Accelerator-based Light Particle Searches

at NA62 Experiment

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On behalf of the NA62 Collaboration

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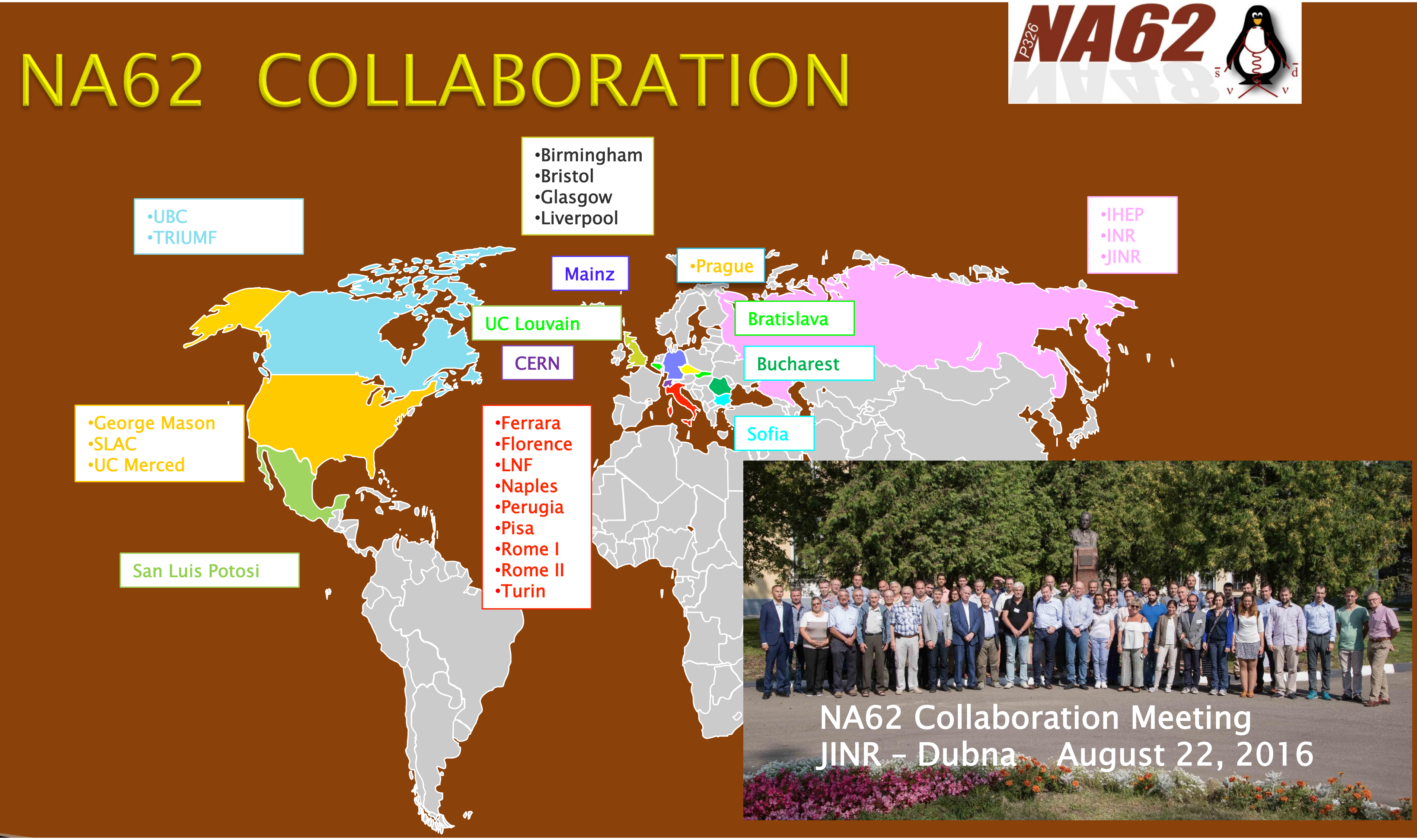
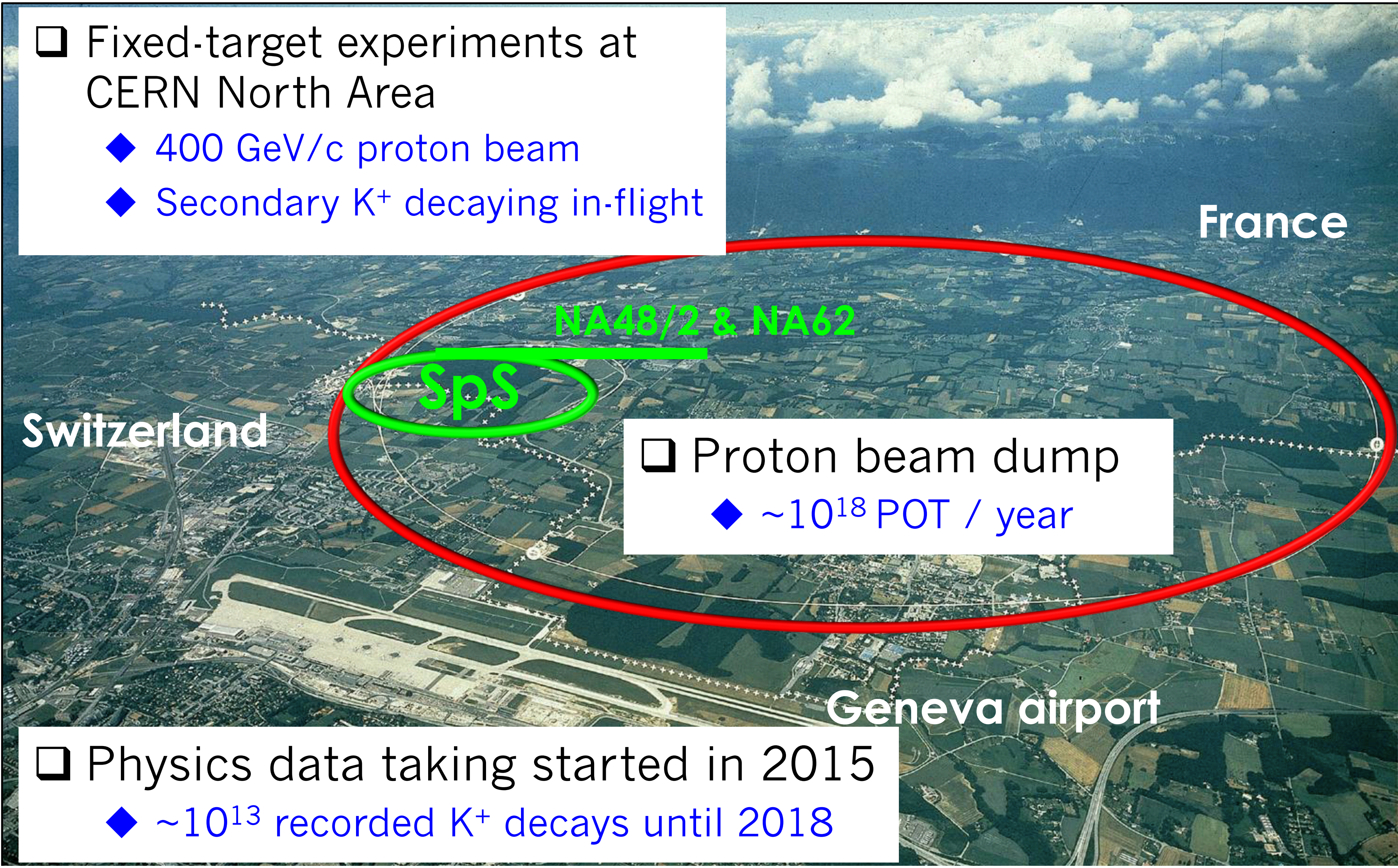
NA62 Collaboration



29 institutes, ≤200 members

NA62 Experiments

- Fixed-target experiments at CERN North Area
  - 400 GeV/c proton beam
  - Secondary K^+ decaying in-flight

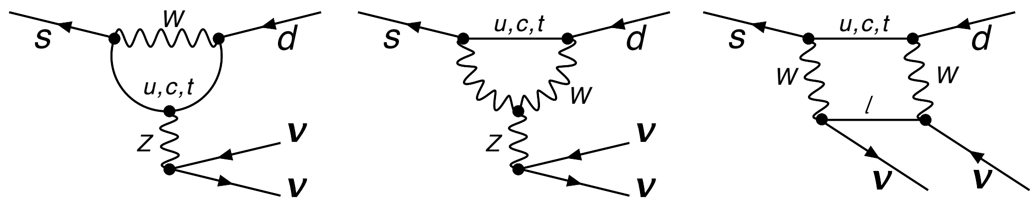


- Proton beam dump
  - $\sim 10^{18}$ POT / year

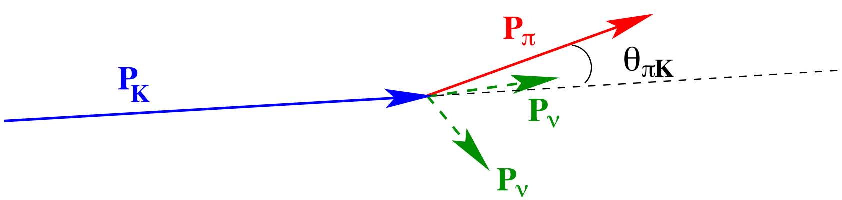
- Physics data taking started in 2015
  - $\sim 10^{13}$ recorded K^+ decays until 2018

NA62 Primary Task

- Indirect search for NP effects at the multi-TeV scale
  - Precise measurement of very rare FCNC decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$
    - $Br_{SM} = (0.84 \pm 0.1)^{-10}$



- NA62 detector: long decay volume, effective K^+ tagging, perfect kinematic reconstruction ($K^+ \rightarrow \pi^+$), particle ID (π, μ), photon veto (π^0 background), timing (~100 ps)



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

- NA62 operation modes: K^+ beam and beam dump
  - Quick (~15 min), fully reversible switch between the modes

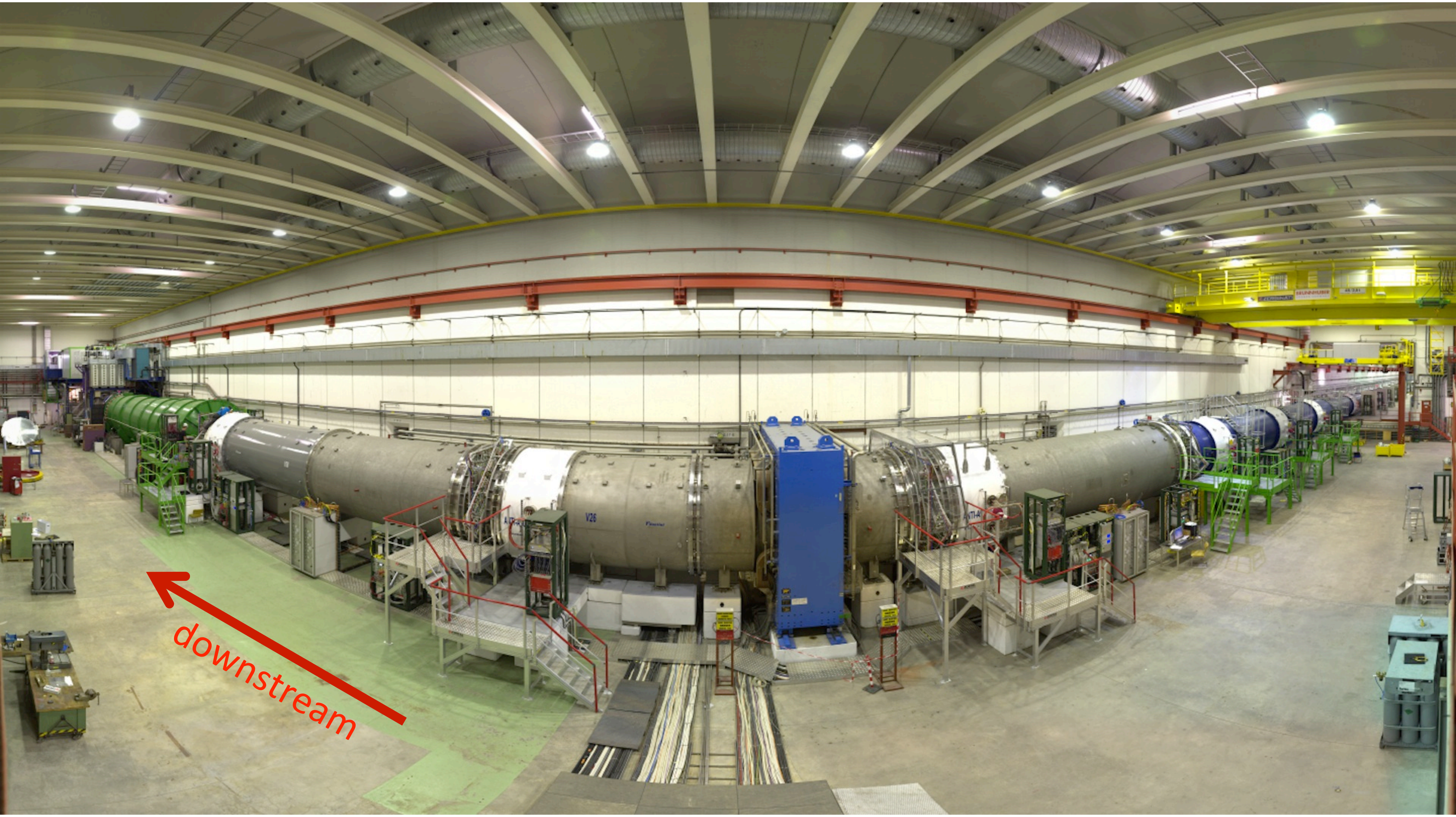
NA62 as a Multipurpose Tool

- High energy & intensity proton beam

- Unique sensitivity (among existing experiments) to New Physics models at MeV-GeV scale → light particles
  - Heavy Neutral Leptons (HNL), Axion-like Particles (ALPs), Dark Photon (A'), Dark Scalar (S)

- Dedicated NA62 studies reviewed in this talk
  - Studies with K^+ beam
    - Invisible HNL production from K^+ decays in the detector fiducial volume (published)
    - Invisible decays of A' produced in π^0 decays in the fiducial volume, (preliminary)
  - Studies with beam dump, only sensitivity estimations
    - Visible decays of HNL, A', S and ALPs produced at the target in the fiducial volume

NA62 Detector

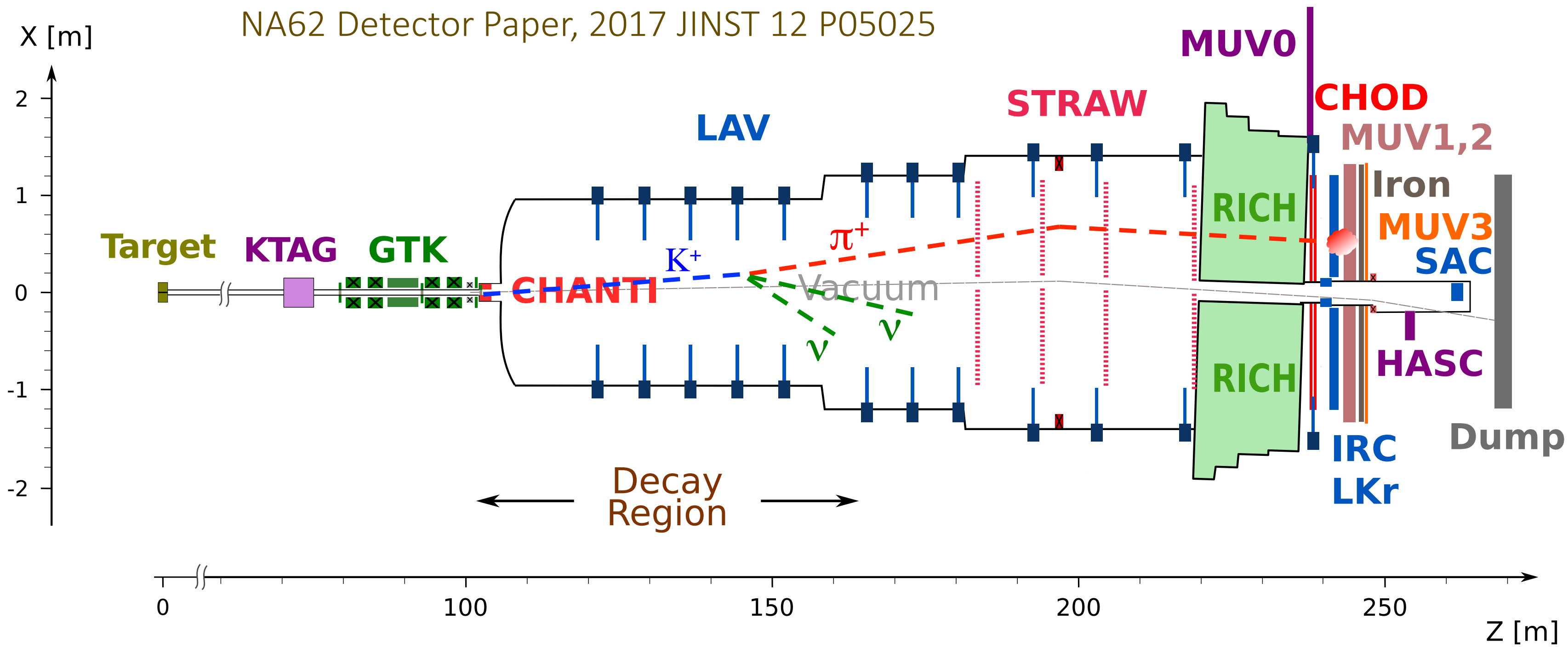


Detector hall + target hall ≈ 270 m

NA62 Detector & K⁺ Beam

- K⁺ secondary beam from the target
  - p = 75 GeV/c ±1% selection with a magnet achromat
    - K⁺ only 6% of the secondary beam (pions, protons, etc.)

NA62 Detector Paper, 2017 JINST 12 P05025

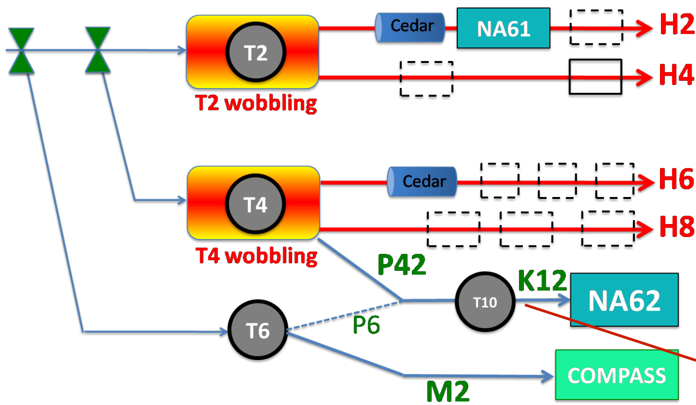


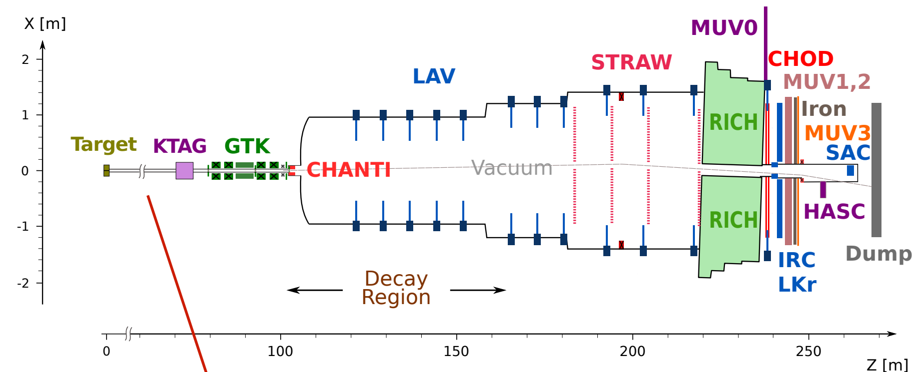
- Collect 4.5 x 10^{12} K⁺ decays in decay region / year
  - Nominal intensity of protons on target: 3 x 10^{12}/spill

NA62 Detector & Primary Beam Dump

- Primary 400 GeV/c proton beam dump on movable secondary beam collimators, TAXes

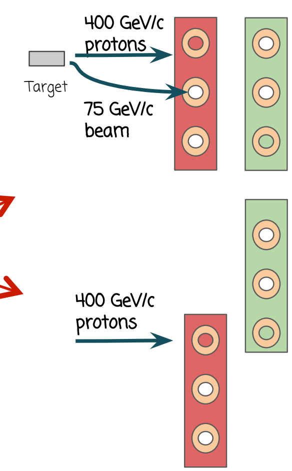
SPS beam and users





- TAXes: copper + iron made collimators of ~22λ_I total
  - Located at ~20 m downstream from target

TAX1&2



- ~10^{18} protons on target (POT) per year can be collected
  - (Remember SHiP's plan of 2 x 10^{20} POT (5 years))

Studies with K^+ Beam

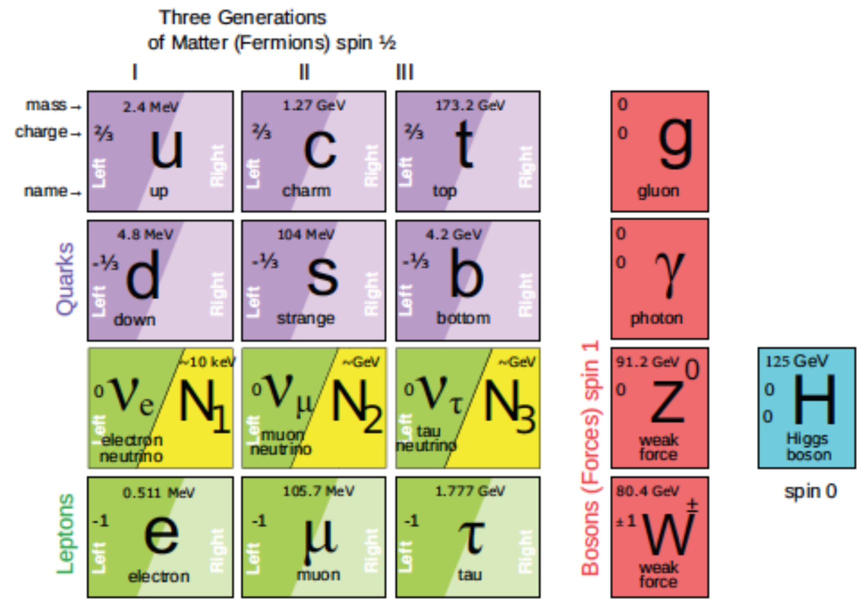
HNL SEARCH

Production

Heavy Neutral Leptons

Asaka, Shaposhnikov, PLB 620 (2005) 17

- ❑ Neutrino Minimal SM extension, νMSM
- ❑ 3 RH neutrinos: N_1, N_2, N_3
- ❑ Light N_1, m ~ 10 KeV
  - ◆ dark matter candidate
- ❑ Heavy N_2, N_3 , m ~ 100 MeV – GeV
  - ◆ Generation of SM neutrino masses (see-saw)
  - ◆ Introduction of extra CPV phases to explain baryon asymmetry trough leptogenesis

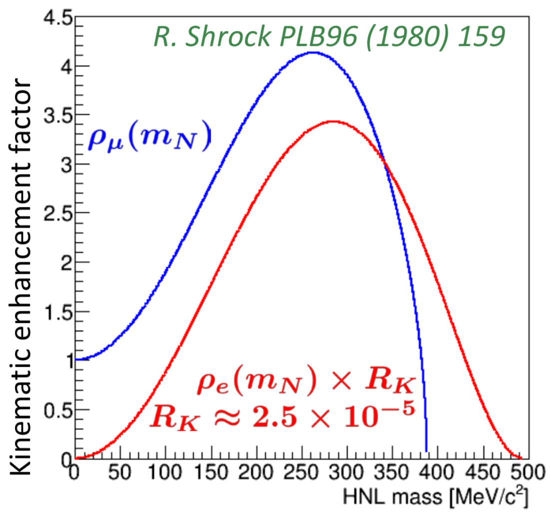


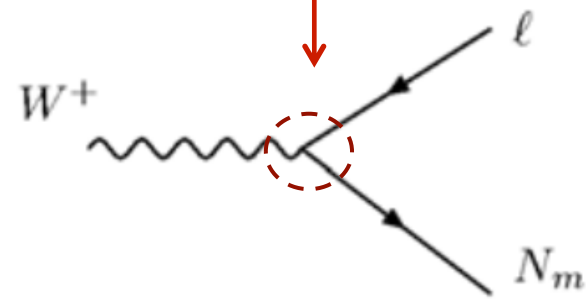
- ❑ HNL can be produced in meson decays → NA62 sensitivity in both K^+ and beam dump modes

NA62 Search for Invisible HNL

- If $m_{HNL} < m_{K+}$, then HNL can be produced in K^+ decays

$$\Gamma(K^+ \to \ell^+ N) = \Gamma(K^+ \to \ell^+ \nu) \cdot \rho_\ell(m_N) \cdot |U_{\ell 4}|^2$$



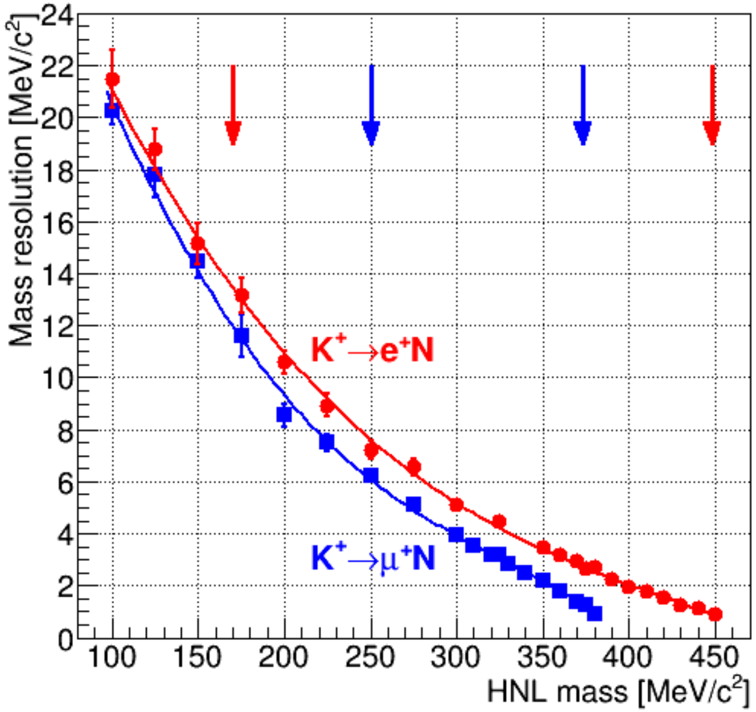


- Expected very weak coupling of HNL with SM
  - e.g. $|U_{l4}|^2 < 10^{-4}$ → HNL mean free path >10 km → invisible
    - $m_{HNL} < 500$ MeV/c^2

- Search for spikes in missing mass spectrum in events with single lepton tracks from K^+ decays

NA62 Search for Invisible HNL

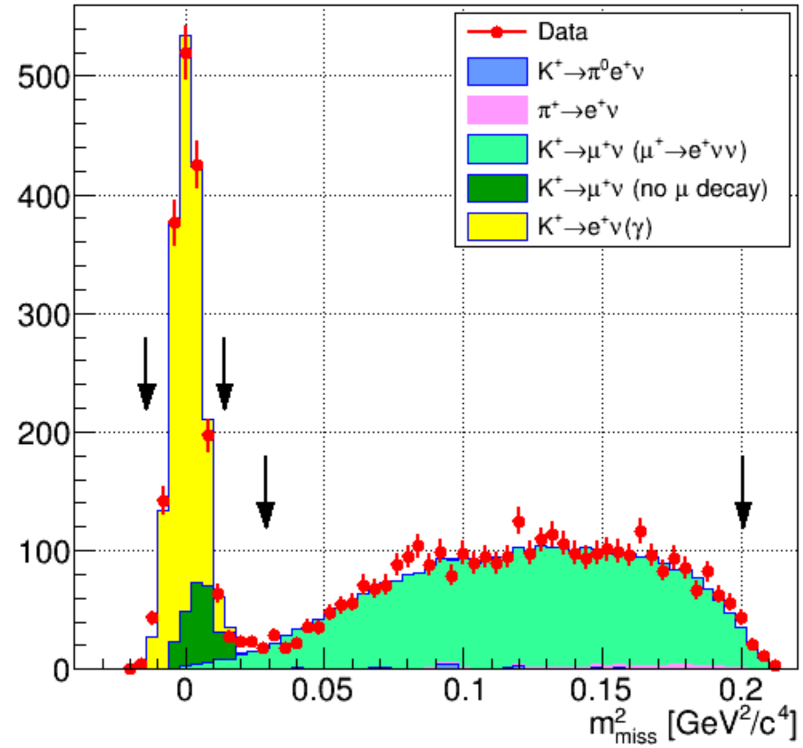
- Analysis of $K^+ \to \mu^+ N$ and $K^+ \to e^+ N$ used minimum bias data collected in 2015 at very low primary beam intensity (1% of nominal)
  - ~10^8 K^+ decays in the NA62 fiducial volume in each positron and muon data samples
- Beam tracker (GTK) was not available by that time → using averaged Kaon momentum
  - Mass resolution studied in MC



- Good mass resolution is very important
  - Amount of background in selected mass window
  - Possible HNL mass splitting

NA62 Search for Invisible HNL

- m^2_{miss} distribution after final selection of positron sample



- Mass window for each mass hypothesis of HNL: $|m - m_{HNL}| < 1.5\sigma(m_{HNL})$
- Scan of HNL mass hypothesis in 1 MeV/c^2 steps
- Convert observed and expected background events in a mass window into an upper limit on the signal
  - Expected background is calculated from polynomial fit of sidebands of the mass window

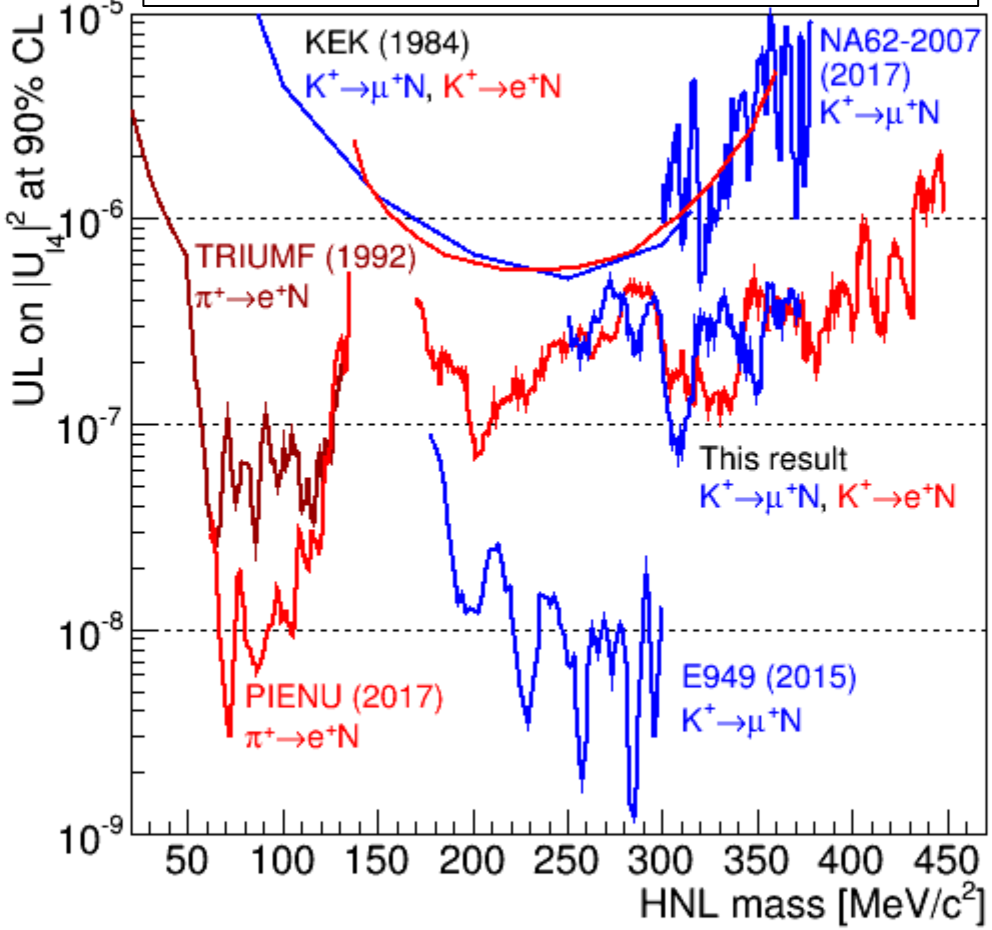
NA62 Search for Invisible HNL

- No more than 2.2σ excess of observed upper limit over the expected one for $|U_{l4}|^2$

- Reached $10^{-6} - 10^{-7}$ limits for $|U_{l4}|^2$ in mass range 170 – 448 MeV/c^2
  - Best limits above 300 MeV/c^2

- Pushing $|U_{l4}|^2$ limits down to 10^{-8} foreseen with data 2016-2018
  - On-going study

NA62 Collaboration, Phys. Lett. B778 (2018) 137



Studies with Beam Dump

HNL SEARCH

Visible Decays

NA62 Sensitivity to HNL

- Neutrino portal to dark sector

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \sum F_{\alpha I}(\bar{L}_\alpha H)N_I$$

- L_{DS} can include mass terms for one or more HNLs
  - Diagonalising mass matrix → mixing of neutrinos and HNLs

$$\nu_\alpha \rightarrow \sum_I U_{\alpha I} N_I$$

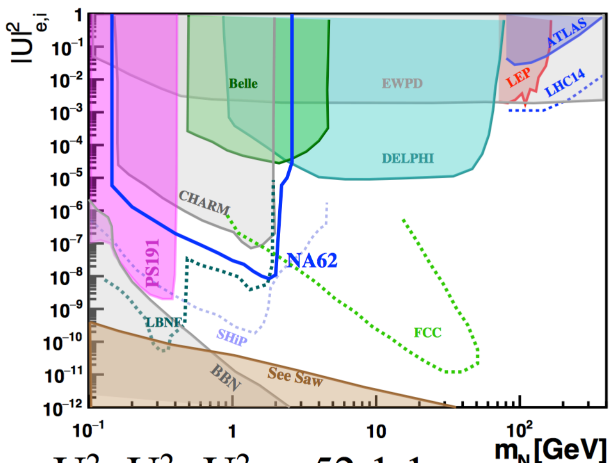
- Sensitivity to three different mixing/coupling scenarios, $U_e^2:U_\mu^2:U_\tau^2$ is studied in the beam dump mode
  - Long lived HNL, decays into 2-track final states

Gorbunov, Shaposhnikov, JHEP10 015 (2017)

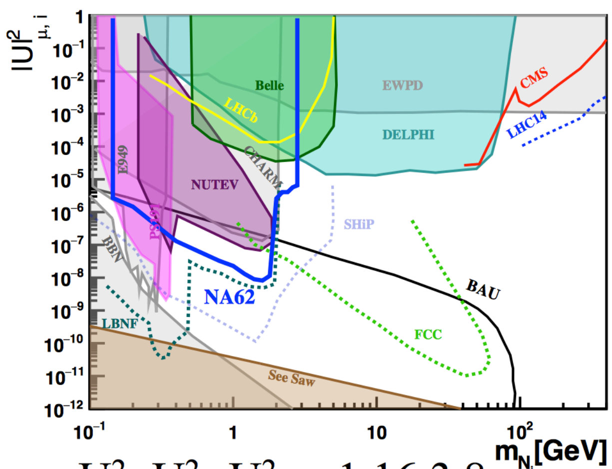
- Available NA62 data sets collected in 2016/2017
  - 10^{17} POT with $\pi\mu$ trigger
  - 10^{16} POT with πe trigger

NA62 Sensitivity to HNL

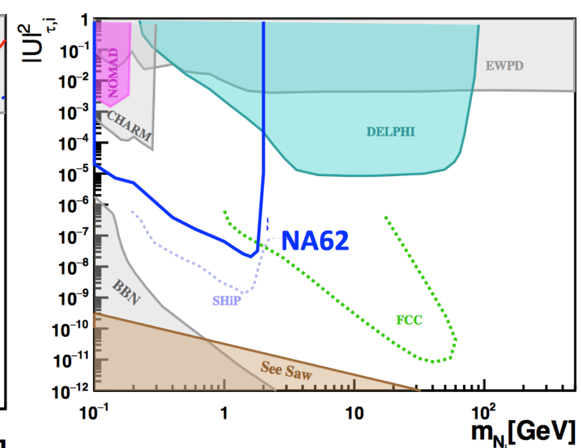
- Long-lived HNL decaying into 2 charged particles
  - Assuming 10^{18} POT (~1 data taking year of NA62)
  - Reconstruction of all 2-track final states from HNL decays
  - Geometrical acceptance and trigger efficiencies
  - 0 background assumption (proved with 10^{15} POT data)
  - Limits @ 90% CL



$U^2_e:U^2_\mu:U^2_\tau = 52:1:1$
Normal hierarchy of active ν masses



$U^2_e:U^2_\mu:U^2_\tau = 1:16:3.8$
Normal hierarchy of active ν masses



$U^2_e:U^2_\mu:U^2_\tau = 0.061:1:4.3$
Normal hierarchy of active ν masses

Studies with K^+ Beam

DARK PHOTON SEARCH

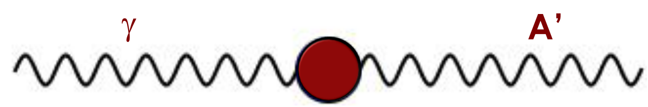
Invisible Decays

Dark Photon

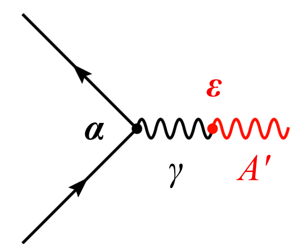
B. Holdom, Phys. Lett. B 166 (1986) 196

- Extra U(1) gauge symmetry connected with the SM U(1) via kinetic mixing of their gauge fields
  - Extra U(1) gauge boson A' (Dark Photon) with a non-zero mass
  - ε – mixing and $m_{A'}$ – mass are the theory free parameters

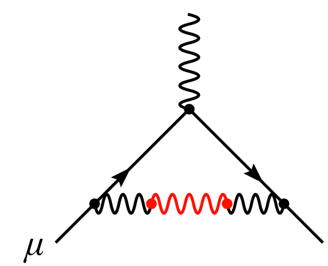
$$\mathcal{L}_{\rm vector} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DS} - \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B_{\mu\nu},$$



- Dark photon can couple (QED-like) with the SM fermions and the dark sector particles



- Can be searched at NA62 into visible and invisible decays (K^+ beam mode)
  - Production: $K^+ \to \pi^+ A'$ or $K^+ \to \pi^+(\pi^0 \to \gamma A')$
  - Decay: $A' \to \mu^+\mu^-, e^+e^-$ or $A' \to \chi\chi$ (invisible)



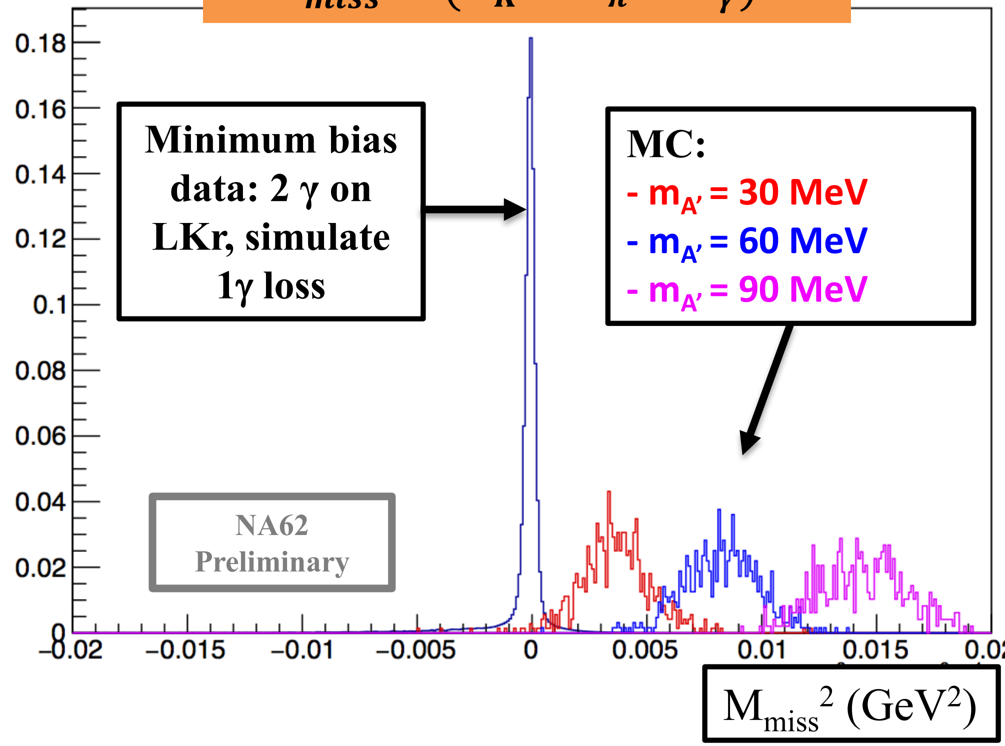
NA62 Study of $\pi^0 \rightarrow \gamma(A' \rightarrow \chi\chi)$

- Large sample of $K^+ \rightarrow \pi^+\pi^0$
  - Control sample for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ analysis
  - Search for decay chain: $\pi^0 \rightarrow \gamma A'$ and $A' \rightarrow \chi\chi$ (invisible)
  - $m_{A'} < m_{\pi 0}$

- Signal event topology
  - Single π^+ track and γ
  - Missing energy, M_{miss}^2

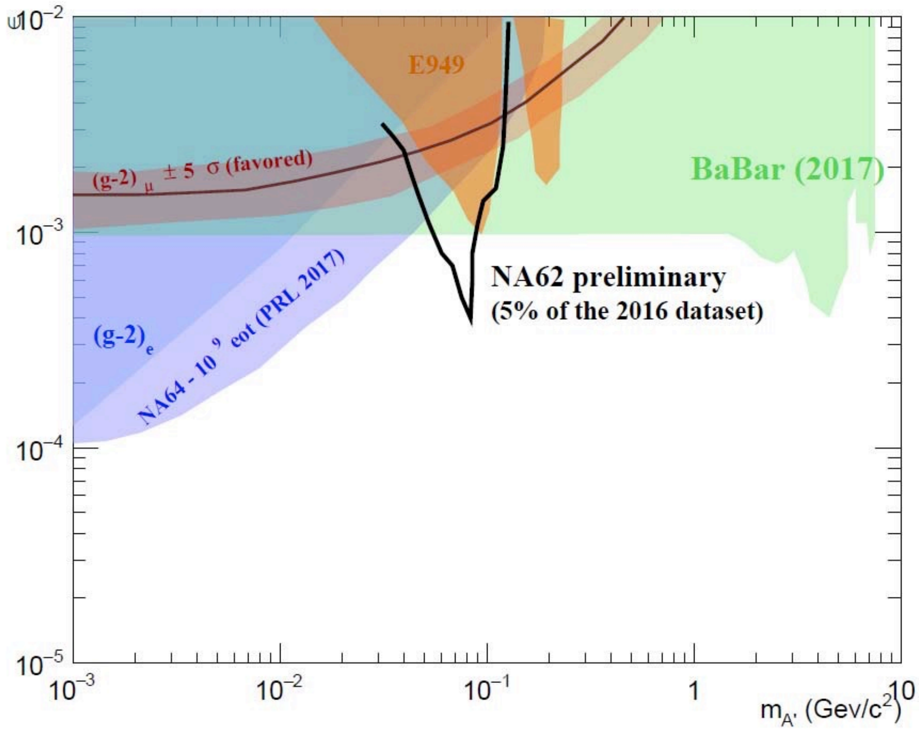
- Data driven background ($\pi^0 \rightarrow \gamma\gamma$ with one photon lost in acceptance) estimation

$$M^2_{miss} = (P_K - P_\pi - P_\gamma)^2$$



NA62 Study of $\pi^0 \rightarrow \gamma(A' \rightarrow XX)$

- No significant excess of events observed → improved limits at 90% CL (preliminary)
  - A' mass range: ~ 50 MeV/c^2 < $m_{A'}$ < 90 MeV/c^2
  - Only small fraction of data 2016 is used, 1.5 × 10^{10} K^+ decays



- Analysis with full 2016 data set is on-going

Studies with Beam Dump

DARK PHOTON SEARCH

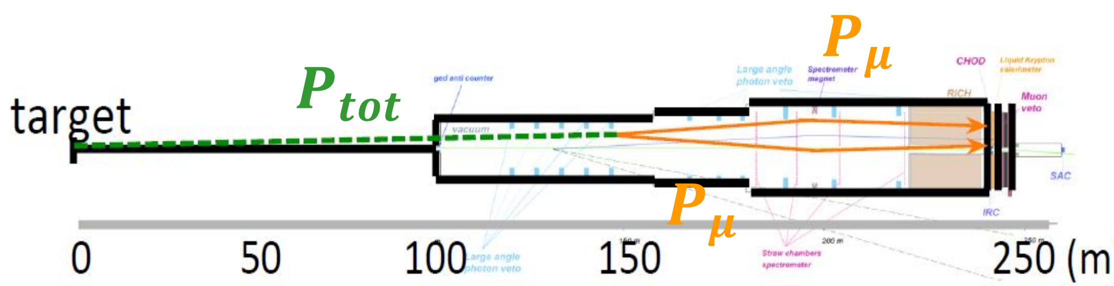
Visible Decays

NA62 Sensitivity to A'→$\mu^+\mu^-$, e^+e^-

- Production of A' directly at the Beryllium target
  - Secondary meson decays: e.g. *pN* –> *X*(π^0 → γA')
  - Bremsstrahlung off primary beam: *pN* –> *X*A'
  - A' production in QCD processes is not included in MC

- Reconstruction of displaced decay vertices of A'→e^+e^-, A'→$\mu^+\mu^-$ in the fiducial volume pointing back to target

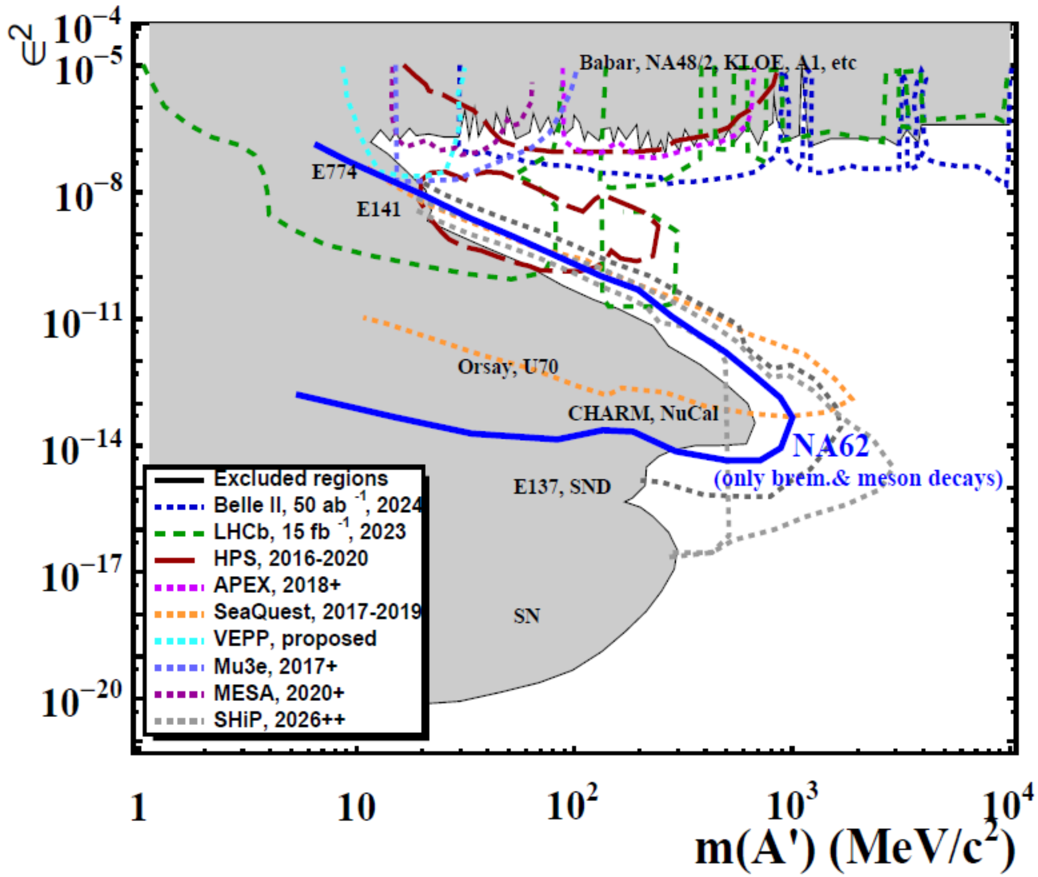
- Sensitivity estimated assuming 10^{18} protons on target and 0 background



- Data sets from 2016/2017 runs for dedicated analysis
  - $3\text{x}10^{17}$ POT with di-muon trigger
  - $5\text{x}10^{16}$ POT with di-electron trigger

NA62 Sensitivity to $A' \to \mu^+\mu^-$, e^+e^-

- ❑ Model of A' coupling with only the SM is considered



- ❑ Higher sensitivity expected with beam dump on TAXes
  - ◆ Enhanced meson production, less background, etc

Studies with Beam Dump

DARK SCALAR SEARCH

Dark Scalar

- Scalar portal to Dark Sector

$$\mathcal{L}_{\rm scalar} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DS} - (\mu S + \lambda S^2) H^\dagger H, \qquad \mathcal{L}_{\rm DS} = S\bar{\chi}\chi + \ldots.$$

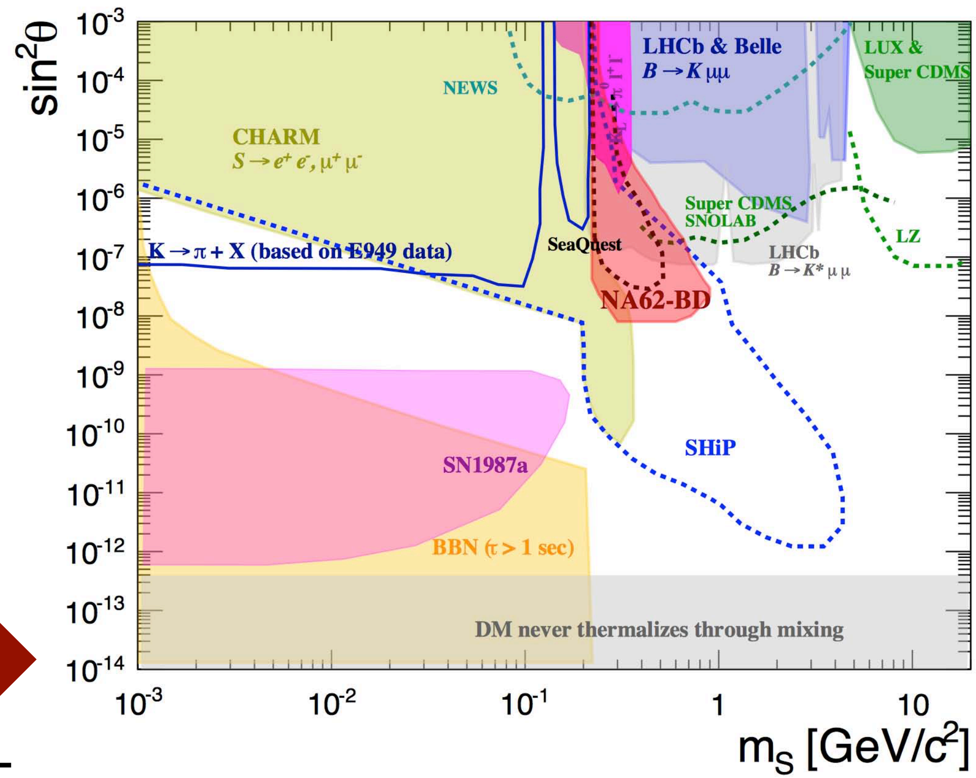
- Sensitivity to simplified model with λ=0 studied by NA62 in the beam dump mode
  - The model implies single S production from meson decays: B,D→KS, K→πS
  - Parameters to be explored are m_S and mixing angle with Higgs

$$\theta = \frac{\mu v}{m_h^2 - m_S^2}$$

- Data sets collected in 2016/2017
  - $3\text{x}10^{17}$ POT with di-muon trigger
  - $5\text{x}10^{16}$ POT with di-electron trigger

NA62 Sensitivity to Dark Scalar

- MC simulation of single S production in meson decays
- Sensitivity estimate assuming 10^{18} POT (~1 year of data taking at NA62 with beam dump mode)
- Reconstruction of all 2-track final states of S decay
  - ee, μμ, ππ, KK
  - Reconstructed vertex pointing back to TAXes
  - Acceptance included
  - 0 background assumed
- Estimate limits @ 90% CL



Studies with Beam Dump

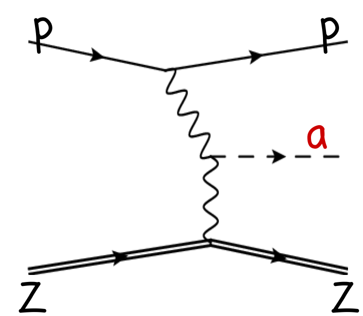
ALPs SEARCH

Axion-Like Particles

- Light ALPs can serve as dark matter candidates and mediators between SM and dark sectors

$$\mathcal{L}_{\text{axion}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \frac{a}{4f_\gamma} F_{\mu\nu}\tilde{F}_{\mu\nu} + \frac{a}{4f_G} \text{Tr} G_{\mu\nu}\tilde{G}_{\mu\nu} + \frac{\partial_\mu a}{f_l} \sum_\alpha \bar{l}_\alpha \gamma_\mu \gamma_5 l_\alpha + \frac{\partial_\mu a}{f_q} \sum_\beta \bar{q}_\beta \gamma_\mu \gamma_5 q_\beta$$

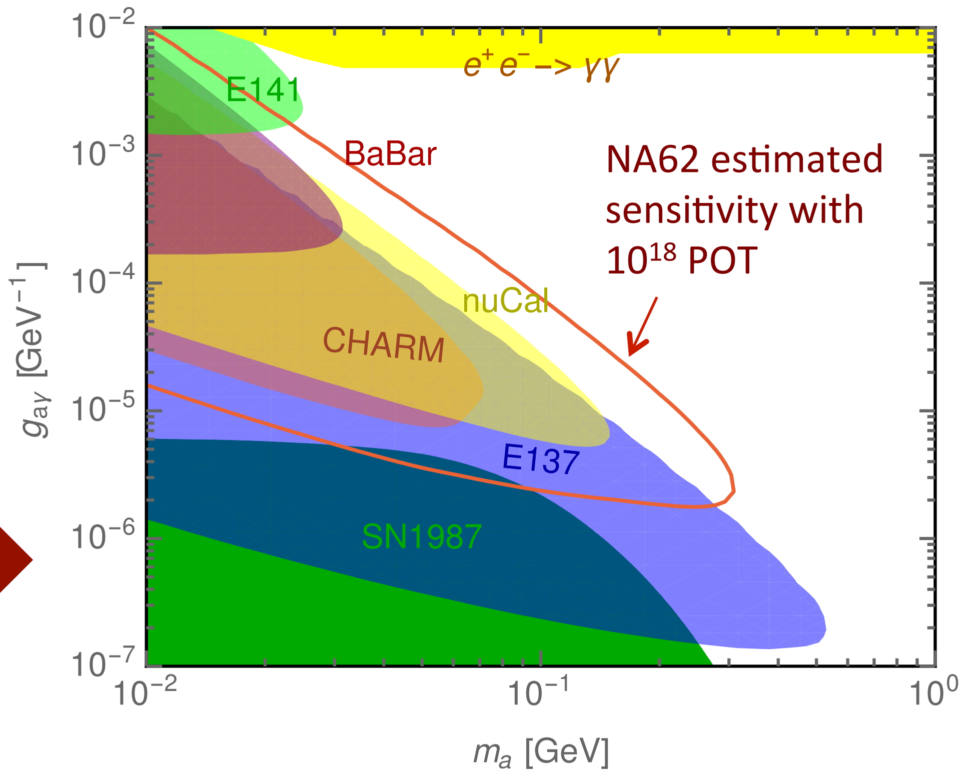
- Sensitivity to long-lived ALPs produced in beam dump mode is studied
  - Assuming dominant interaction of ALPs with SM photons



- ALPs produced only in photon fusion (Primakoff production) are simulated
  - Copper TAXes → coherent Z^2 enhancement of production rate
  - Low p_T ALPs → good acceptance in detector

NA62 Sensitivity to ALPs

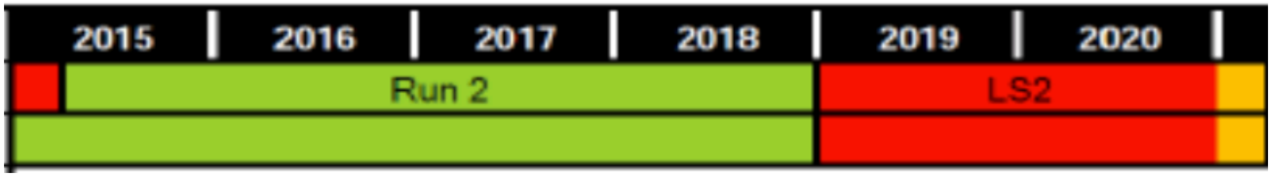
- Sensitivity is estimated assuming 10^{18} POT at TAXes
  - 1 day data (~10^{16} POT) is already enough to obtain significant results
- ALPs decaying into two photons in the fiducial volume are simulated
  - Both photons are in the acceptance of LKr (el.mag. calorimeter)
  - 0 background assumed
- Estimate limits @ 90% CL



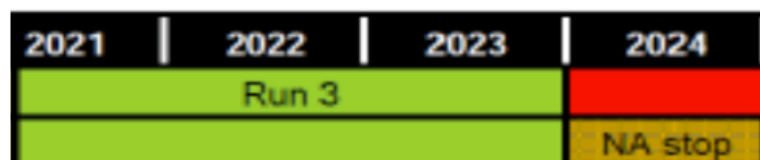
- Analysis with $5\text{x}10^{15}$ POT data (2017) is on-going

NA62 Present & Future: Run 2 & 3

- Run 2: K^+ beam for $K^+ \to \pi^+ \nu\bar{\nu}$, dark photon, HNL, LNV/LFV decays, etc.



- Run 3: many interesting fields to be studied with minimal (or no upgrades at all) of the existing setup
  - In K^+ beam mode:
    - If needed improve $K^+ \to \pi^+ \nu\bar{\nu}$, A'→invisible, invisible HNL
      - All benefit from the same trigger signature
  - In proton beam dump mode:
    - ALPs, Dark scalar, A', HNL : all in visible decays

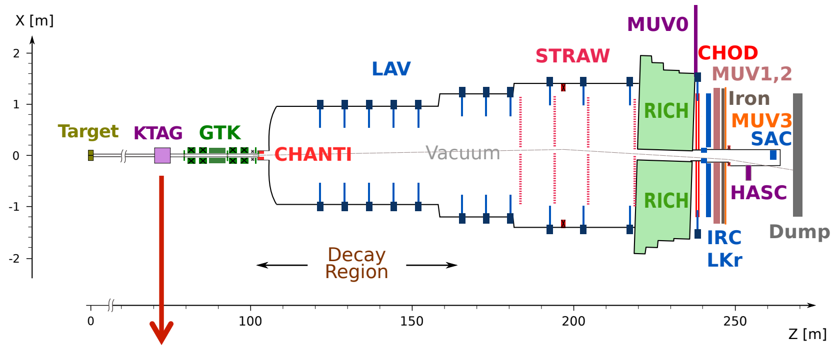


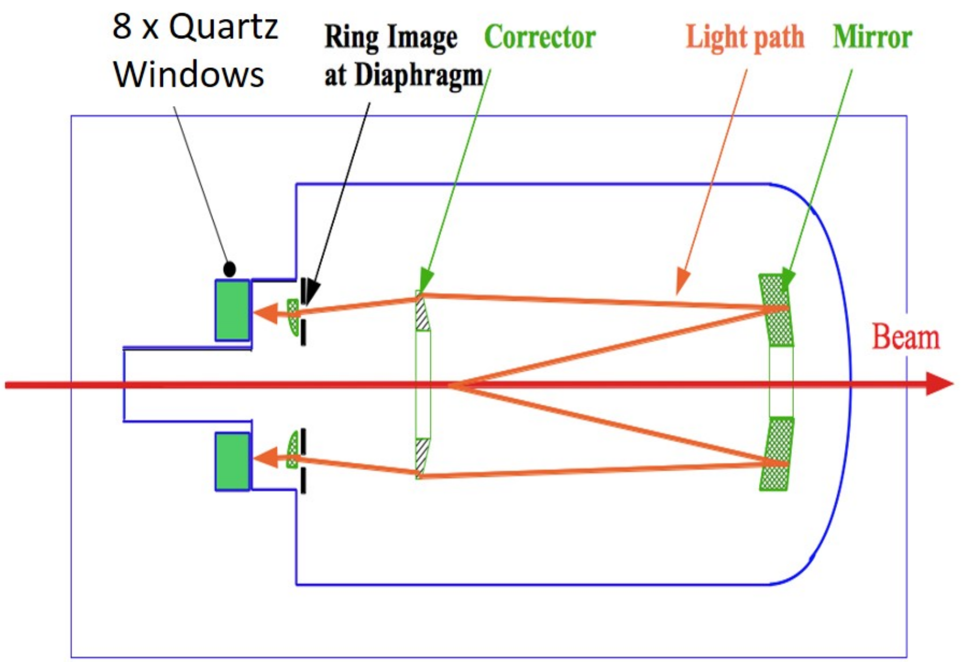
- 1 year of data taking in beam dump mode during Run 3 is under consideration

Summary

- NA62 experiment at CERN to measure K^+ rare (BR ~10^{-10}) decay $K^+ \to \pi^+ \nu \bar{\nu}$: very promising first result
- High energy & intensity proton beam + long decay volume & advanced detector system → NA62 as a very powerful tool to search for hidden sector light particles
  - Dark Photon, Dark Scalar, ALPs, HNL
  - MeV to GeV mass range, weak coupling with the SM
  - Visible and invisible decays
- Operation in K^+ beam or proton beam dump mode
  - Easy switch between the modes
  - Both considered after the long shutdown 2 (2021)
- Results (published, preliminary, MC) of various analysis of searches for particles in MeV-GeV mass scale at NA62 were presented

Kaon Identification – KTAG (CEDAR)

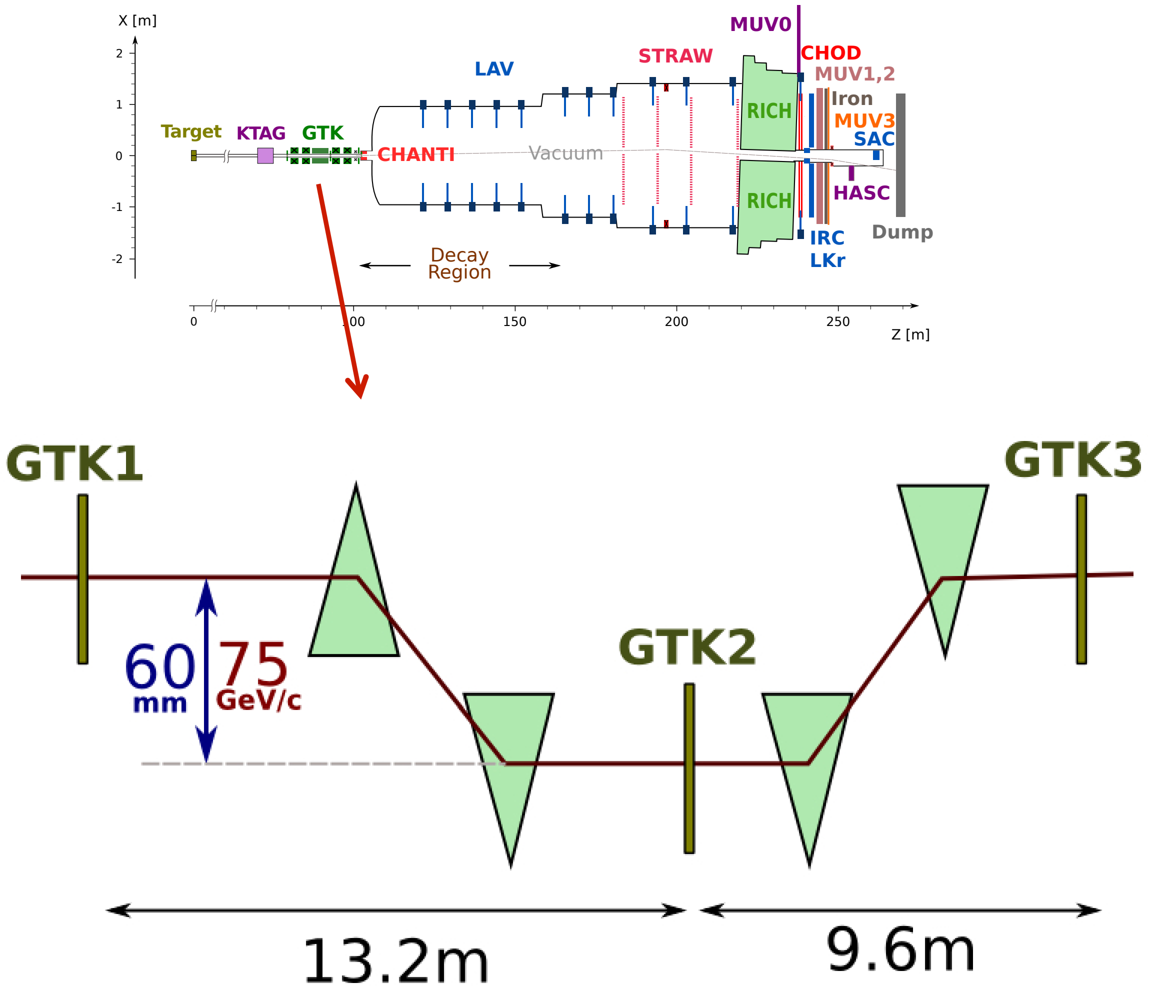




- **Ch**erenkov **D**ifferential counter with **A**chromatic **R**ing focus
  - Filled with Nitrogen
  - Time resolution ≈70 ps
  - 45 MHz of total rate

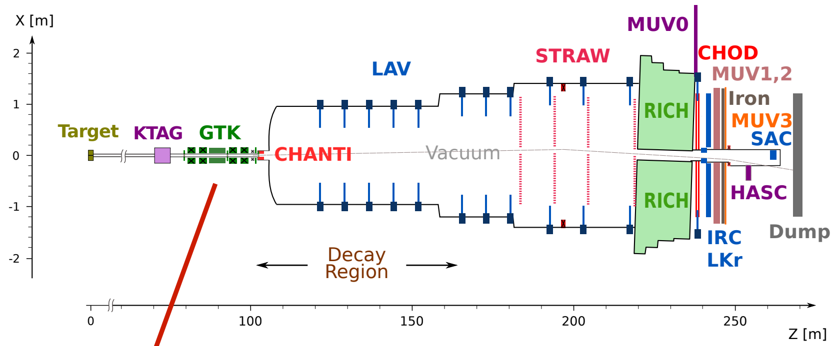
- Gas pressure adjusted for K^+ selection with p_K = 75 GeV/c

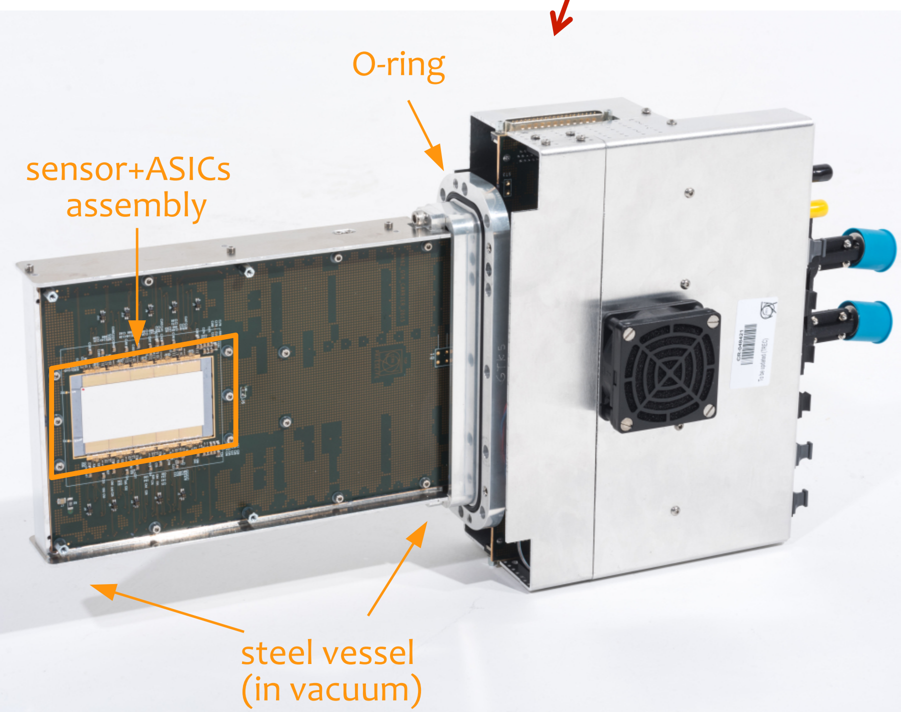
Beam Spectrometer Pixel Detector



- ❑ GigaTracker (GTK) consists of three stations of silicon pixel detectors and the achromat of dipole magnets

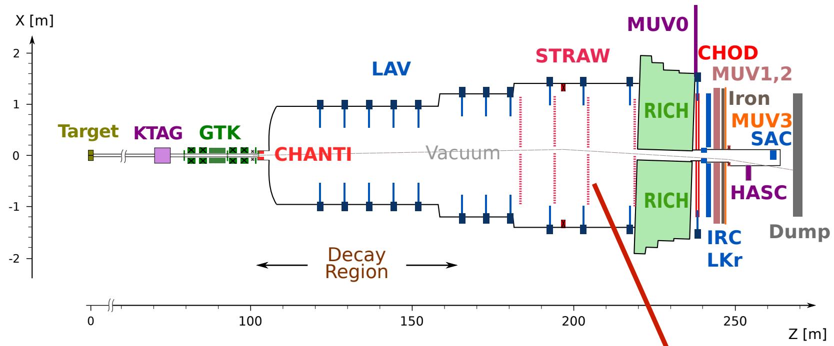
Beam Spectrometer Pixel Detector



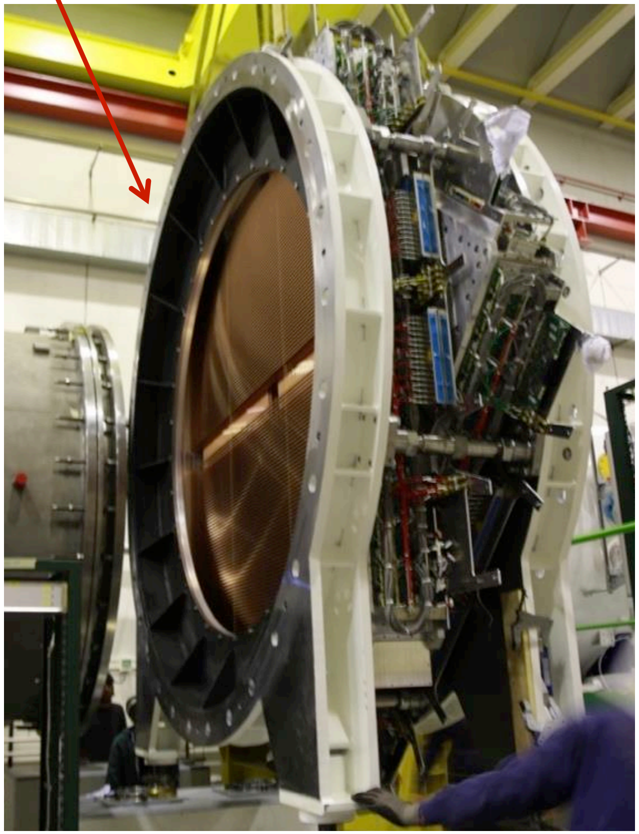


- 3 equal stations
  - 18000 channels per station
  - 0.005 X_0 per station
  - Momentum resolution: 0.2%
  - Angular resolution (in x-z and y-z planes): 16 µrad
  - Track time resolution: 74 ps
- 750 MHz total rate of incident particles

STRAW Spectrometers



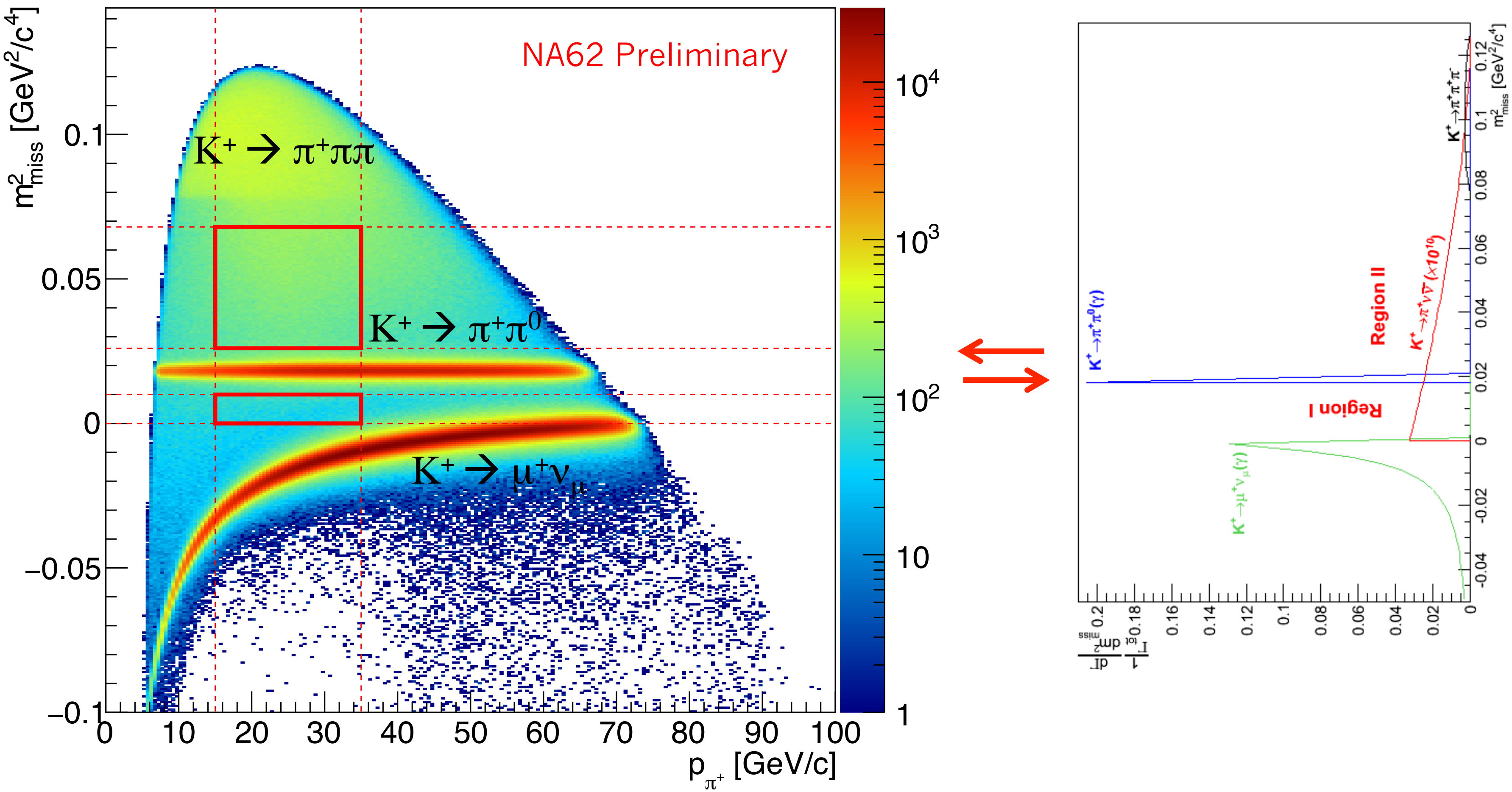
- 4 equal stations
  - 4 straw chambers per station
    - X-Y and U-Y views



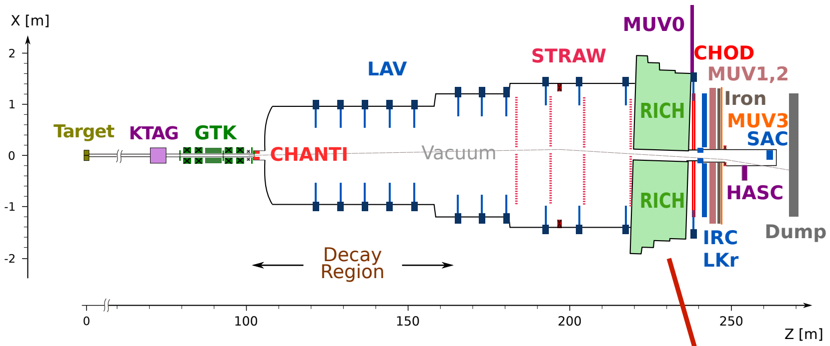
- First time straw chambers operating in vacuum
  - 0.018 X_0 in total

Resolution of Spectrometers

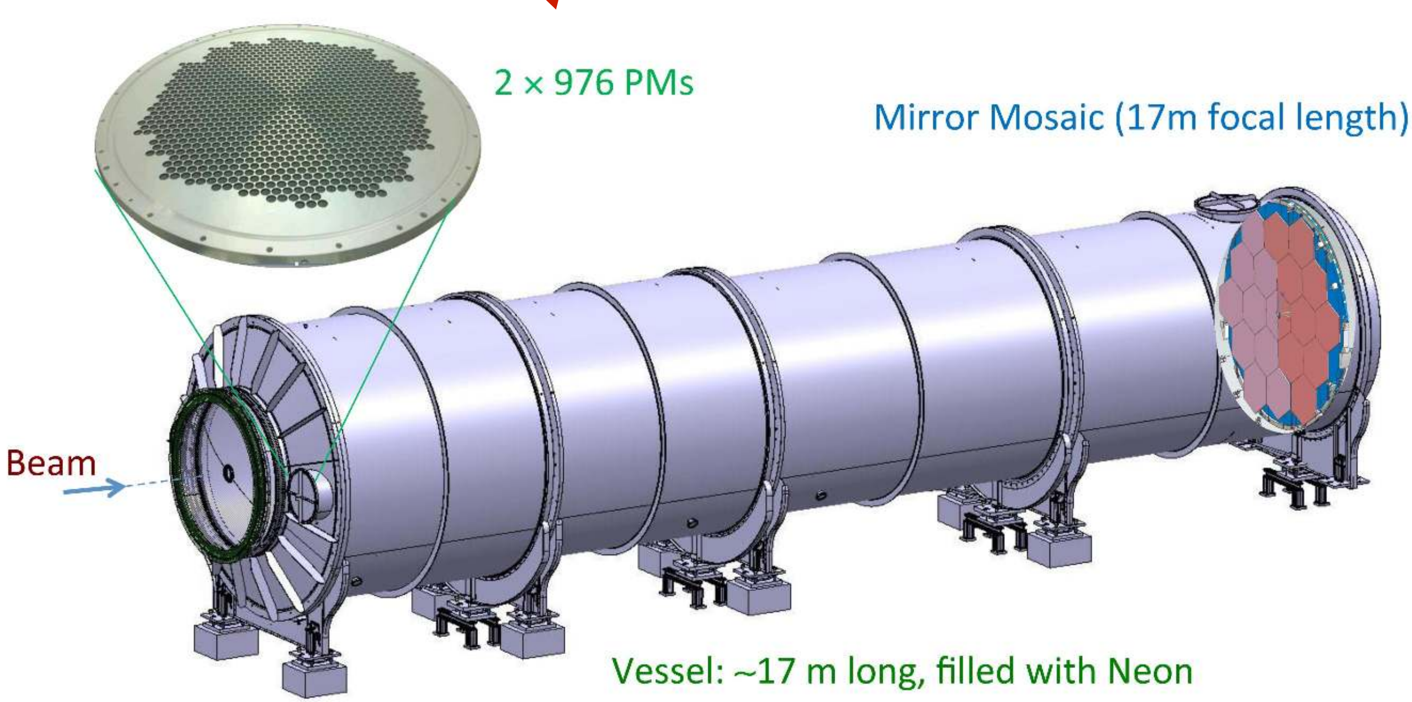
- 1-track event selection
  - Good track originated from a Kaon decay in the fiducial volume
    - Pion track hypothesis



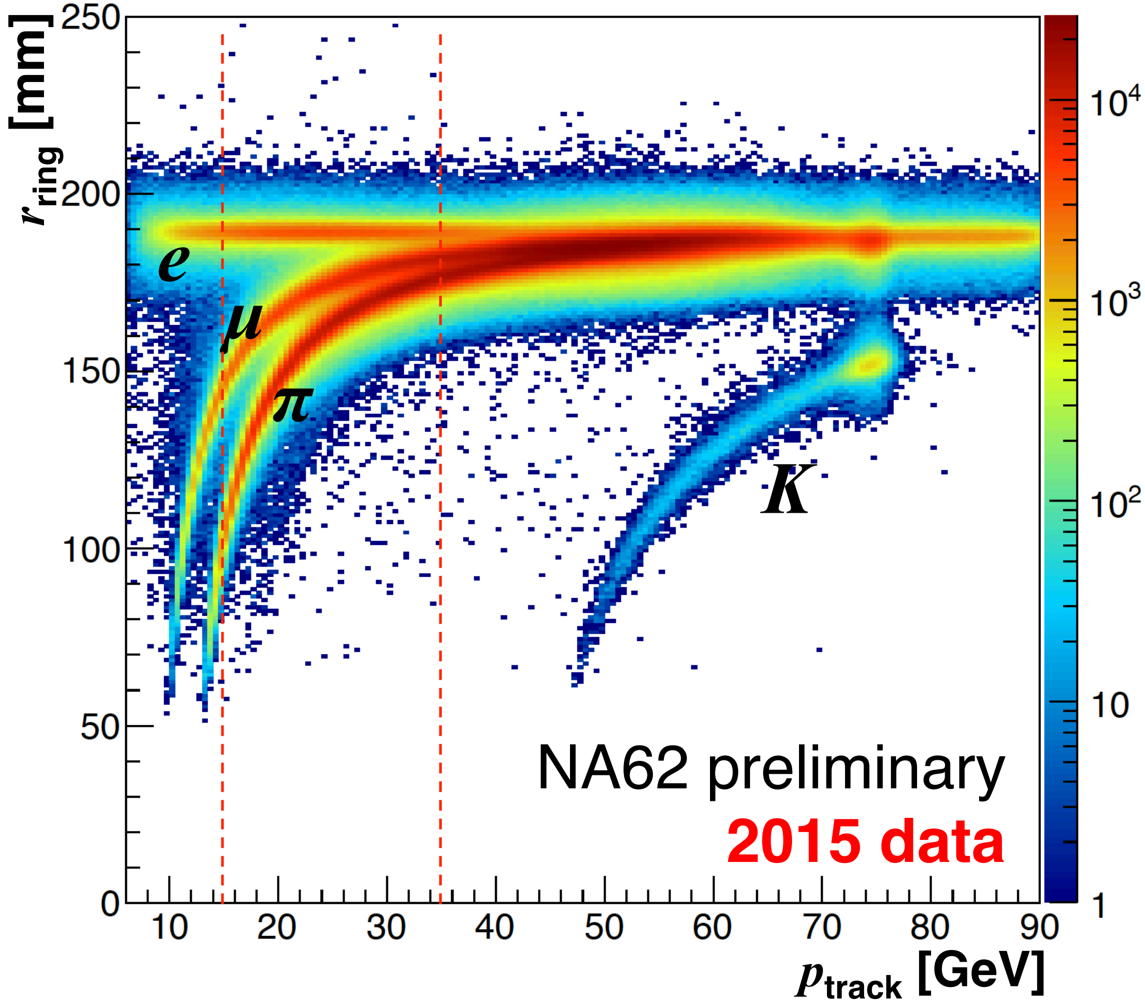
Particle Identification - RICH



- **R**ing **I**mage **CH**erenkov Counter
  - Neon at 1 bar
  - 70 ps track time resolution
    - Reference detector for L0 trigger

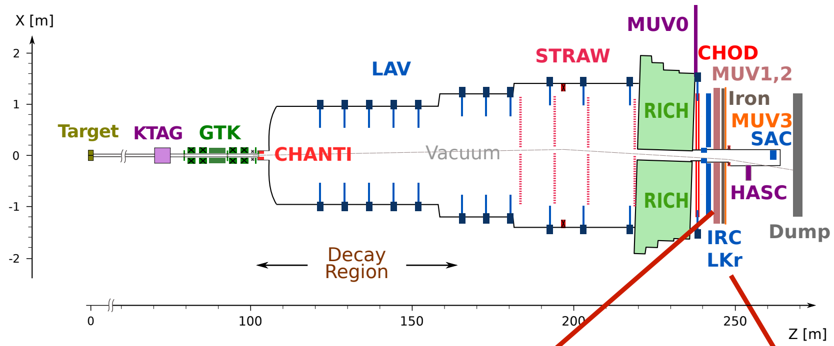


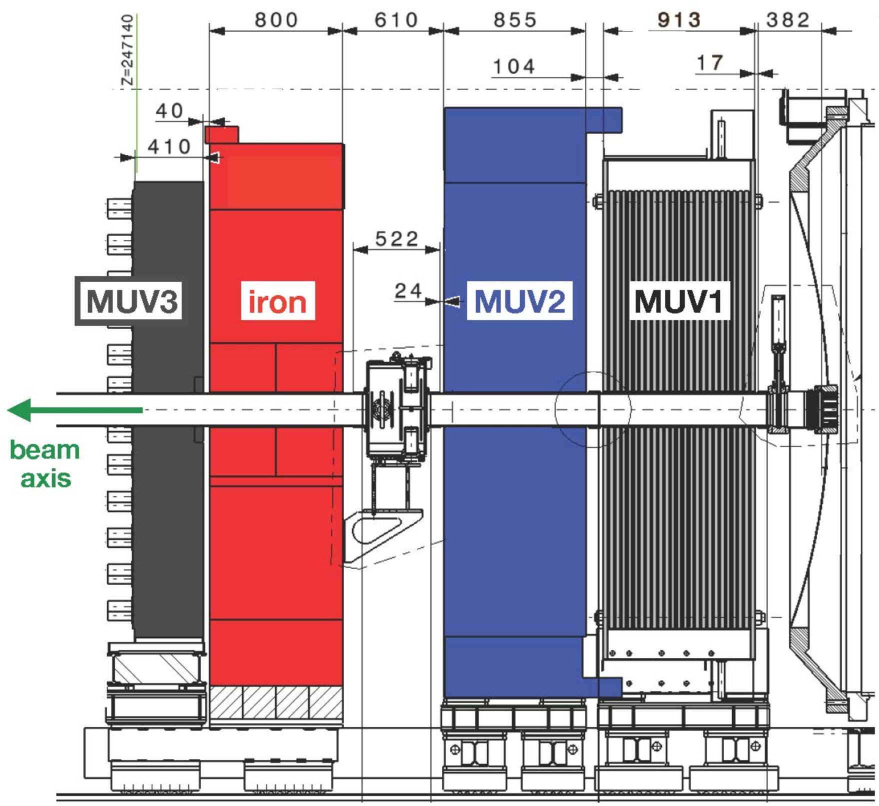
Particle Identification - RICH

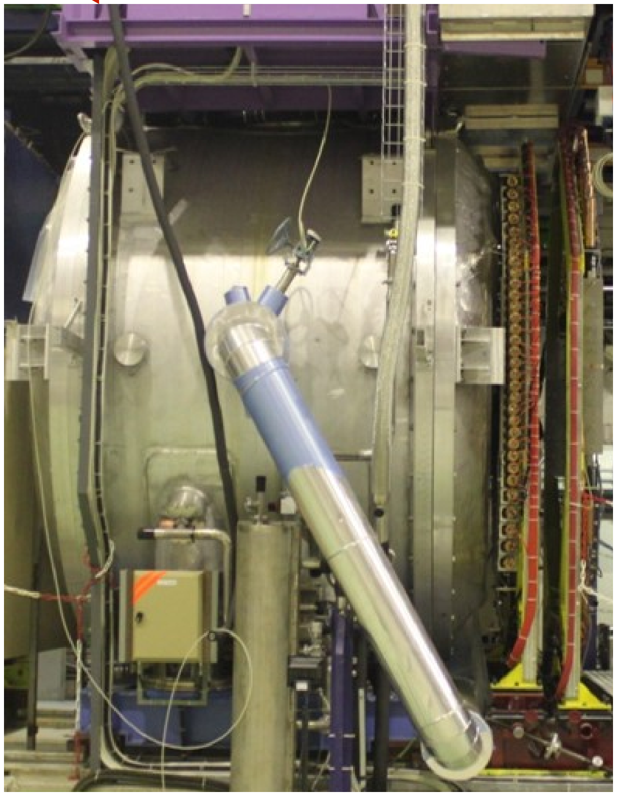


- ~10^2 muon suppression factor in a work region
  - → 15 GeV/c < p_{track} < 35 GeV/c

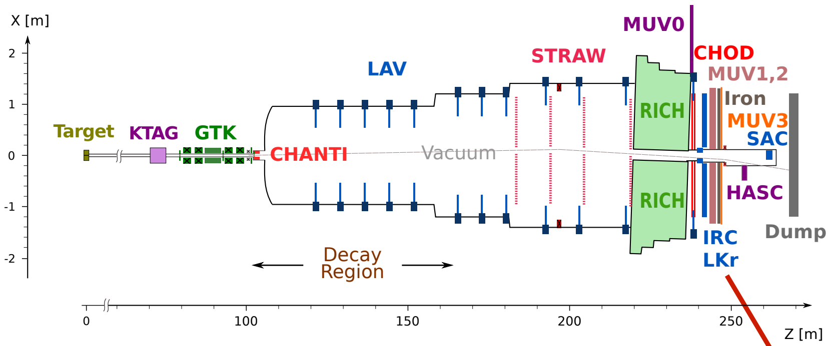
Particle Identification – LKr & MUVs

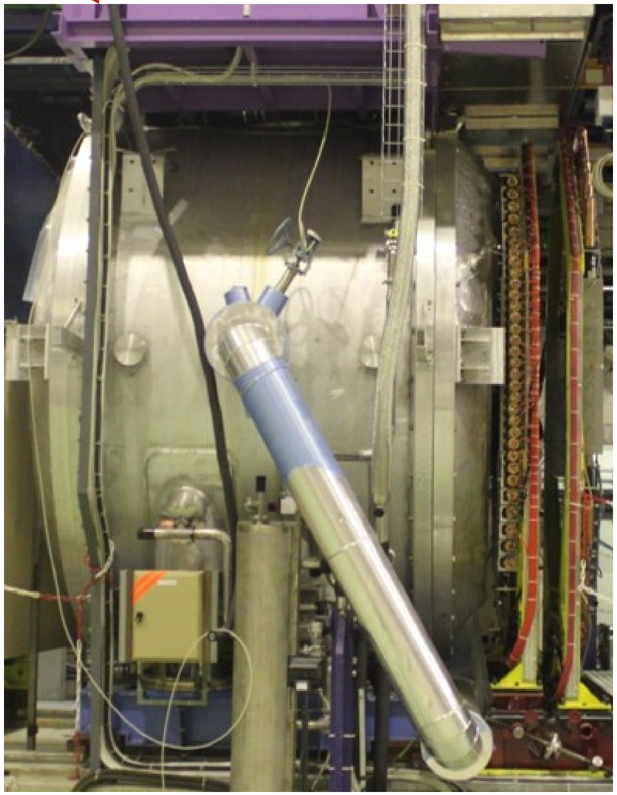






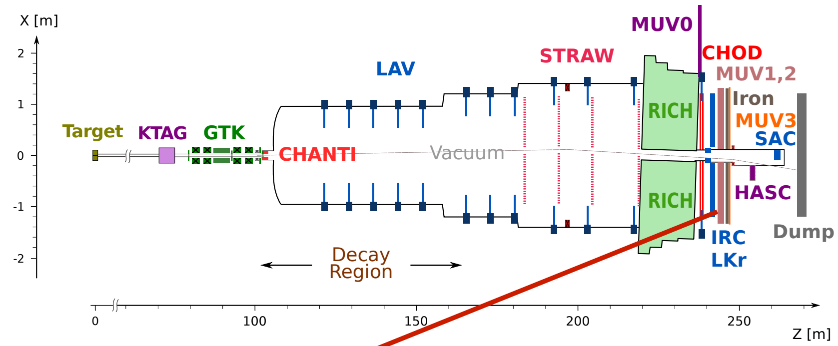
Particle Identification - LKr

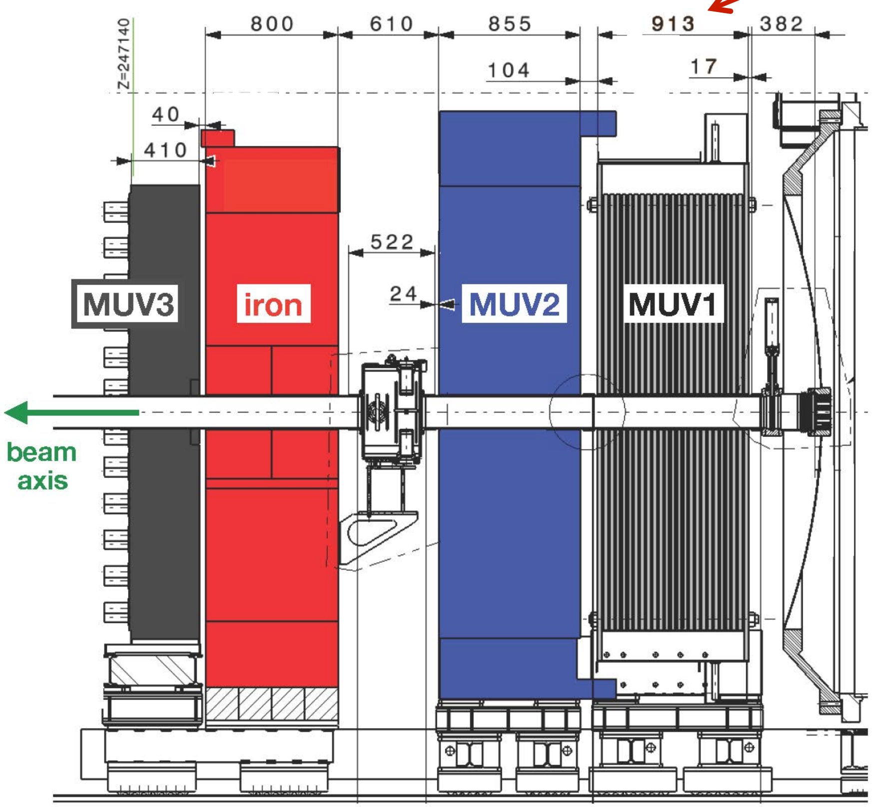




- 9000 litres of liquid krypton
  - T = 120 K
- As a middle angle photon veto
  - Angular coverage: 1- 8.5 mrad
  - Time resolution: 300 ps
  - Detection inefficiency $10^{-3} – 10^{-5}$
    - $E\gamma$ = 1 – 10 GeV
- <1% Resolution @ 20 GeV
  - $27X_0$

Particle Identification - Muon Vetos

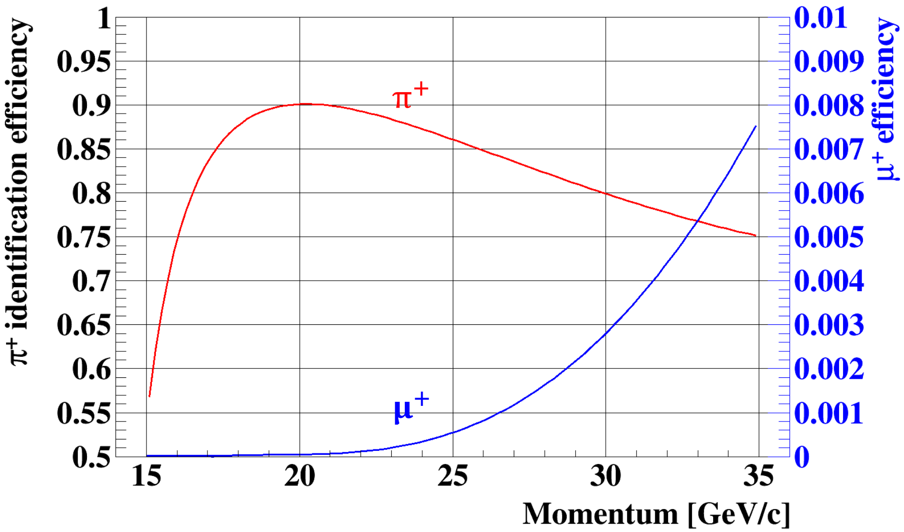




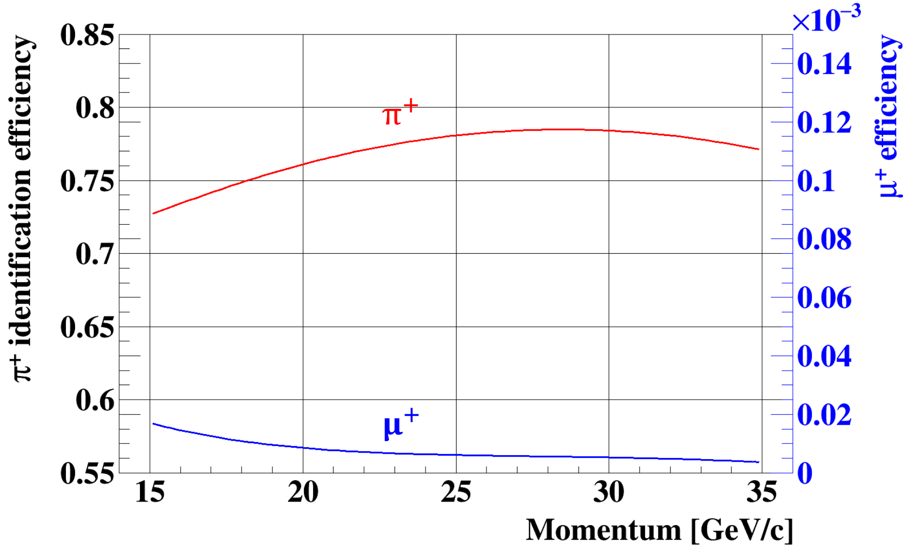
- MUV1 & MUV2
  - "Sandwich"-type calorimeters
    - Iron + scintillator
  - 7.4λ
- MUV3: fast muon L0 trigger
  - 2 orthogonal planes of scintillator slabs
- 10^5 muon suppression factor from MUVs

Particle Identification Performance

- RICH
  - Likelihood discriminator

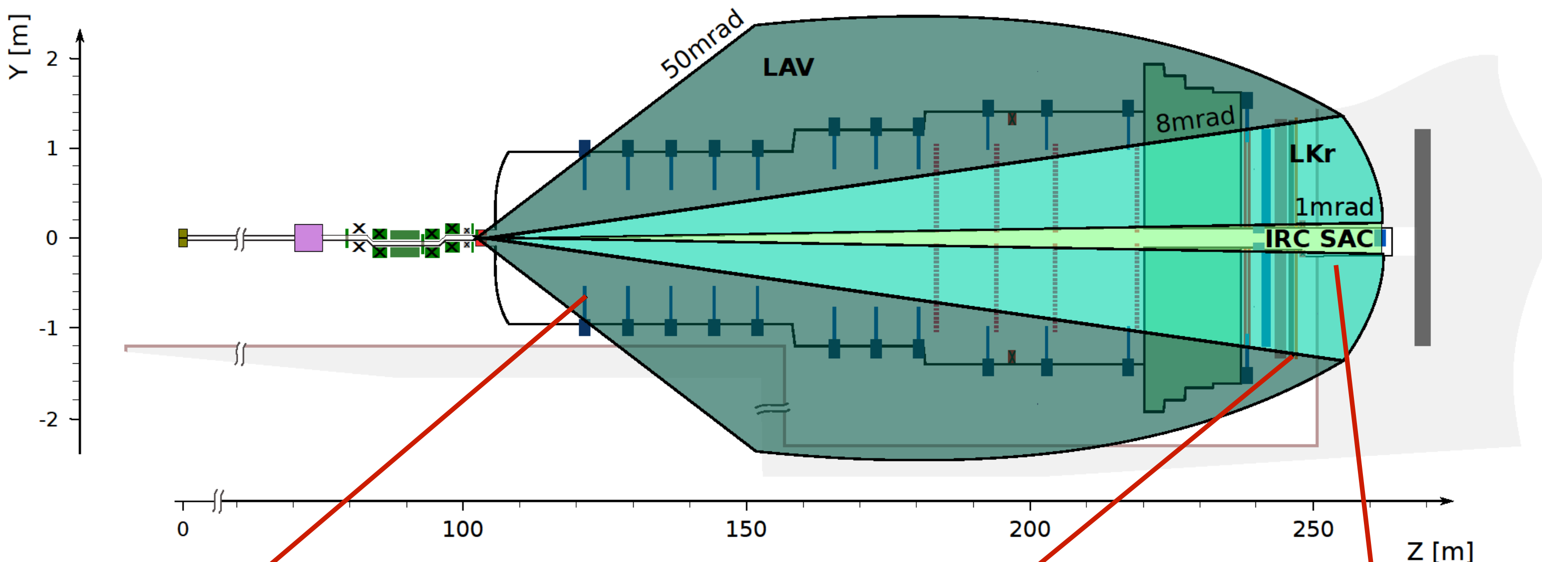


- Calorimeters
  - Boosted Decision Trees

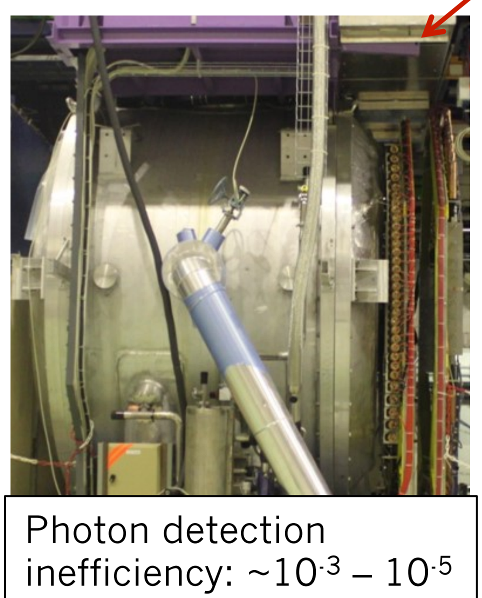


PID	π^+ efficiency	μ^+ efficiency
Calorimeters	77%	$0.6 \cdot 10^{-5}$
RICH	80%	$2.5 \cdot 10^{-3}$

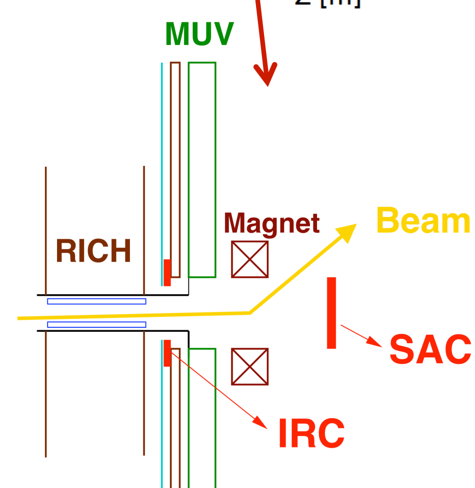
Photon Vetos



Photon detection inefficiency: ~10^{-4}

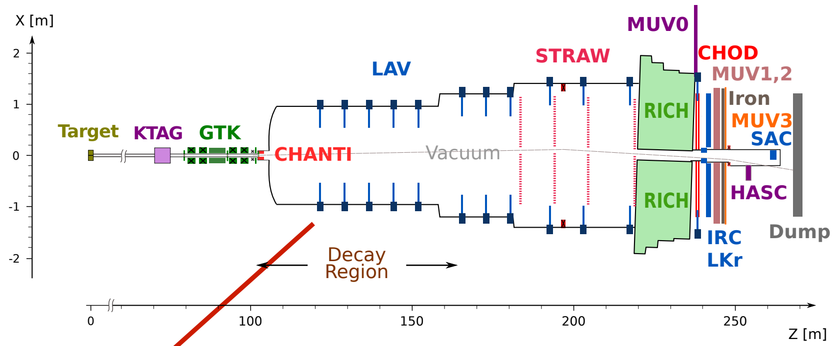


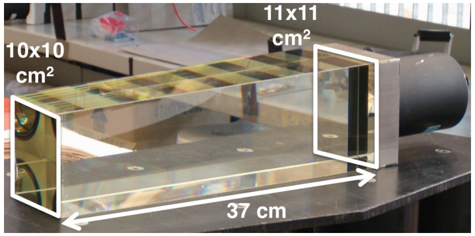
Photon detection inefficiency: ~10^{-3} – 10^{-5}



Photon detection inefficiency: ~10^{-3} – 10^{-4}

Large Angle Photon Veto

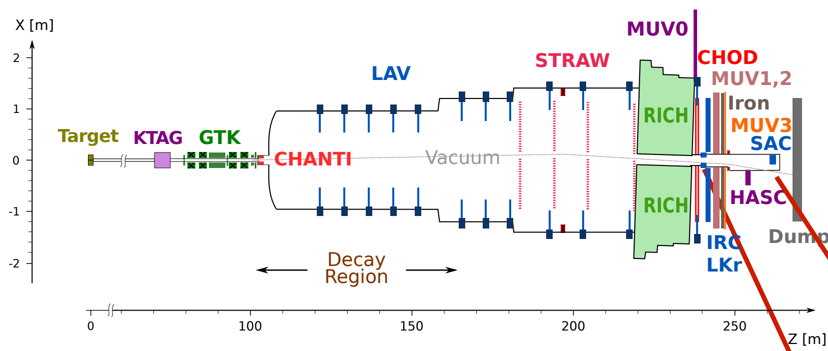




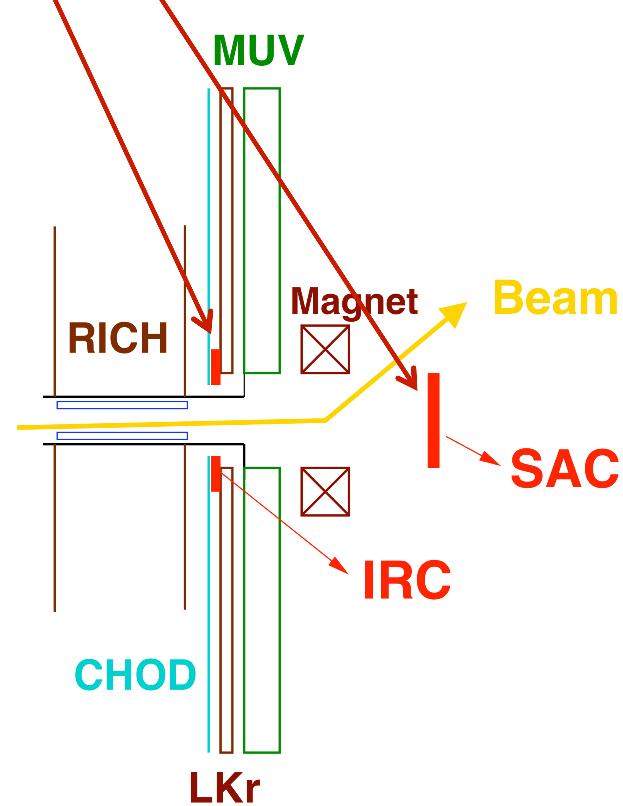
- 12 ring-shaped stations
  - 11 stations operating in vacuum
  - Angular coverage: 8.5 – 50 mrad
  - Detection inefficiency: 10^{-4}
    - $E\gamma > 200$ MeV
- Sensitive material: lead-glass blocks from the OPAL calorimeter
- At least $21X_0$ depth for incident particles

Small Angle Photon Vetos: IRC & SAC

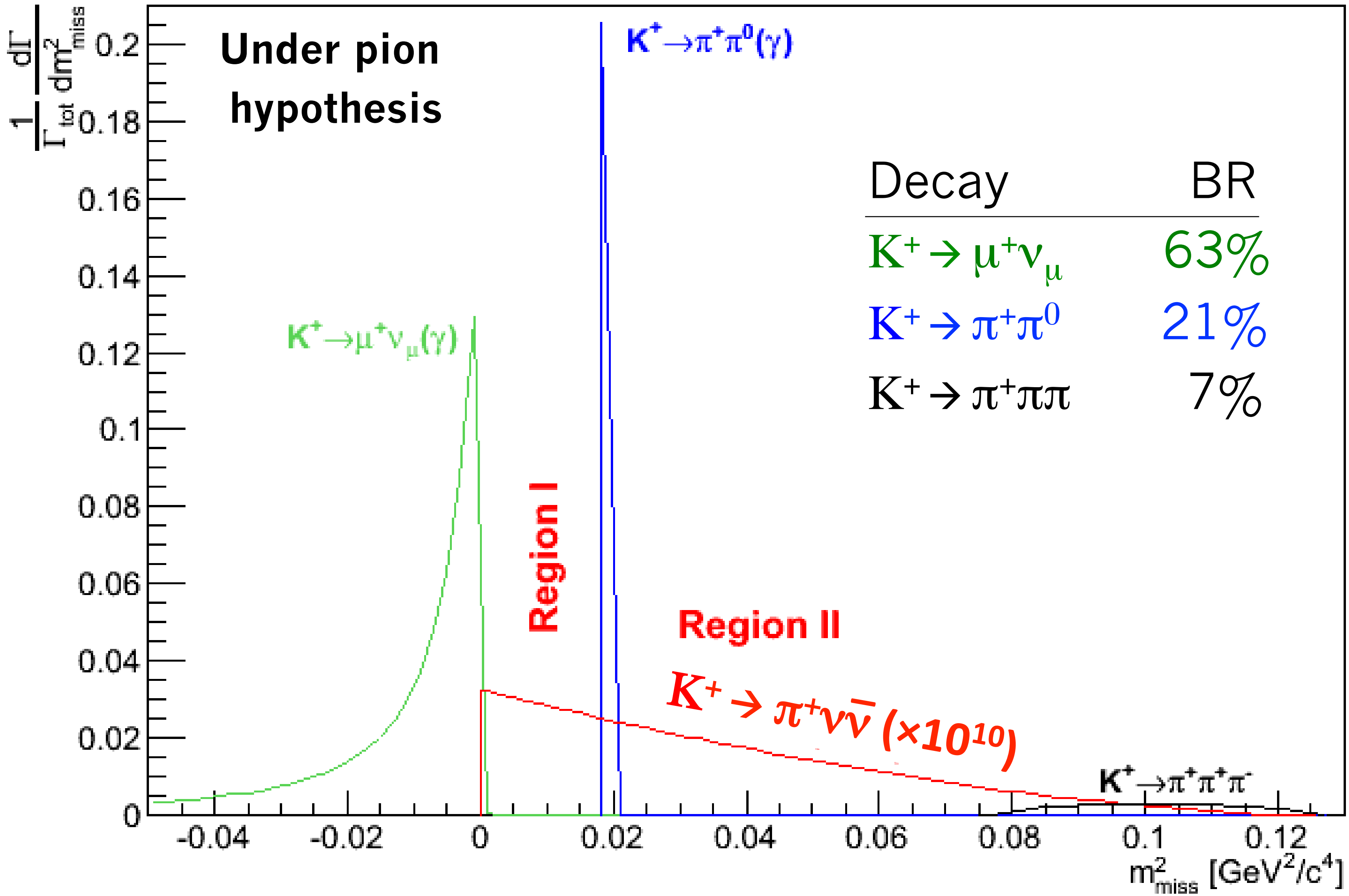
NA62



- ❑ **I**ntermediate **R**ing **C**alorimeter
- ❑ **S**mall **A**ngle **C**alorimeter
- ❑ **10^8** total π^0 rejection together with large and middle angle photon vetos

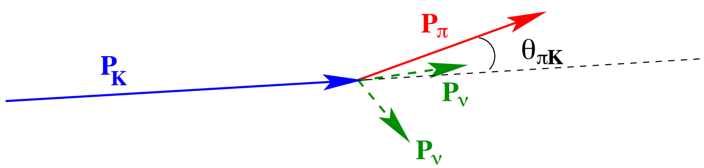


Regions of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ Selection

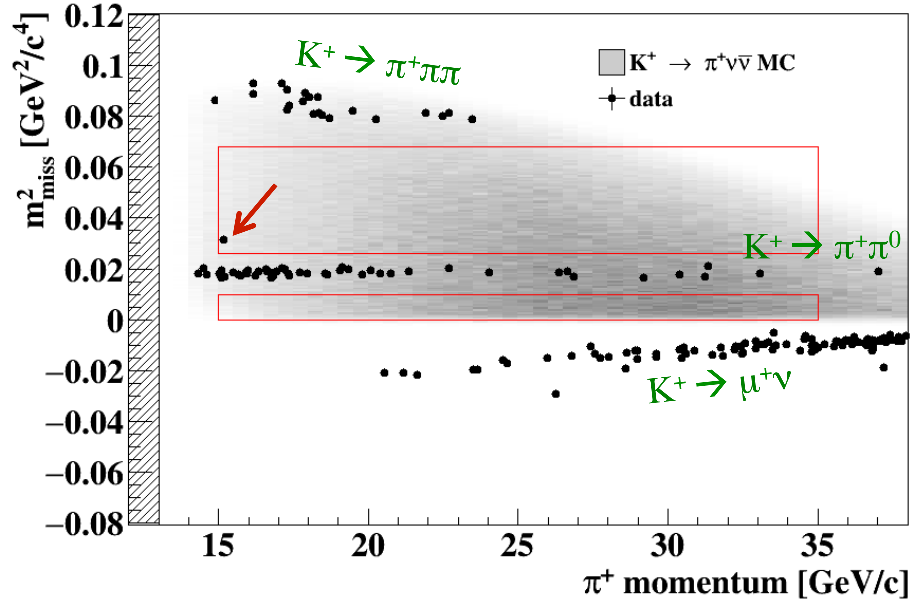


Side Note

- First result of $Br(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ measurement with 2016 data
  - 1 signal candidate observed (expected 0.27 SM signal events against 0.15 background events)



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



- SM expectation
  - $Br_{SM} = (0.84 \pm 0.1)^{\cdot 10}$

- Results (published soon) →

$$BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 14 \times 10^{-10} \text{ @ } 95\%\ CL$$

$$BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = 2.8^{+4.4}_{-2.3} \times 10^{-10} \text{ @ } 68\%\ CL$$

- Current best result from E787/949 at BNL (@ 68% CL)

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

NA62 Search for Invisible HNL

- Number of observed events, expected background events with uncertainties and stemmed observed and expected upper limits on the signal @ 90% CL as functions of HNL mass