ trigger): 6 (room for improvements $\times$2 at least)
- On – line muon reduction factor ($\pi\nu\bar{\nu}$ trigger): O(100)
- Data collected so far: $\pi\nu\bar{\nu}$ sensitivitiy below 10^{-9} (assuming O(10%) signal acceptance)