The NA62 Experiment at CERN

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11th Terascale Detector Workshop
28.02.2018 – 02.03.2018
MPI für Physik – München

Content

- Theoretical motivation for the NA62 experiment
  - Kaon rare decays → test of the SM
    - $K^+ \rightarrow \pi^+ \nu\nu$
- The NA62 collaboration, experiment and detector
  - **Sub-detectors (selected)**
- NA62 searches of New Physics at MeV-GeV scale
  - Beam operation modes

Golden Rare Kaon Decays

- $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L \to \pi^0 \nu \bar{\nu}$: very clean FCNC processes
  - SM branching ratios **~10^{-10}**
  - $K_L \to \pi^0 \nu \bar{\nu}$: completely CP-violating decay

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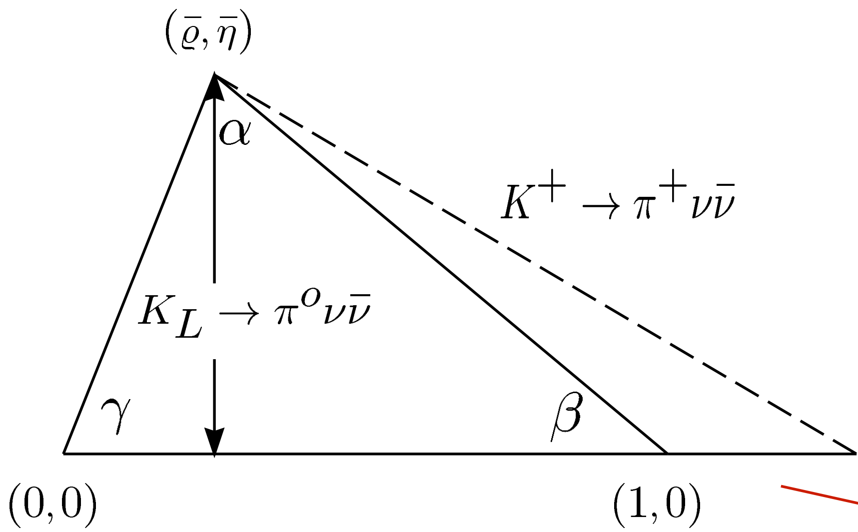
$$K^+ \to \pi^+ \nu\bar{\nu}$$

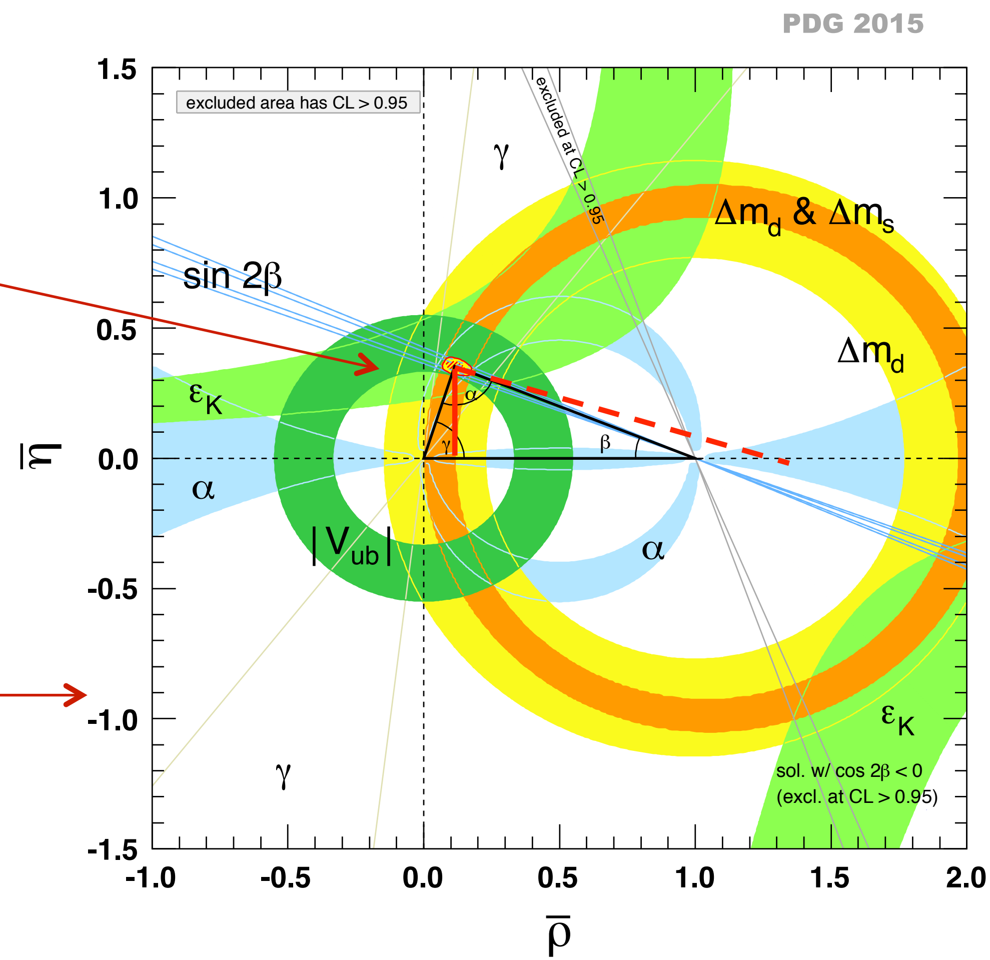
$$K_L \to \pi^0 \nu\bar{\nu}$$

@ CERN

@ J-PARC

Relation with Unitarity Triangle

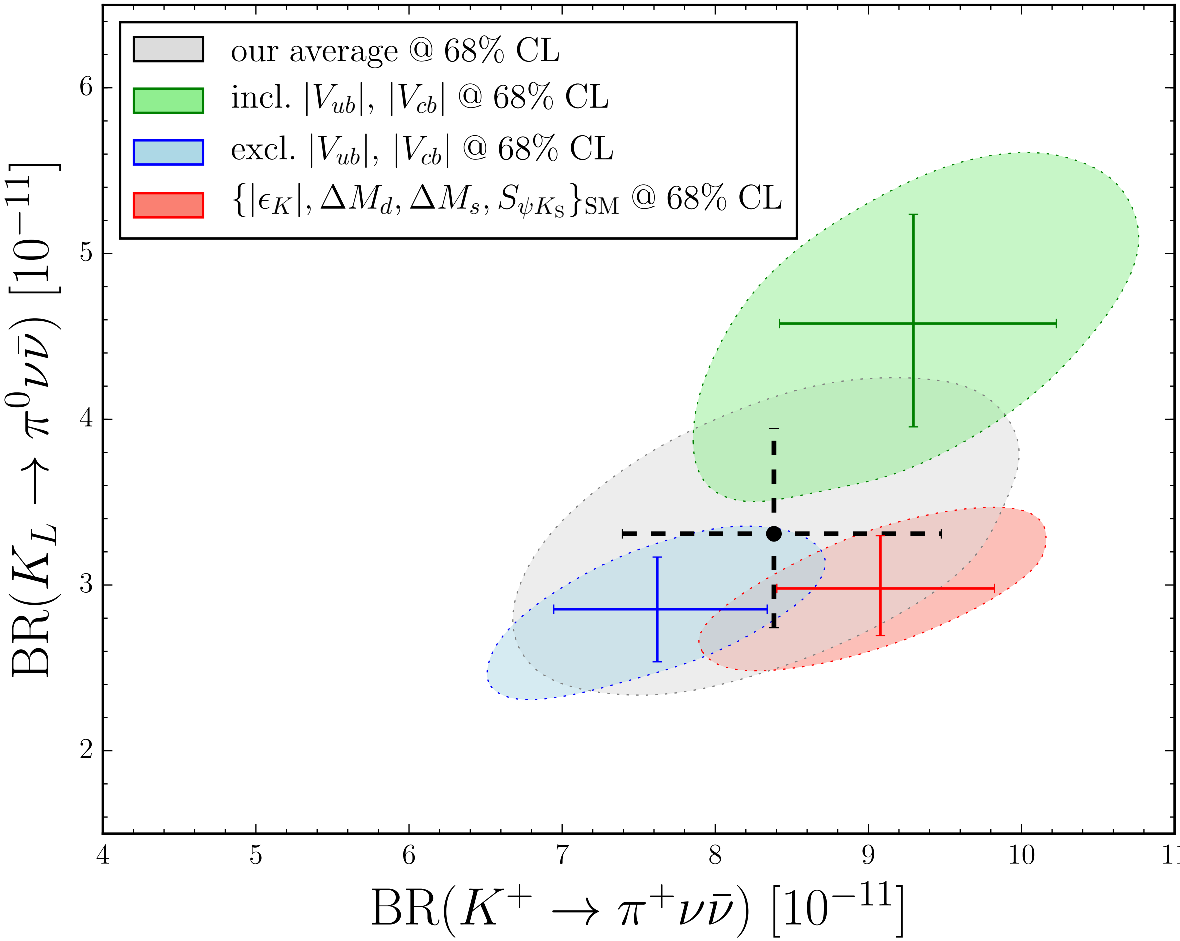




- ❑ Different New Physics models predicting deviations from the SM expectation

BR($K^{+,0}{}_L \rightarrow \pi^{+,0}\nu\bar{\nu}$) SM Predictions

Buras et al., JHEP11 (2015) 033



- Main uncertainty from the knowledge of $|V_{ub}|$ and $|V_{cb}|$

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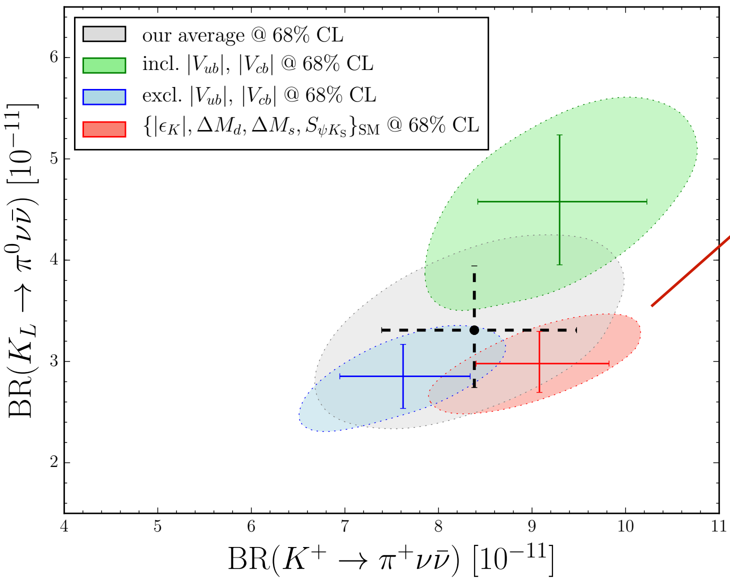

$$\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$$
$$\mathcal{B}(K_L \rightarrow \pi^0\nu\bar{\nu}) = (3.00 \pm 0.31) \times 10^{-11}$$

- BR($K^+ \rightarrow \pi^+\nu\bar{\nu}$) and BR($K_L \rightarrow \pi^0\nu\bar{\nu}$) uncertainties: **8%** and **10%**
  - Theory uncertainty: **only 2%** !
    - Excellent precision in flavour physics

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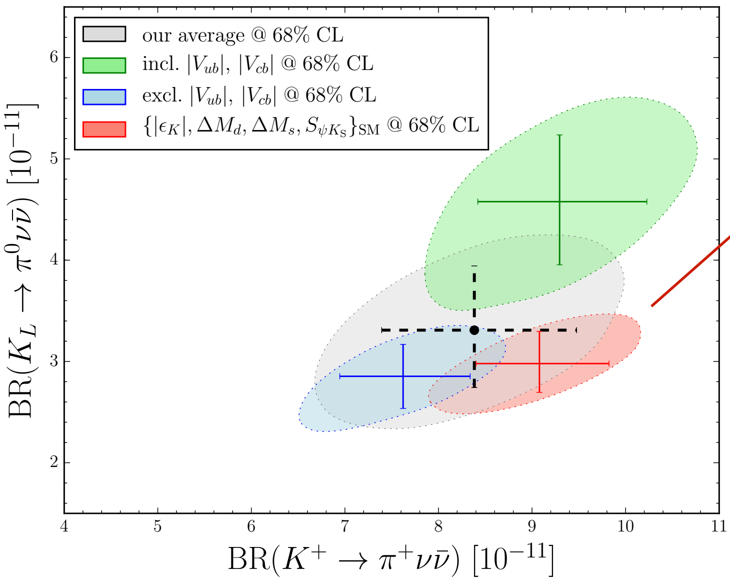

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- The NA62 goal: BR($K^+ \rightarrow \pi^+\nu\bar{\nu}$) with **10%** precision
  - **10^{12}** background rejection factor to be achieved

- Experimental status: E787/E949 experiments at BNL

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

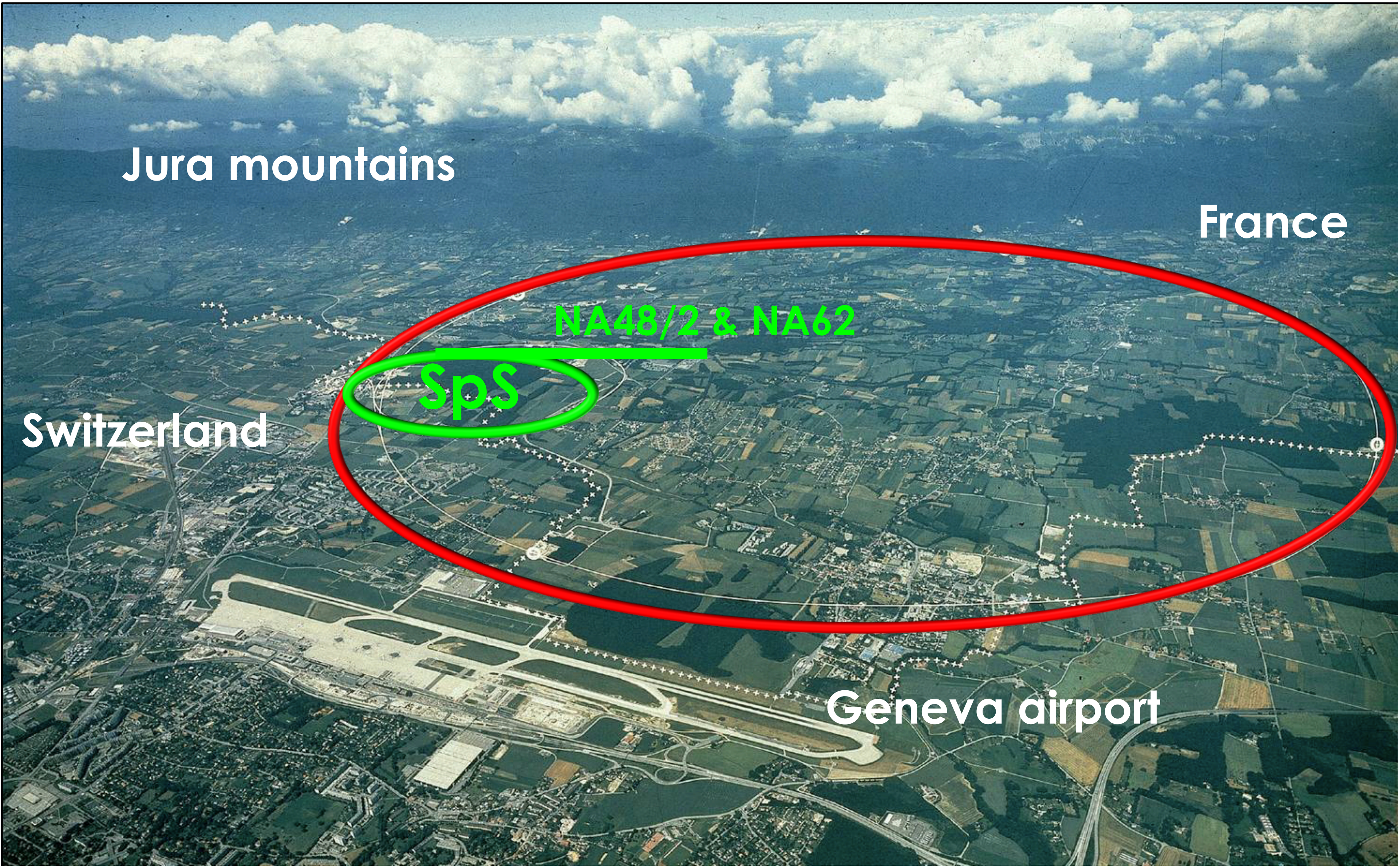
BNL E787/E949 PRL 101 (2008) 191802

The NA62 Collaboration

NA62 COLLABORATION

29 institutes, more than 200 members

The NA62 Experiment



The NA48 & NA62 Experiments

- Fixed-target experiments at CERN North Area
  - 400 GeV/c proton beam from SPS
  - Kaons from target decaying in-flight

NA48 – Discovery of direct CPV
- 1997: ε'/ε: K_L+K_S
- 1998: K_L+K_S
- 1999: K_L+K_S | K_S HI
- 2000: K_L only | K_S HI
- 2001: K_L+K_S | K_S HI

NA48/1
- 2002: K_S/hyperons

NA48/2 – Direct CPV search in $K^\pm$
- 2003: K^+/K^-
- 2004: K^+/K^-

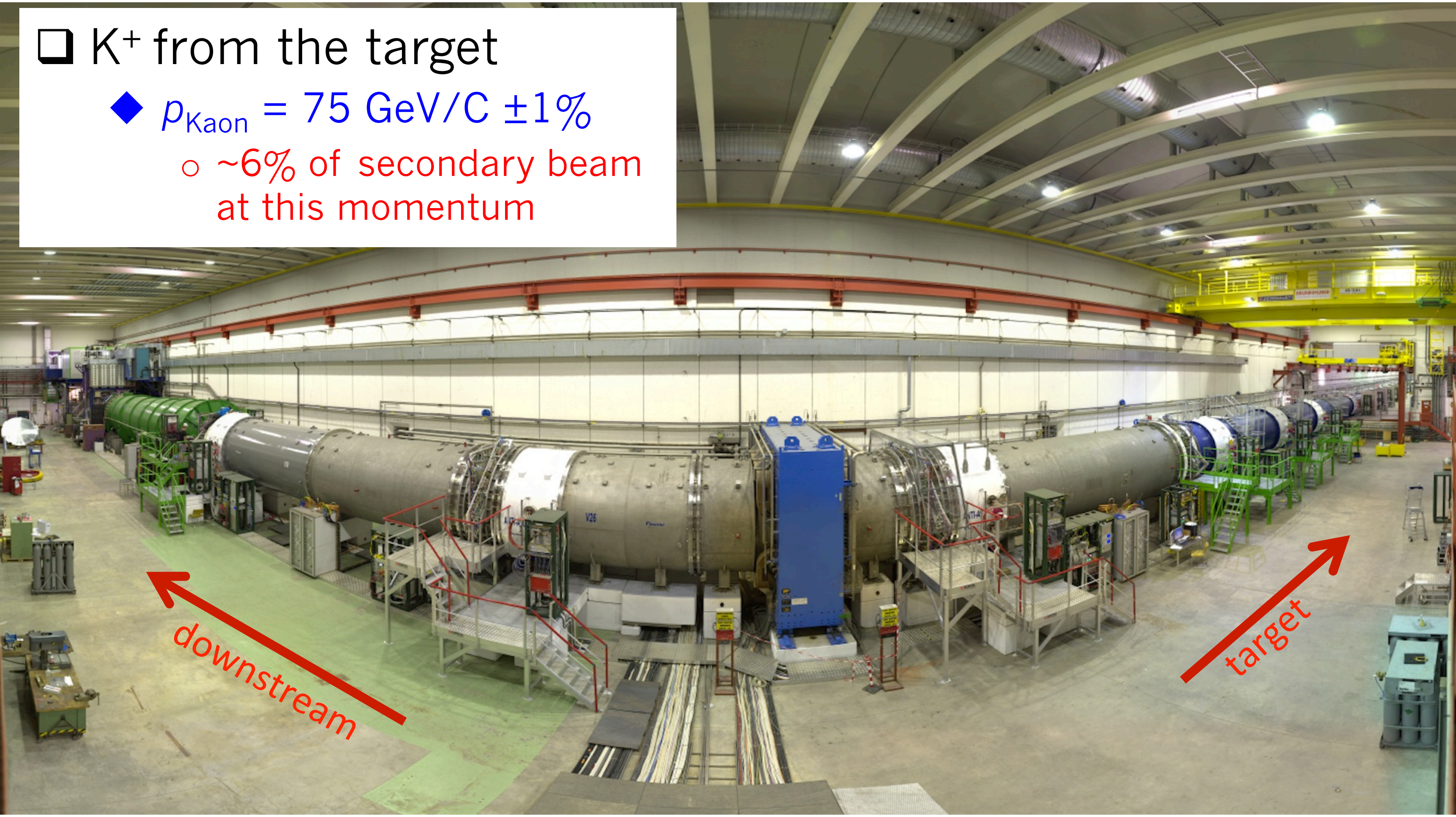
NA62 – R_K phase
- 2007: $K^\pm_{e2}/K^\pm_{\mu 2}$ | tests
- 2008: $K^\pm_{e2}/K^\pm_{\mu 2}$ | tests

NA62 – $K^+ \to \pi^+\nu\bar{\nu}$
- *2015:* 1st $K^+ \to \pi^+\nu\bar{\nu}$ run

~10^{13} K^+ decays to be recorded in total

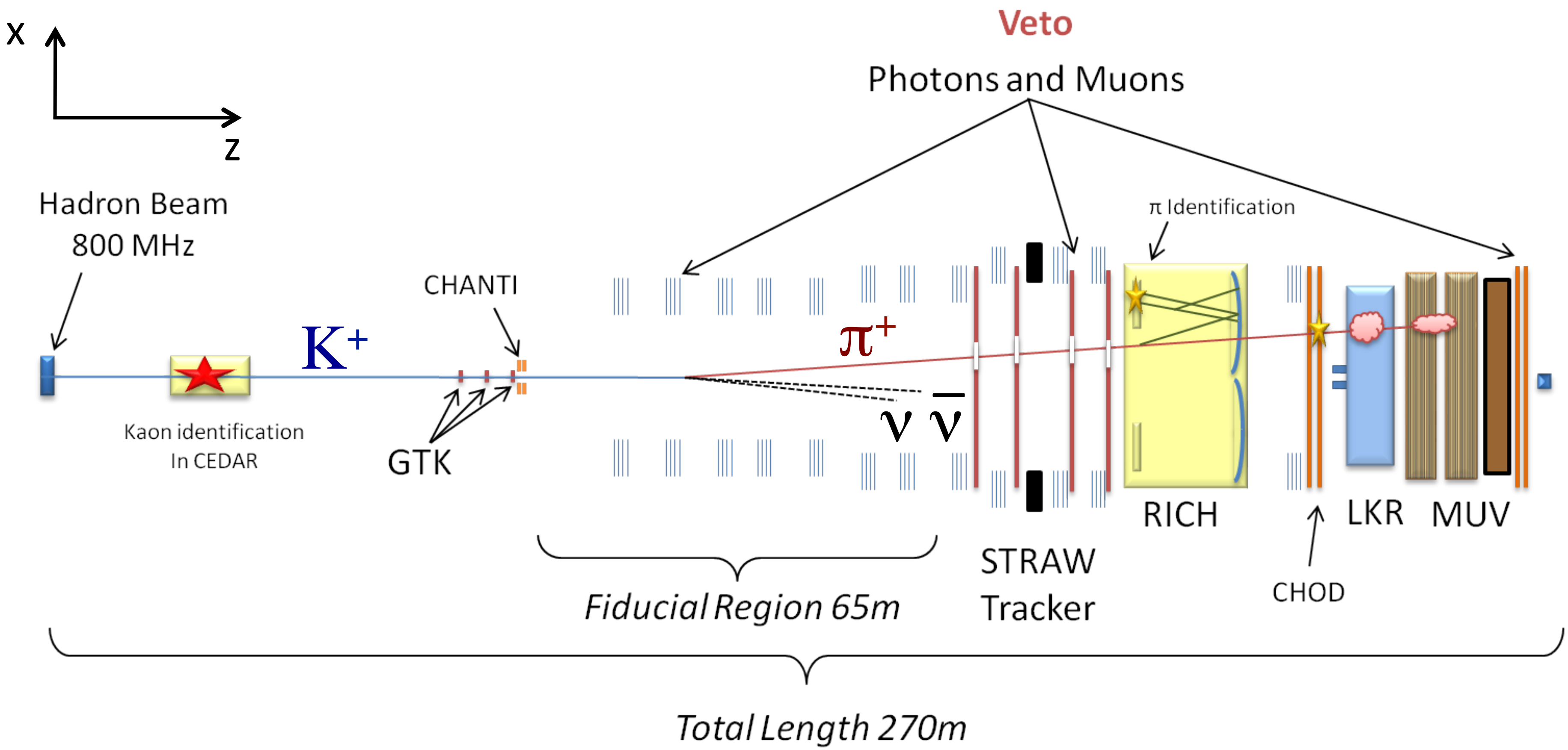
The NA62 Detector Hall

- K^+ from the target
  - p_{Kaon} = 75 GeV/C ±1%
    - ~6% of secondary beam at this momentum



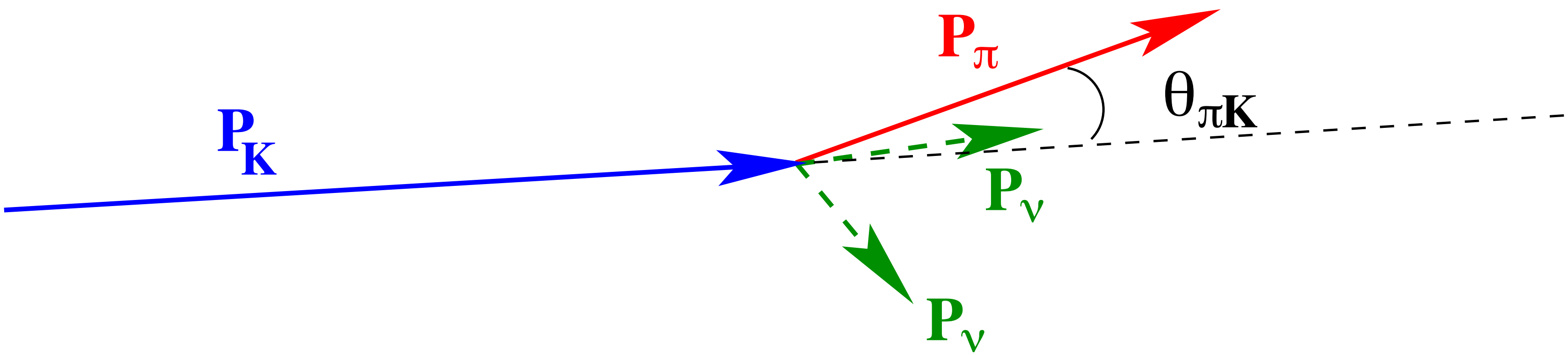
Detector hall + target hall = 270 m

The NA62 Detector



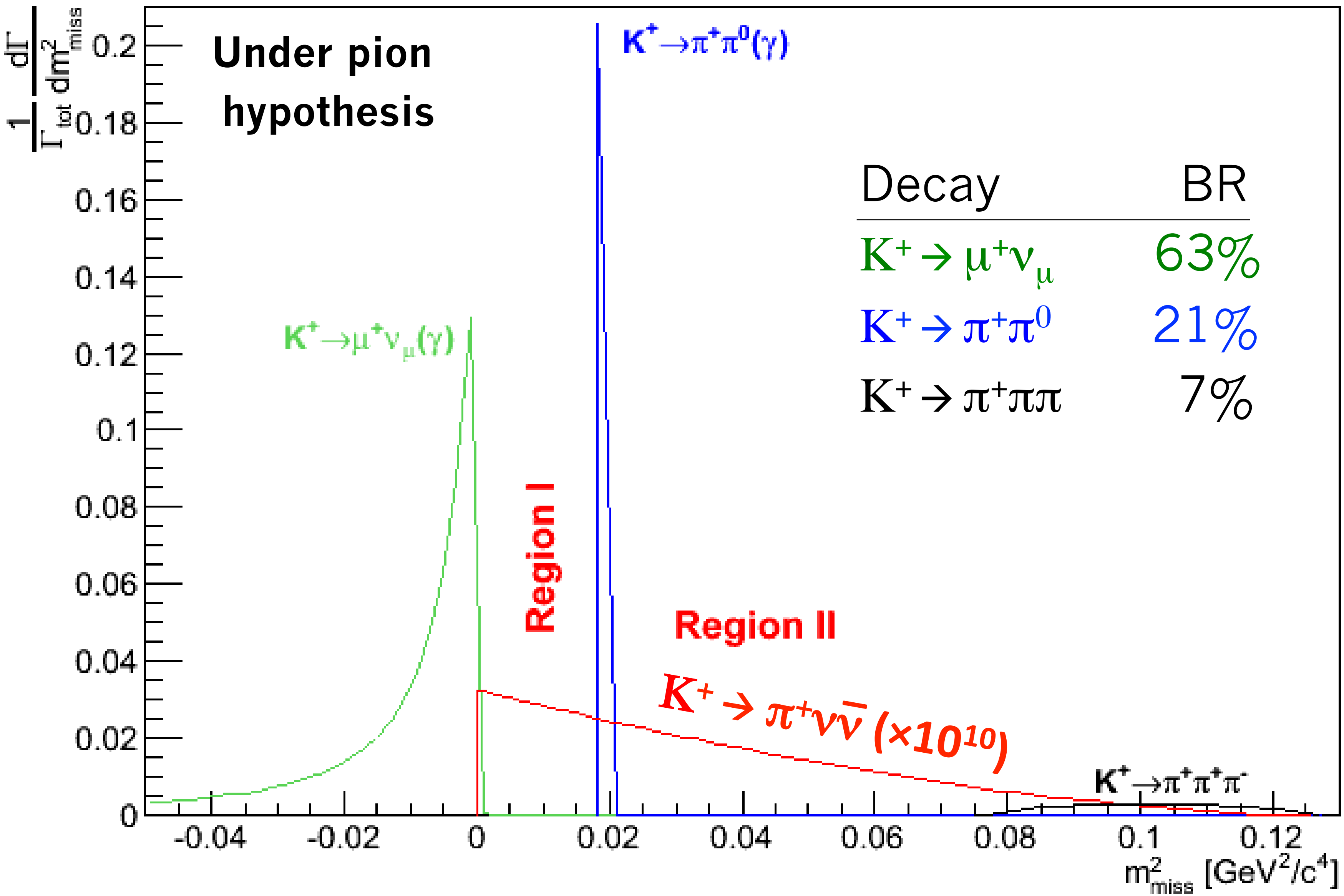
- ❑ 4.5 x 10^{12} K^+ decays in the fiducial region per year
  - ◆ @ nominal intensity of the primary proton beam: 3 x 10^{12}/pulse

NA62 Strategy of Measurement



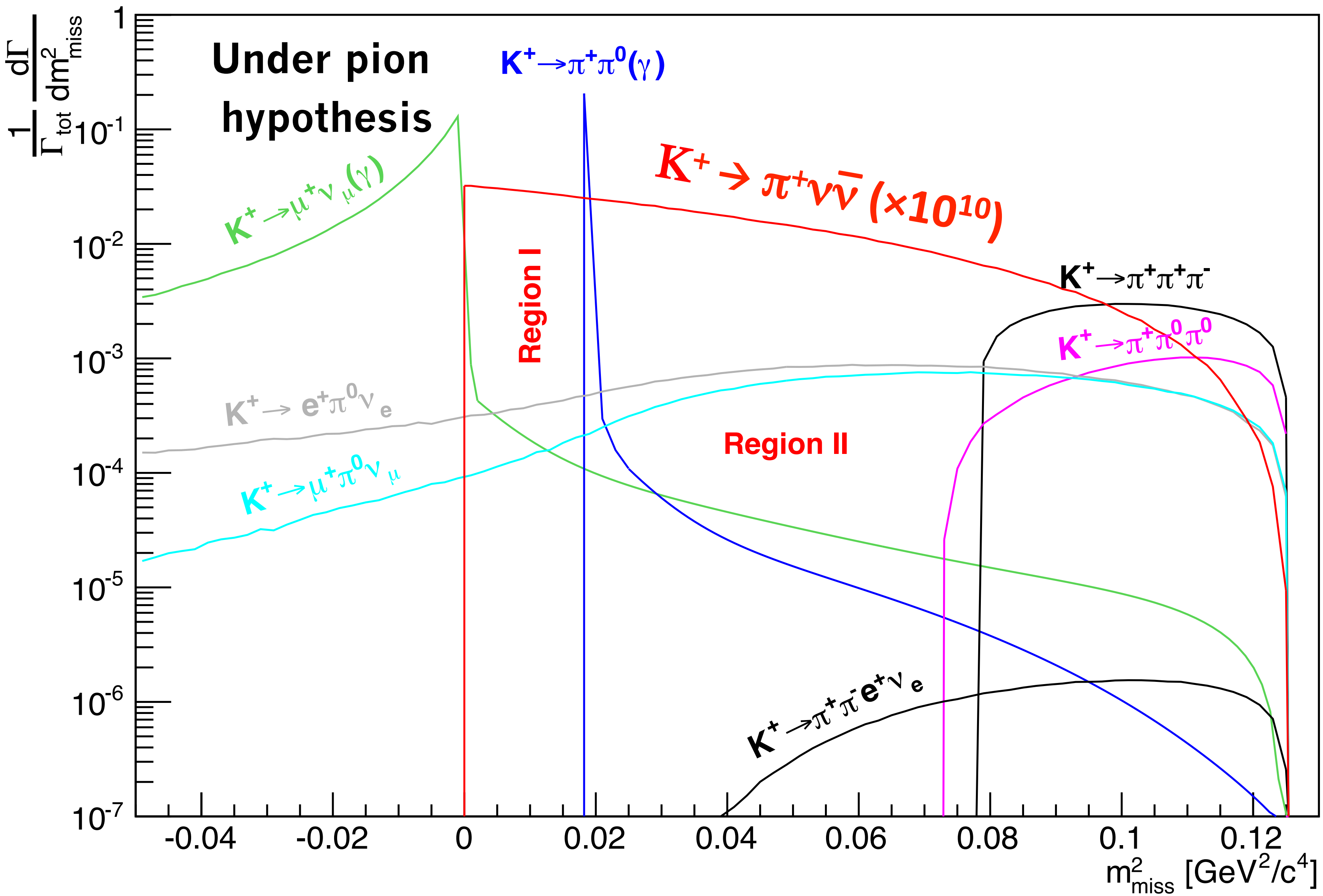
$$m^2_{miss} = \left(P_{K^+} - P_{\pi^+}\right)^2$$

NA62 Strategy of Measurement

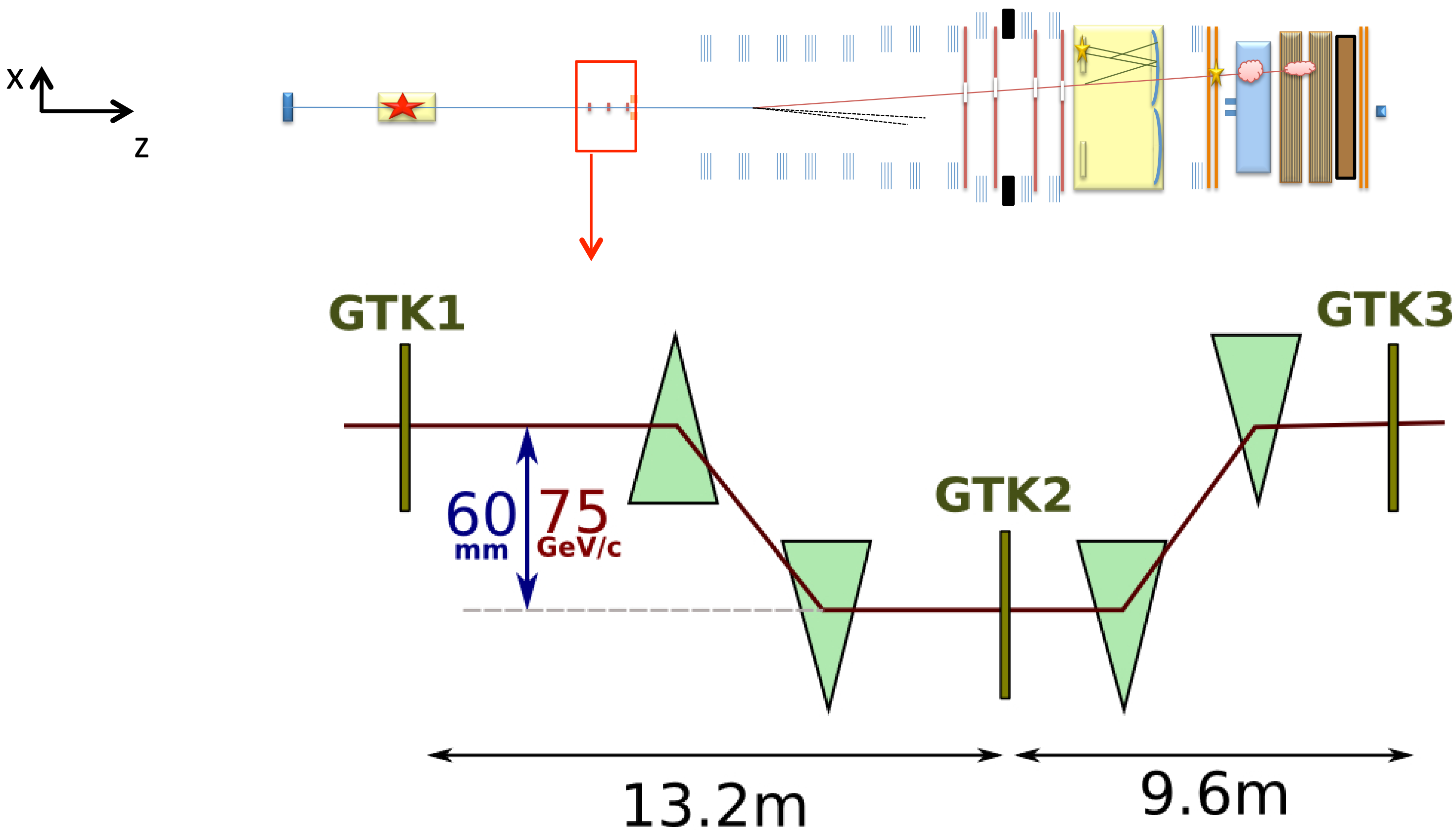


Decay	BR
$K^+ \rightarrow \mu^+\nu_\mu$	63%
$K^+ \rightarrow \pi^+\pi^0$	21%
$K^+ \rightarrow \pi^+\pi\pi$	7%

NA62 Strategy of Measurement

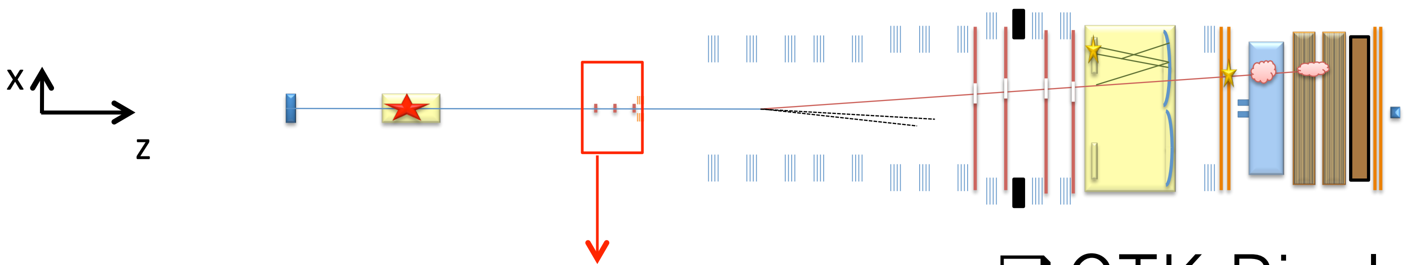


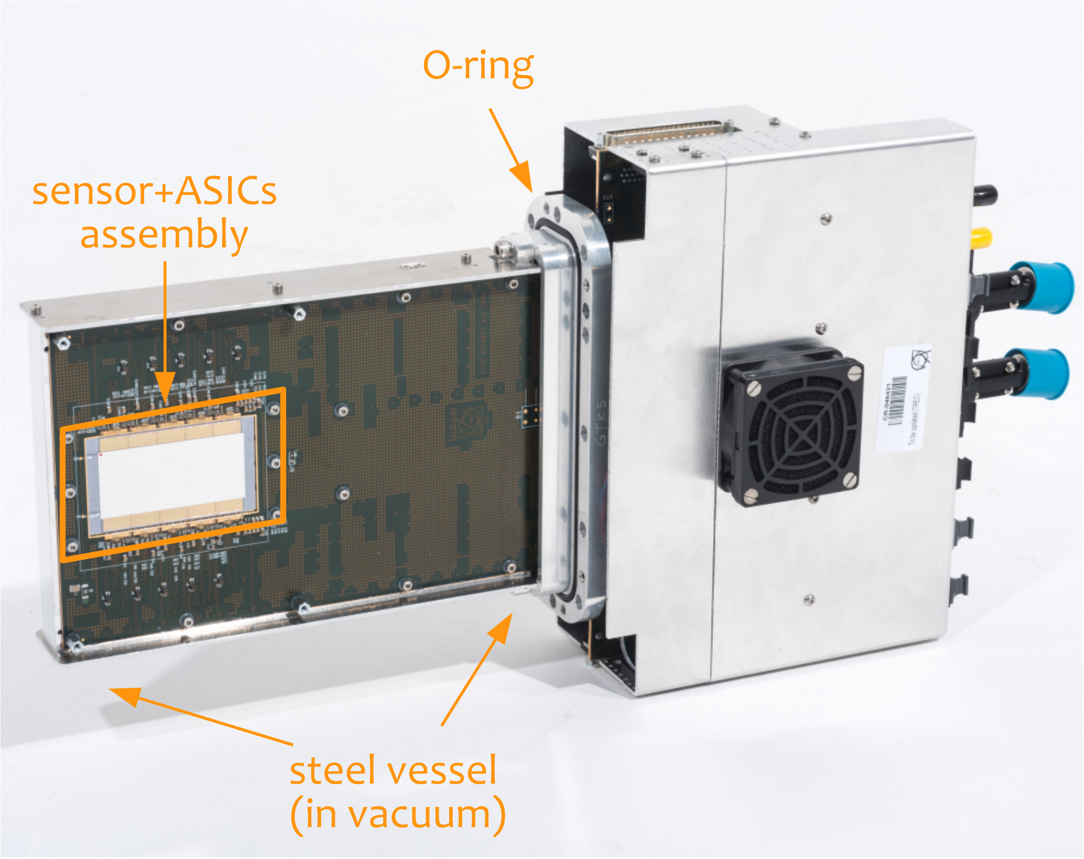
Beam Spectrometer Pixel Detector



- GigaTracker (GTK) consists of three stations of silicon pixel detectors
  - Operates together with the achromat of the dipole magnets

Beam Spectrometer Pixel Detector





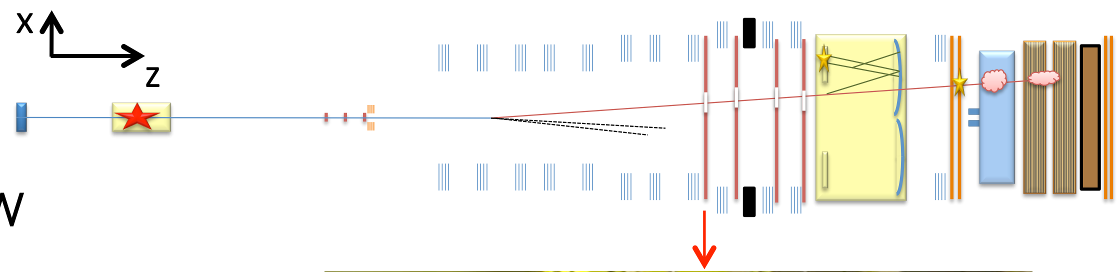
- ❑ GTK Pixel Detector
  - 3 equal stations
    - 18000 channels/station
    - 300x300 μm² pixels
    - 200 μm thickness
    - $0.005X_0$/station
  - 750 MHz total rate
    - ≈1.5 MHz/mm² peak rate
  - 10 TDCPix (IBM) readout ASICs / station
    - Thinned down to 100 μm

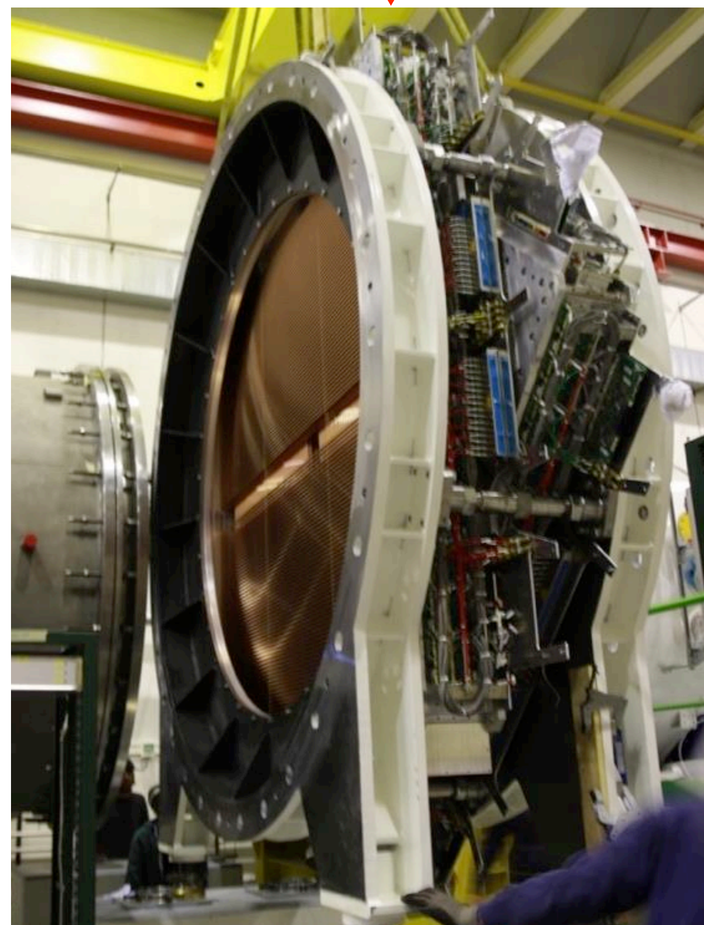
Beam Spectrometer Pixel Detector

- Performance
  - Momentum resolution: 0.2%
  - Angular resolution (in x-z and y-z planes): 16 μrad
  - Single hit resolution: 200 ps
  - Single track resolution: 74 ps (2016)

- Irradiation
  - Fluence at the nominal beam intensity: 4×10^{14} n_{eq}/cm^2 in 1 year of data taking (~200 days)
  - Operating at −15 °C to minimize radiation damage
  - About 100 days of continues operation w/o any significant degradation of performance
  - Replacement of single station requires only one day

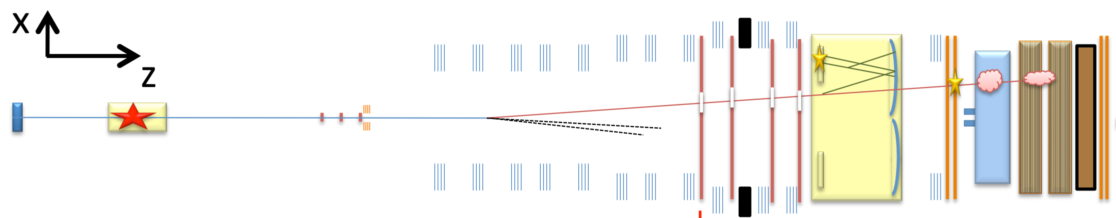
Charged Track Spectrometer - STRAW



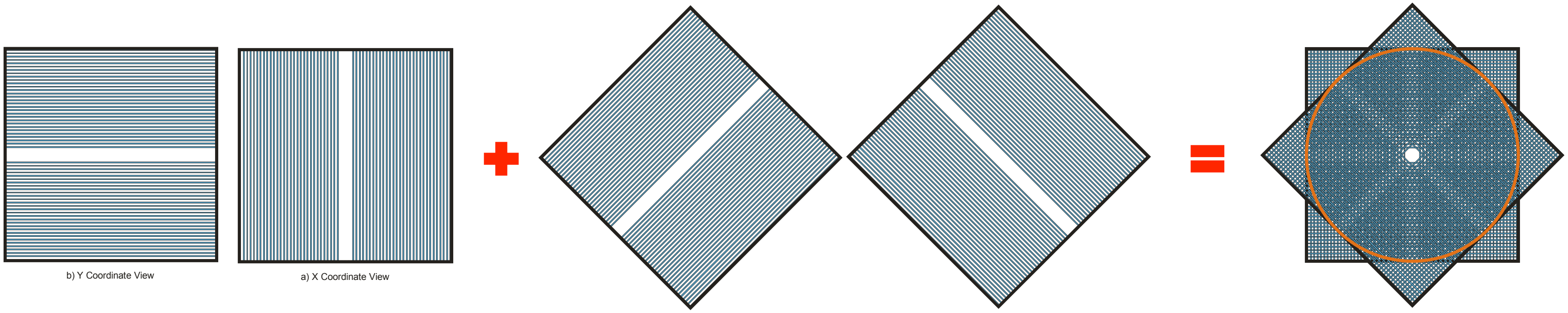


- 4 chambers of straw detectors
- Dipole magnet
  - B=0.38 T
- 70% Ar and 30% CO_2 at 1 bar
- First time straw chambers operating in vacuum!
  - $0.018X_0$ in total!

Charged Track Spectrometer - STRAW

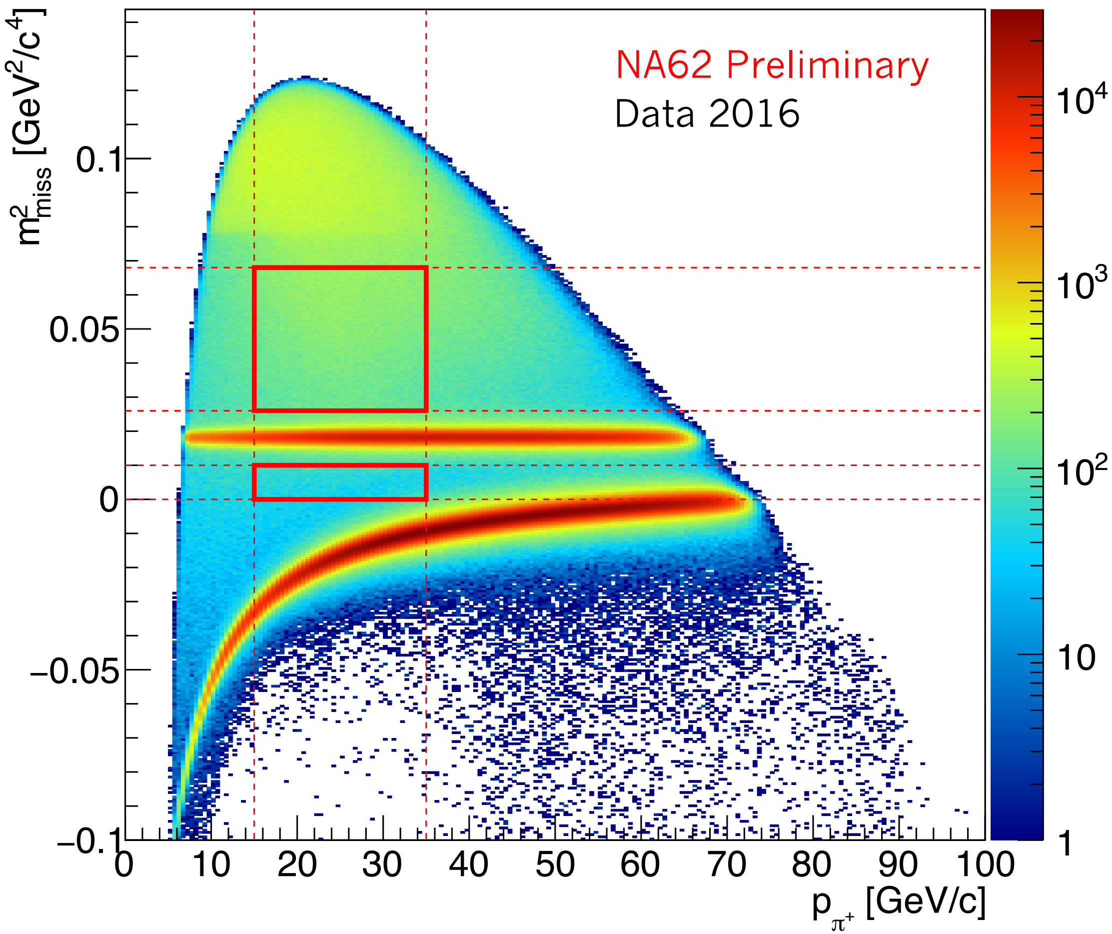


- ≥3-coordinates for tracks per chamber
  - X-Y and U-V views



$K^+ \rightarrow \pi^+\nu\bar{\nu}$ Analysis in Data 2016

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



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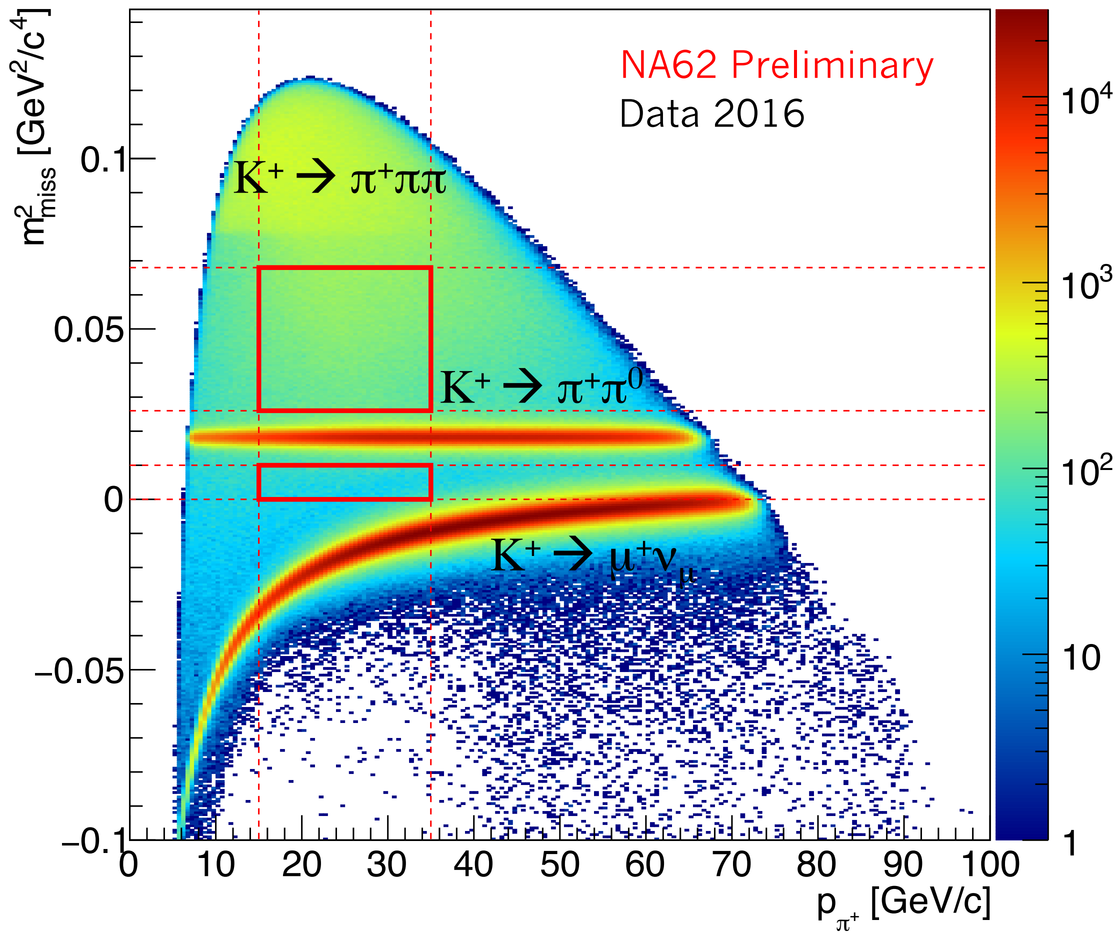
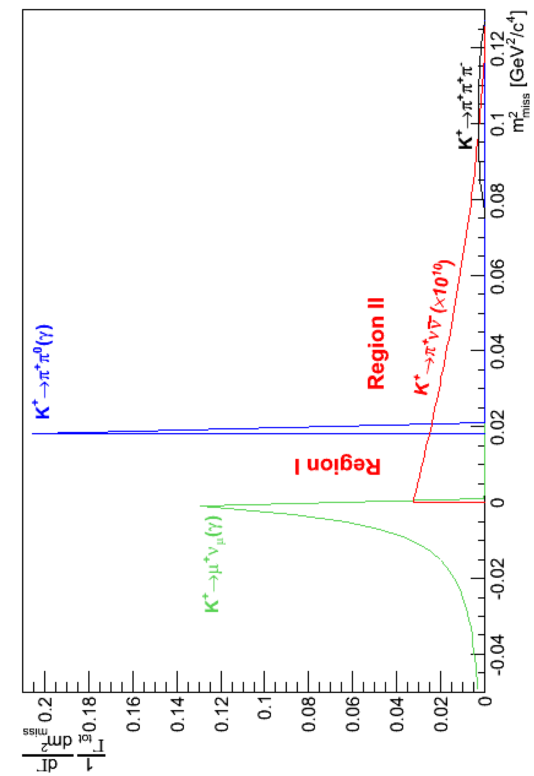
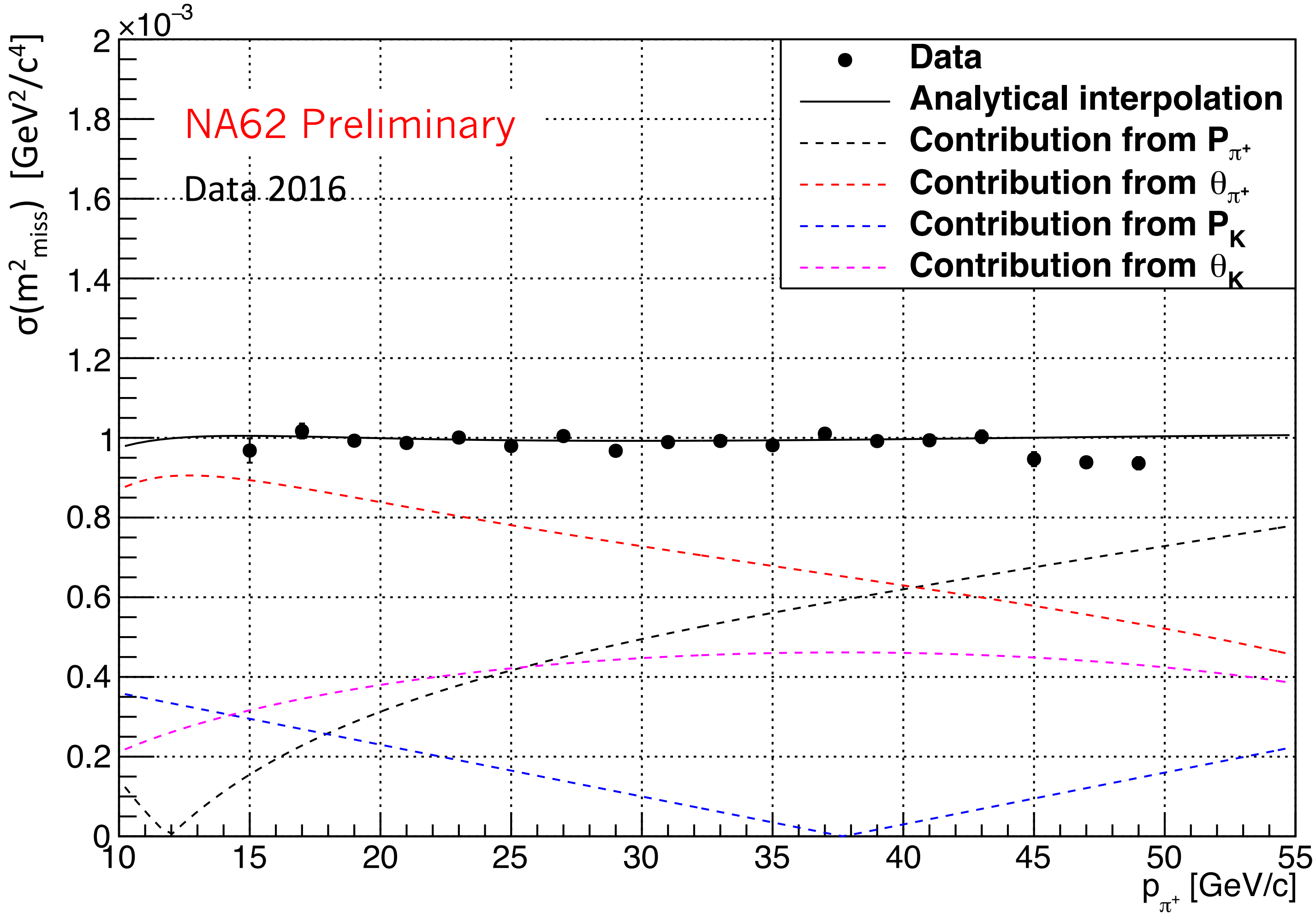


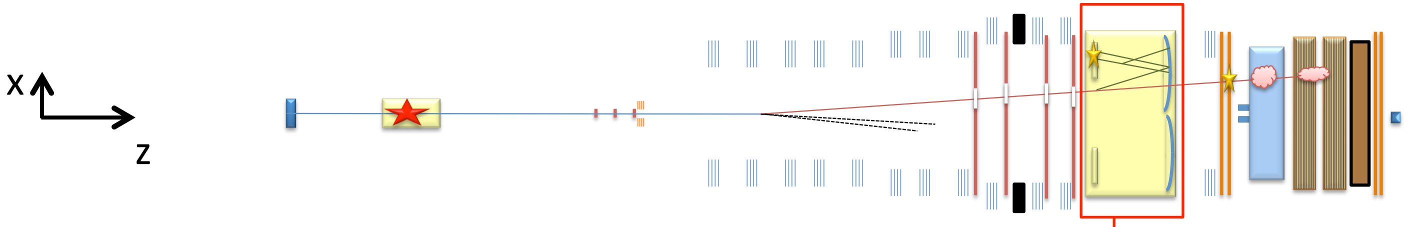


Resolution of Spectrometers

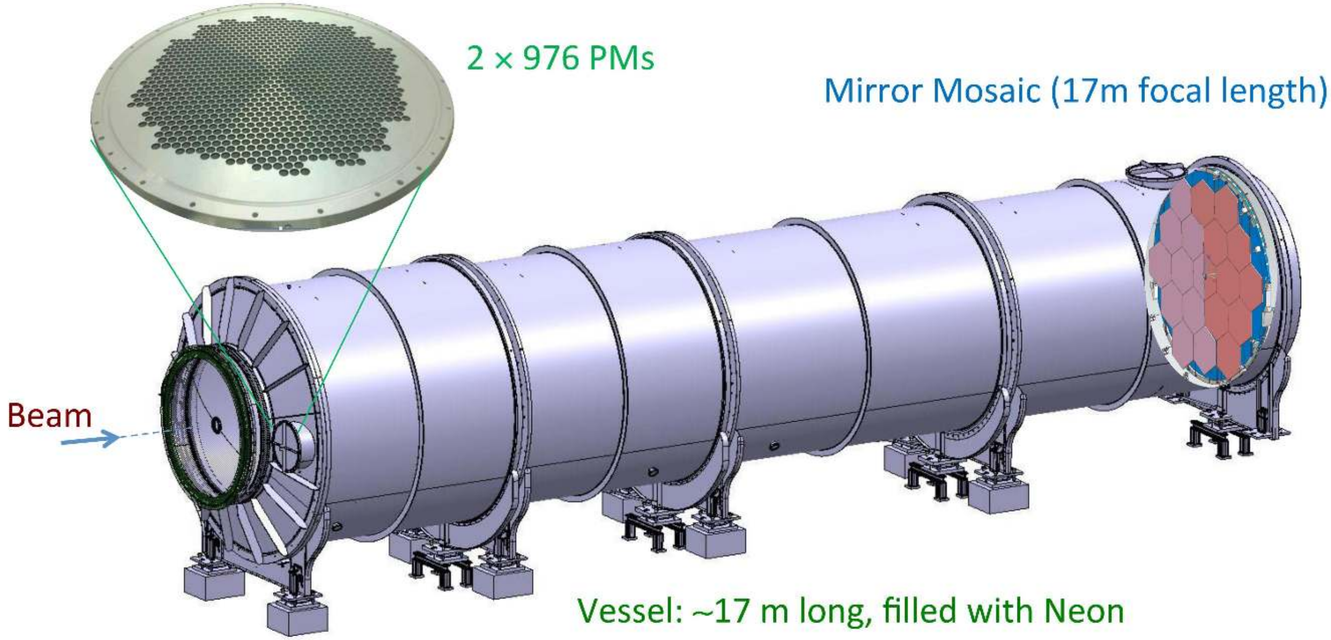
- $K^+ \rightarrow \pi^+\pi^0$ selection requiring 2γ in LKr compatible with π^0
  - No photons in other sub-detectors



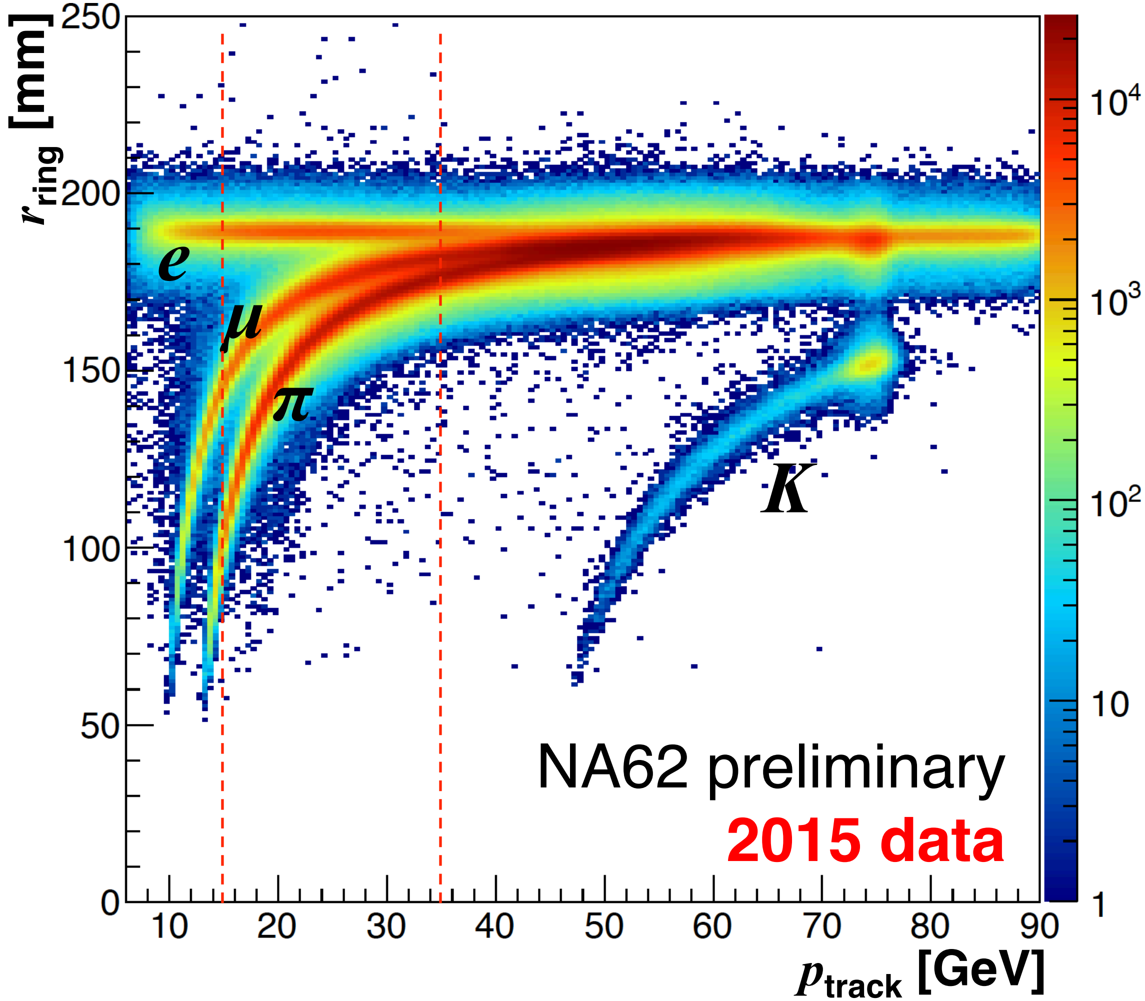
Particle Identification - RICH



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



Performance of RICH



- ~10^2 muon suppression factor
  - 15 GeV/c < p_{track} <35 GeV/c

Summary of Detector Performance

- ~10^4 kinematic suppression of the background
  - GTK, STRAW

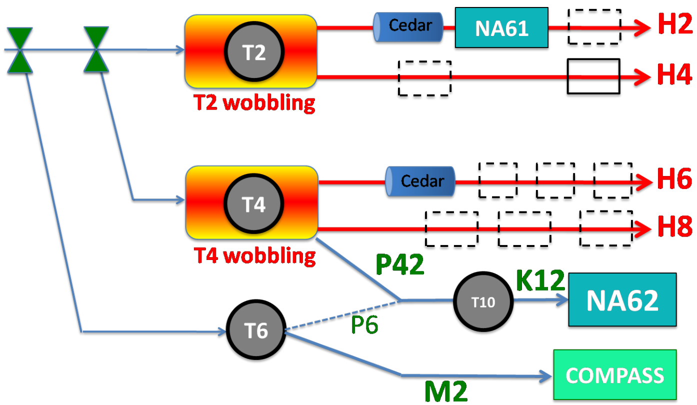
- Highly effective photon veto system, ~10^8 π^0 – rejection
  - LAV (large angle vetos), LKr (as a medium angle veto), IRC and SAC (small angle vetos, down to 0 radian)

- ~10^7 muon suppression from particle identification with calorimeters, fast muon veto (MUV3) and RICH
  - LKr+MUV1/2: 10^5 muon rejection @ ~80% pion efficiency
  - RICH: ~10^2 muon rejection in range 15 GeV/c < p_{track} <35 GeV/c

- Good time resolution: ~100 ps

NA62 Beam Operation Modes

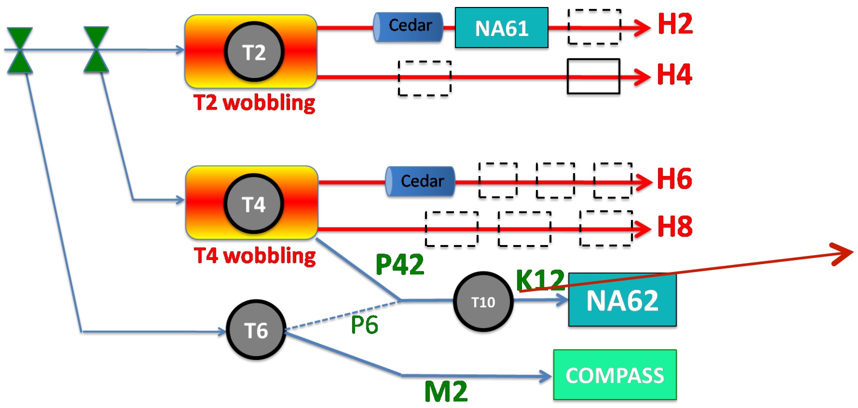
SPS beam and users



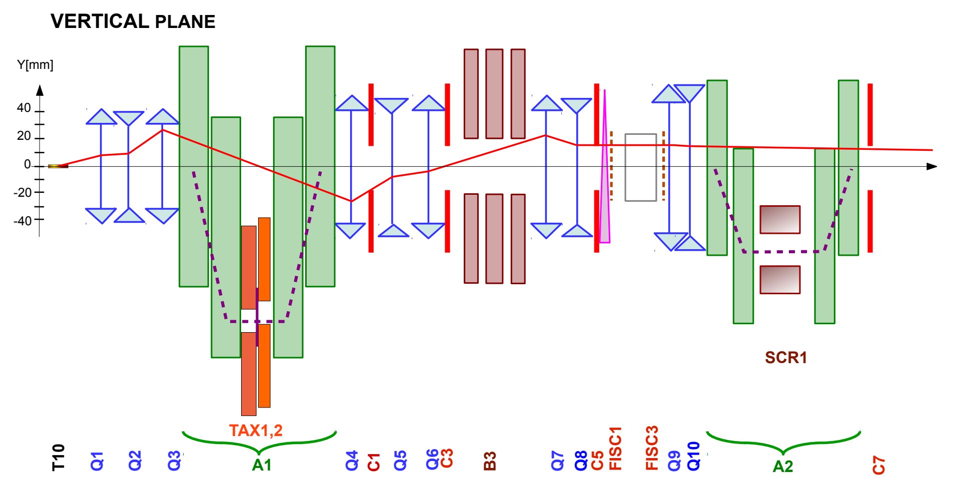
NA62 Beam Operation Modes

- 75 GeV/c K^+ beam or proton dump modes using "TAXes"
  - Easily switchable modes in the current beam setup of NA62

SPS beam and users



NA62 beam-line from target to decay volume



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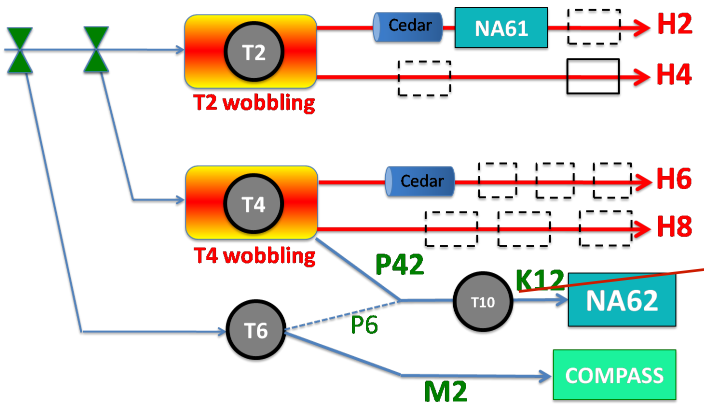

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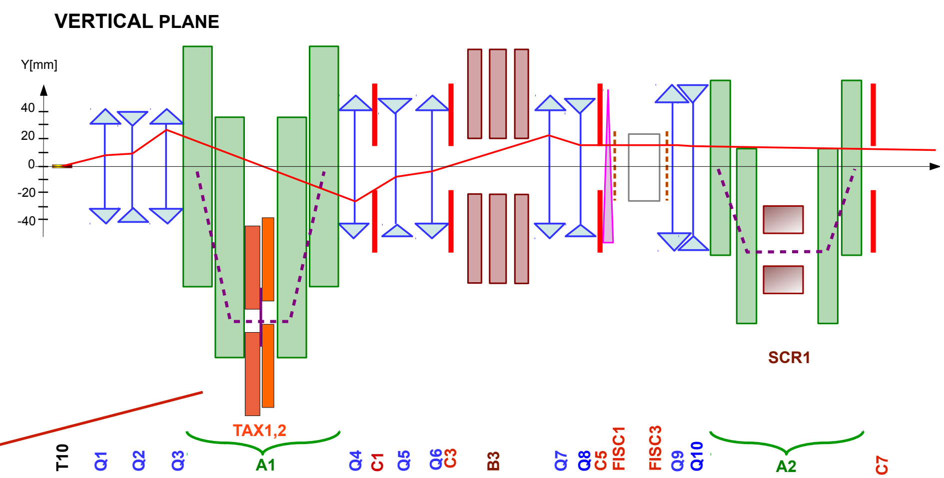
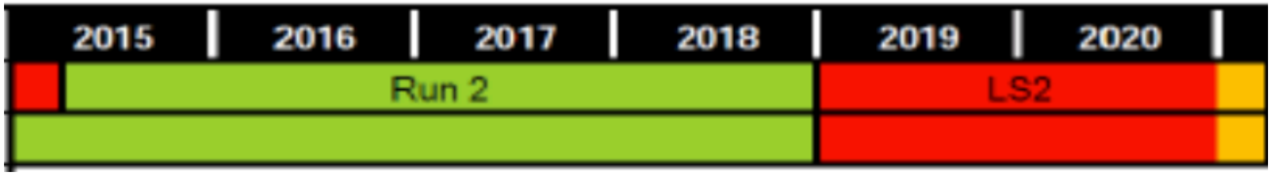


TAX1&2

- ❑ TAXes: movable copper + iron made collimators of ~22λ_I total thickness

NA62 in Run 2, 3 and 4

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



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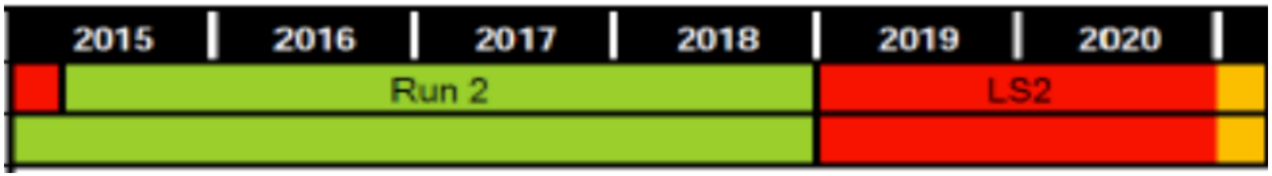
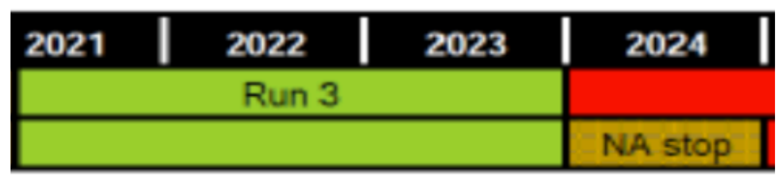


- Run 3: many interesting fields to be studied with minimal (or no upgrades at all) of the existing setup
  - In K^+ beam mode:
    - If needed improve $K^+ \to \pi^+ \nu\bar{\nu}$, A'→invisible, HNL single track decays
      - All benefit from the same trigger signature
  - In proton dump mode:
   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



- Run 4: there are some ideas and also some efforts too

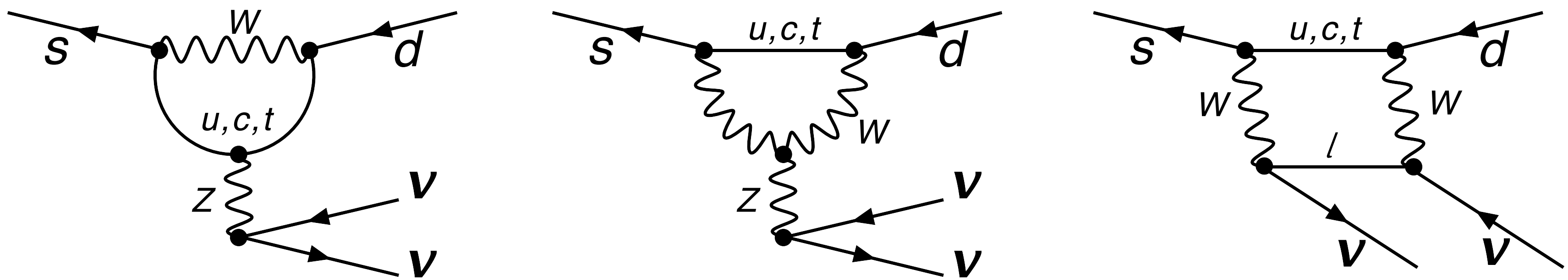
Summary

- NA62 experiment at CERN to precisely measure K^+ rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ (BR ~10^{-11}) indirectly searching for NP effects

- High energy & intensity proton beam + long decay volume & advanced detector system → NA62 as a very powerful tool to search for hidden sector particles
  - Dark photon, Axion-like particles, Heavy neutral leptons
  - MeV to GeV mass range, weak coupling with the SM
  - Visible and invisible decays

- Operation in K^+ beam or proton beam dump mode
  - Easy to switch between the modes
  - Both modes considered after the long shutdown 2 (2021)

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



- Amplitude ~ $m^2_{u,c,t} / m^2_W$ → short-distance dynamics
  - Effective theory framework for calculation of the decay amplitude
  - Negligible up-quark contribution

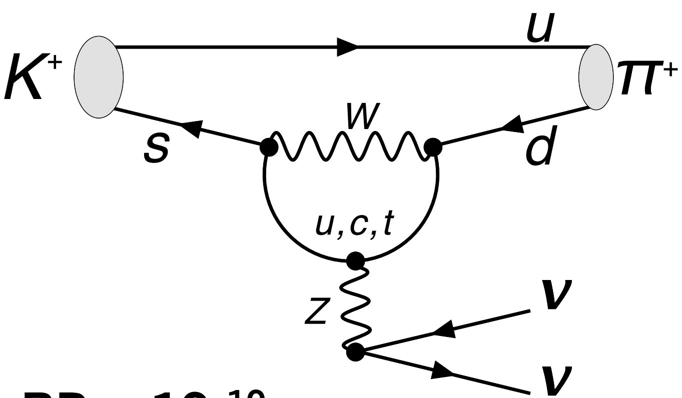
Buras et al., hep-ph/0405132 (2007)

$$\mathcal{H}_{\rm eff}^{\rm SM} = \frac{G_{\rm F}}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_{\rm w}} \sum_{l=e,\mu,\tau} \left(V_{cs}^* V_{cd} X_{\rm NL}^l + V_{ts}^* V_{td} X(x_t)\right) (\bar{s}d)_{V-A} (\bar{\nu}_l \nu_l)_{V-A}$$

- Theoretically calculable X^l_{NL} and $X(x_t)$ loop functions
  - Remarkable progress over the last decade

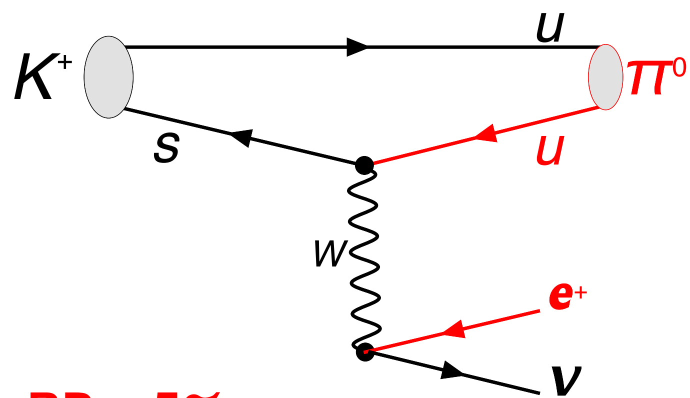
Hadronic Matrix Element $\langle \pi^+ \nu \bar{\nu} | H_{eff}^{SM} | K^+ \rangle$

- Non-perturbative QCD problem



BR ~ 10^{-10}

$d \leftrightarrow u$



BR ≈ 5%

- QCD symmetry under Isospin rotation
  - Same Form Factors for semi-leptonic $K \to \pi$ transitions

- Precisely measured leading order decay $K^+ \to \pi^0 e^+ \nu$
  - Extracted Form Factors used in BR($K^+ \to \pi^+ \nu \bar{\nu}$) calculations
    - Known small corrections due to broken Isospin symmetry

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

Nucl. Phys. B718 (2005) 319-338

Phys. Rev. D76 (2007) 034017

$$\kappa_+ = (5.173 \pm 0.025) \cdot 10^{-11} \left[\frac{\lambda}{0.225}\right]^8$$

$$\lambda = |V_{us}|$$

$$\Delta_{\mathrm{EM}} = -0.003$$

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = \kappa_+ (1 + \Delta_{\mathrm{EM}}) \cdot \left[\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X(x_t)\right)^2 + \left(\frac{\mathrm{Re}\lambda_c}{\lambda} P_c(X) + \frac{\mathrm{Re}\lambda_t}{\lambda^5} X(x_t)\right)^2\right]$$

Buras et al., JHEP11 (2015) 033

$$P_c(X) = 0.404 \pm 0.024$$

Phys. Rev. Lett. 95 (2005) 261805

JHEP 11 (2006) 002

Phys. Rev. D78 (2008) 034006

$$X(x_t) = 1.481 \pm 0.005_{\mathrm{th}} \pm 0.008_{\mathrm{exp}}$$

Phys. Lett. B451 (1999) 161-169

Nucl. Phys. B548 (1999) 309-327

Phys. Rev. D57 (1998) 216-223

Phys. Rev. D83 (2011) 034030

- $\lambda_t = V^*_{ts} V_{td}$ - known from $|V_{ub}|$ and $|V_{cb}|$ measurements

BR($K^0_L \rightarrow \pi^0\nu\bar{\nu}$) Master Formula

Nucl. Phys. B718 (2005) 319-338

Phys. Rev. D76 (2007) 034017

$$\kappa_L = (2.231 \pm 0.013) \cdot 10^{-10} \left[\frac{\lambda}{0.225}\right]^8$$

$$\lambda = |V_{us}|$$

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = \boxed{\kappa_L} \cdot \left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X(x_t)\right)^2$$

Buras et al., JHEP11 (2015) 033

- ❑ No charm quark contribution
- ❑ No QED radiative corrections

Input Parameters from CKM Matrix

- Parameterization of λ_t and λ_c

Buras et al., JHEP11 (2015) 033

$$\mathrm{Re}\lambda_t \simeq |V_{ub}||V_{cb}|\cos\gamma(1-2\lambda^2) + (|V_{ub}|^2 - |V_{cb}|^2)\lambda\left(1-\frac{\lambda^2}{2}\right)$$

$$\mathrm{Im}\lambda_t \simeq |V_{ub}||V_{cb}|\sin\gamma$$

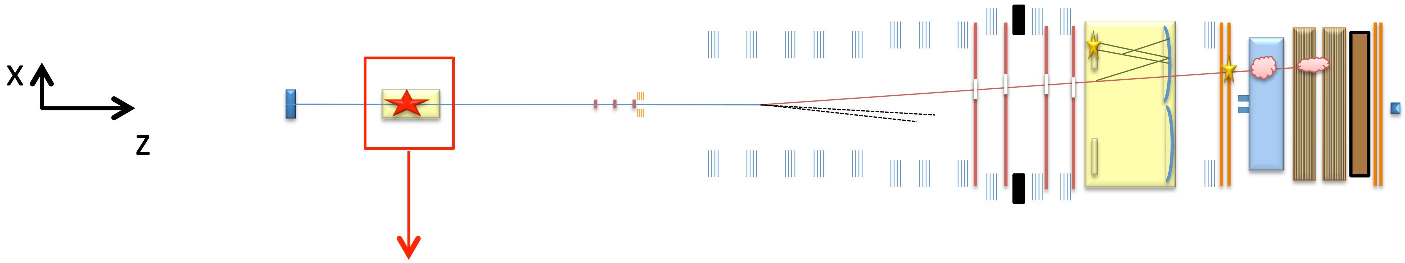
$$\mathrm{Re}\lambda_c \simeq -\lambda\left(1-\frac{\lambda^2}{2}\right)$$

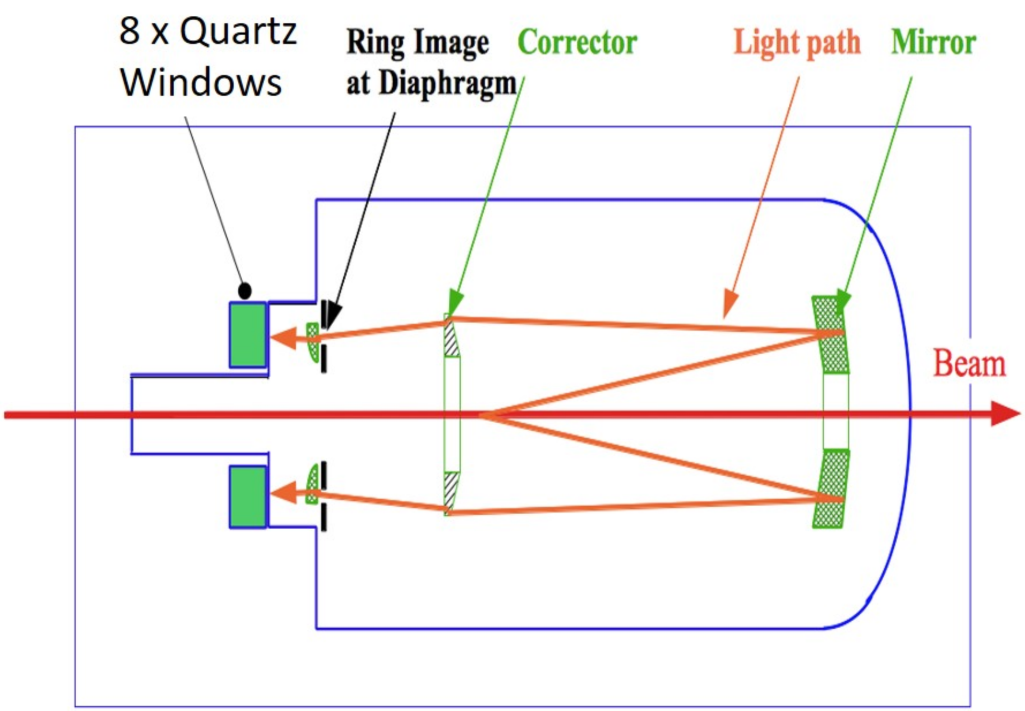
$$\lambda = |V_{us}|$$

- Direct measurement from leading order decays
  - Insensitive to New Physics effects
  - Discrepancy between exclusive vs. inclusive $|V_{ub}|$ and $|V_{cb}|$

- Extracted from precisely measured FCNC observables
  - More accurate determination $\varepsilon_K,\quad \Delta M_s,\quad \Delta M_d,\quad S_{\psi K_S}$
  - Sensitivity to New Physics effects

Kaon Identification – KTAG (CEDAR)

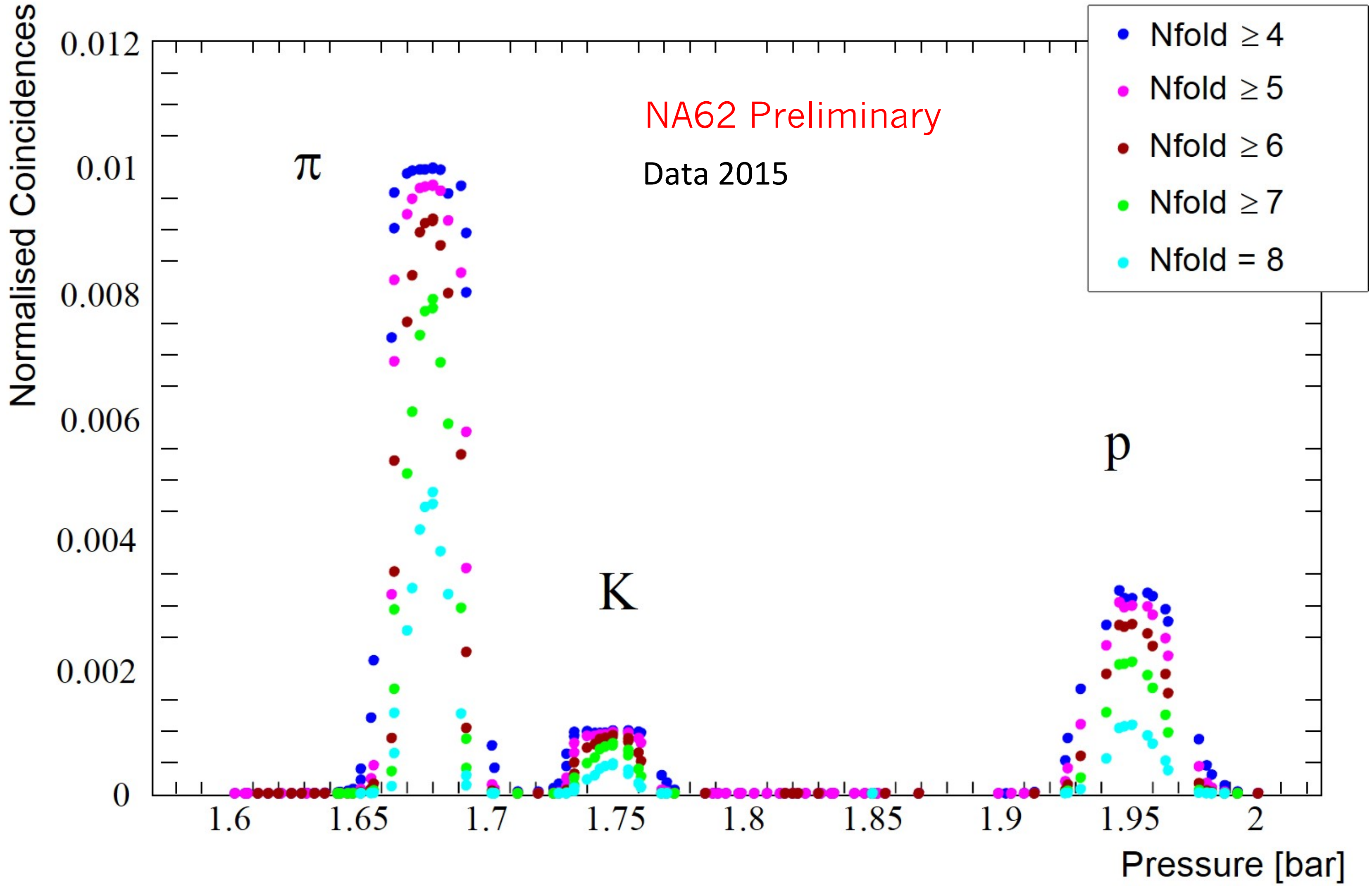




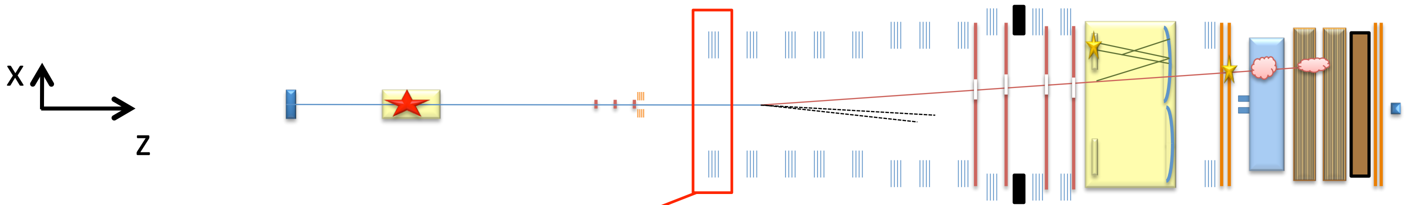
- ❑ **C**h**E**renkov **D**ifferential counter with **A**chromatic **R**ing focus
  - Filled with Nitrogen
  - Time resolution ≈70 ps
  - 45 MHz of total rate

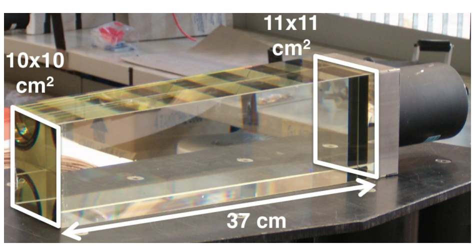
- ❑ Gas pressure adjusted for K^+ selection with p_K = 75 GeV/c

KTAG Performance – Pressure Scan



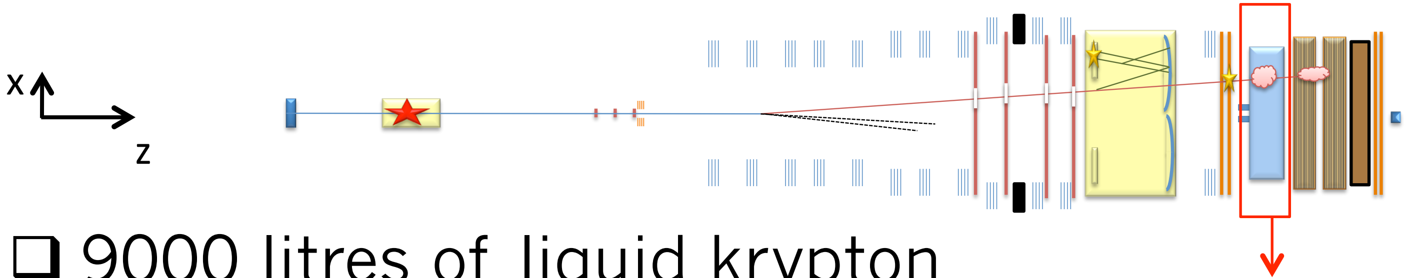
Large Angle Photon Veto





- 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

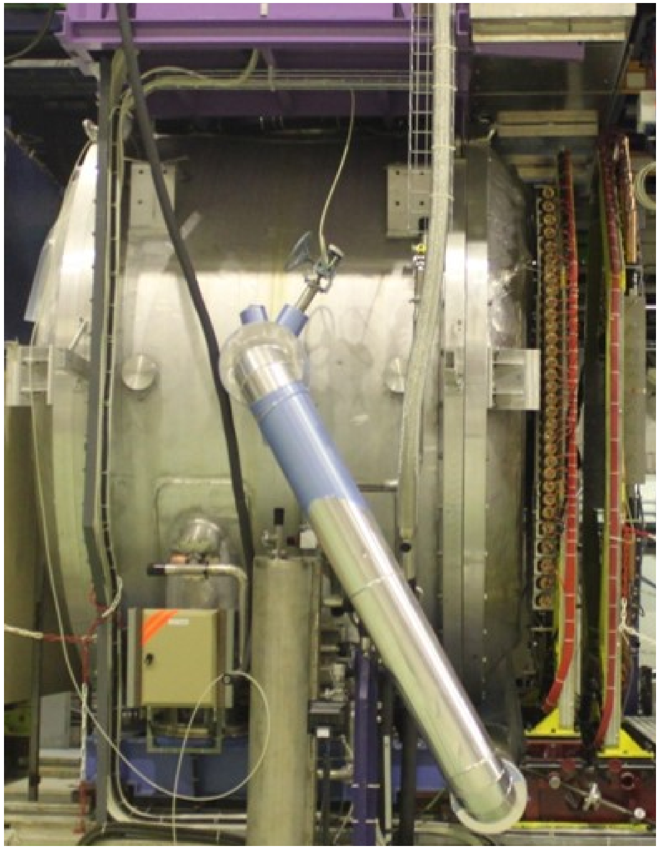
Middle Angle Veto – EM Calorimeter



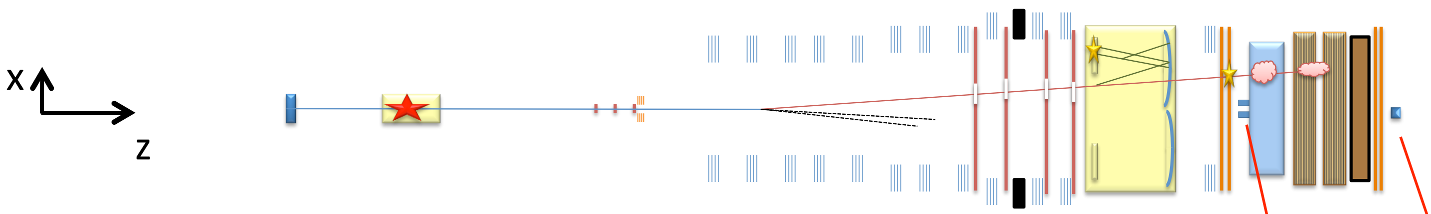
- 9000 litres of liquid krypton
  - T = 120 K
  - 13,248 readout cells

- 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

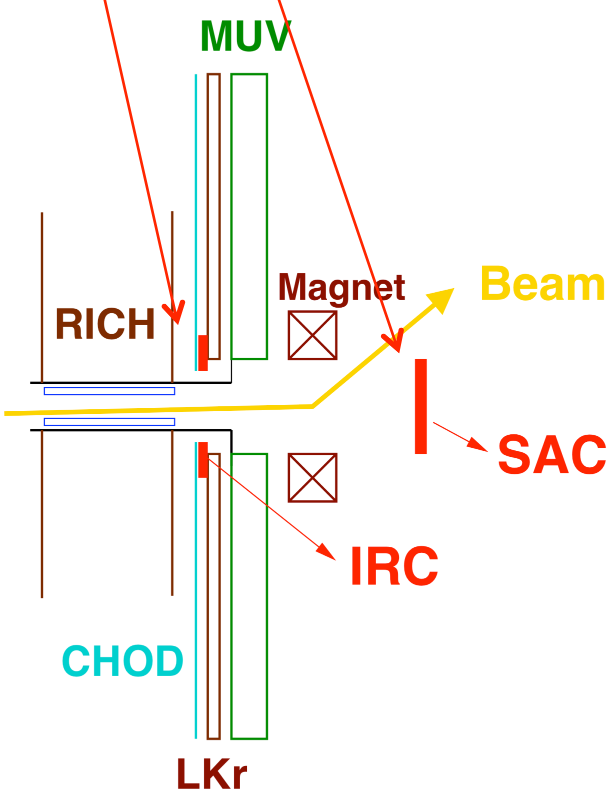
- <1% Resolution @ 20 GeV
  - $27X_0$



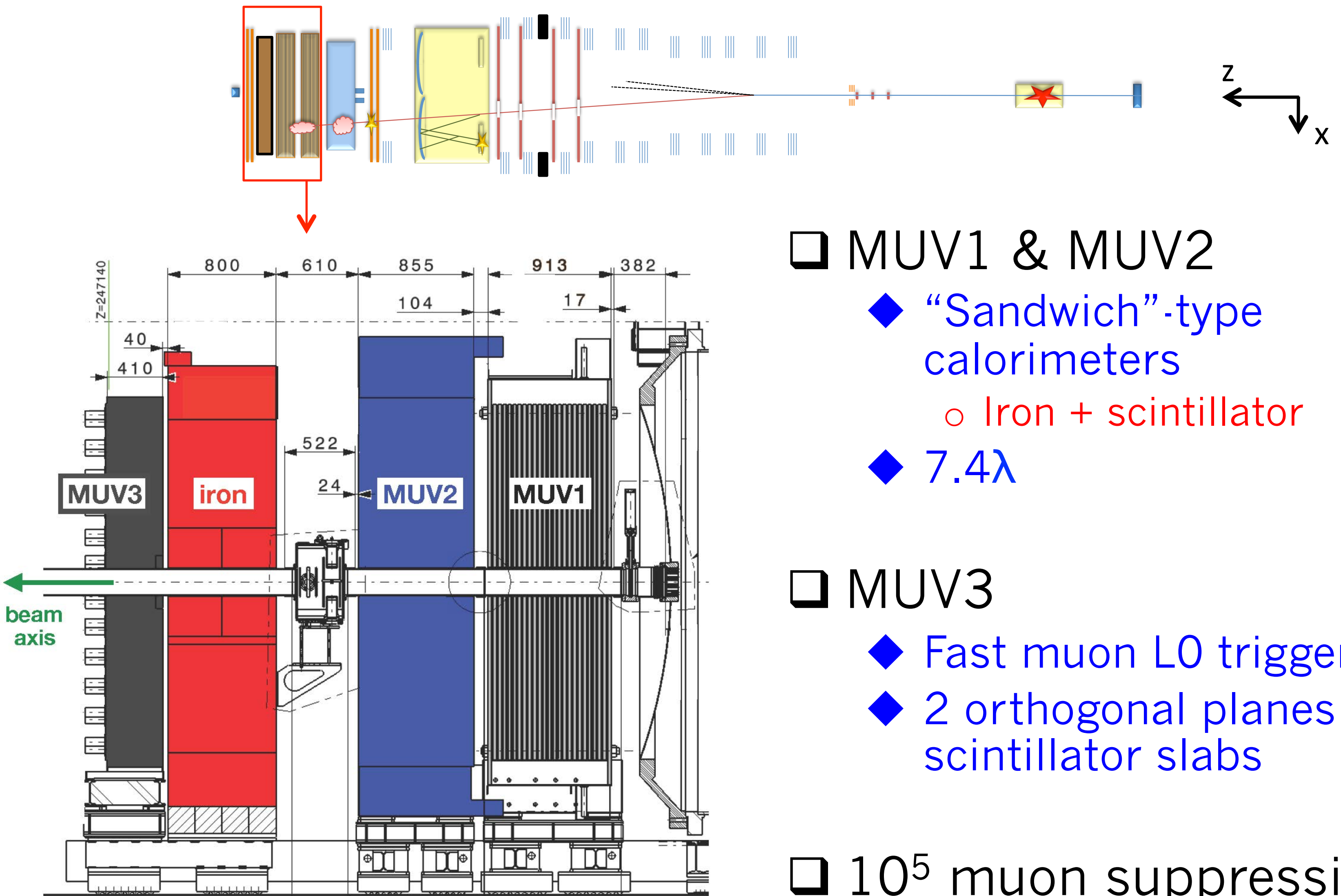
Small Angle Photon Vetos: IRC & SAC



- **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



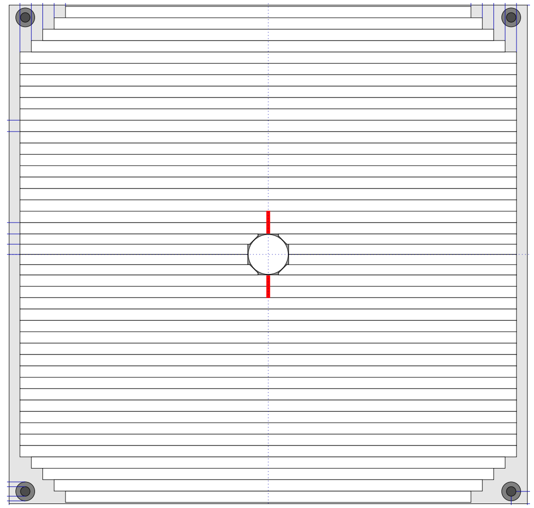
Particle Identification – Muon Veto

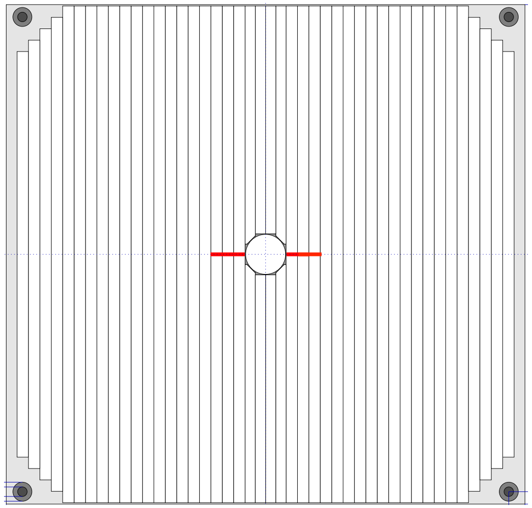


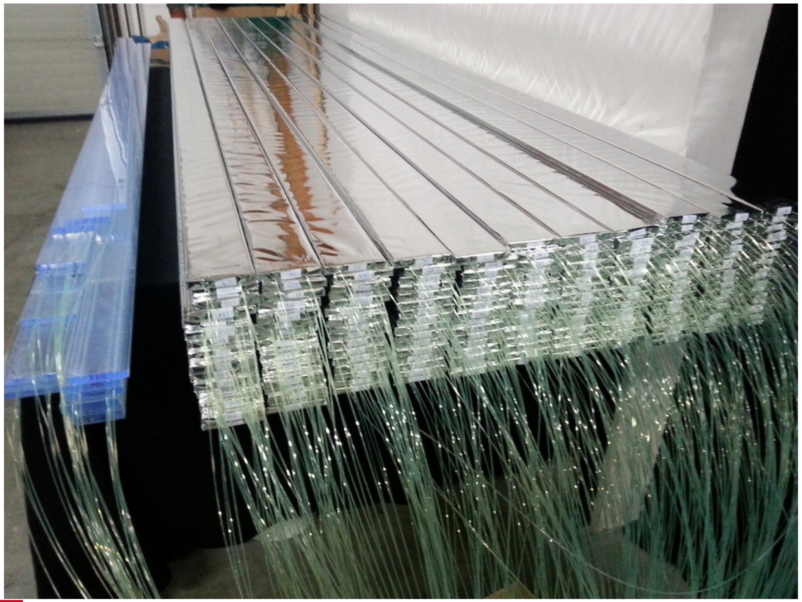
- MUV1 & MUV2
  - "Sandwich"-type calorimeters
    - Iron + scintillator
  - 7.4λ
- MUV3
  - Fast muon L0 trigger
  - 2 orthogonal planes of scintillator slabs
- 10^5 muon suppression factor

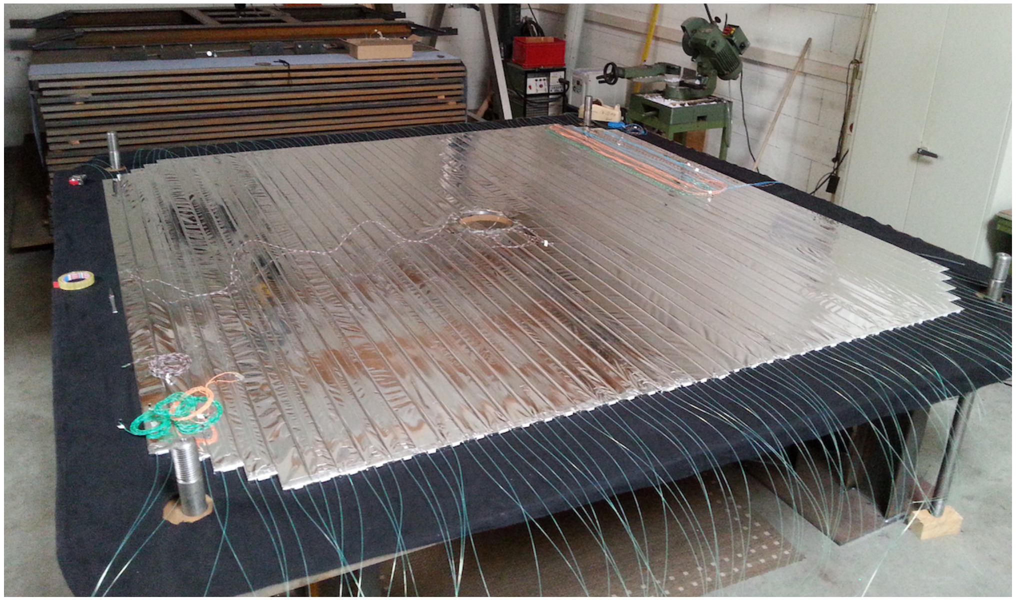
MUV1 Construction Work in Mainz

- 12 horizontal and 11 vertical layers of scintillator strips with WLS optical fibers
  - 1218 strips in total





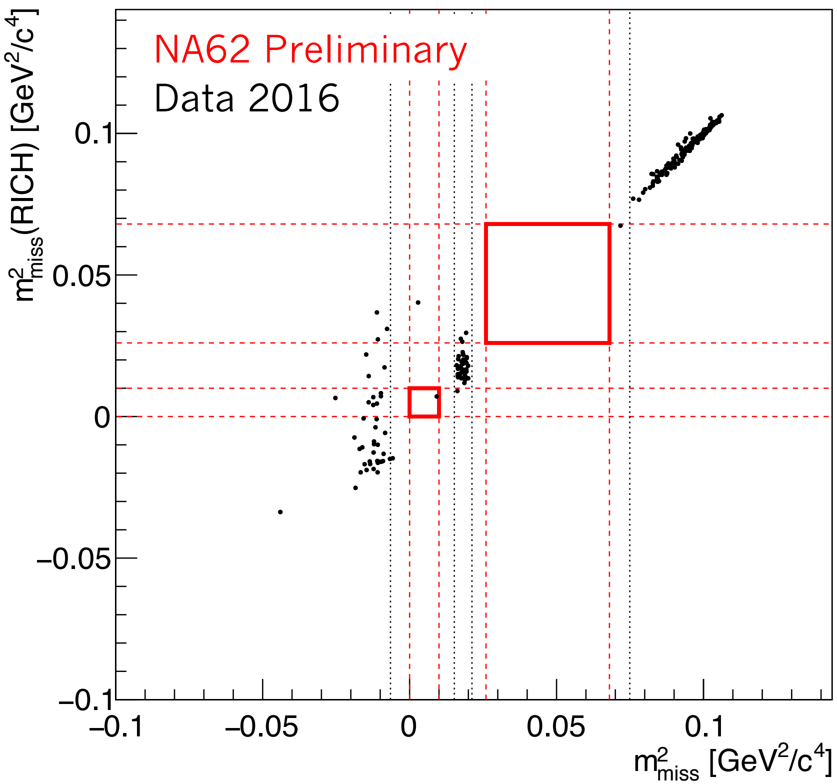




MUV1 Construction Work in Mainz

$K^+ \to \pi^+ \nu \bar{\nu}$ Analysis in Data 2016

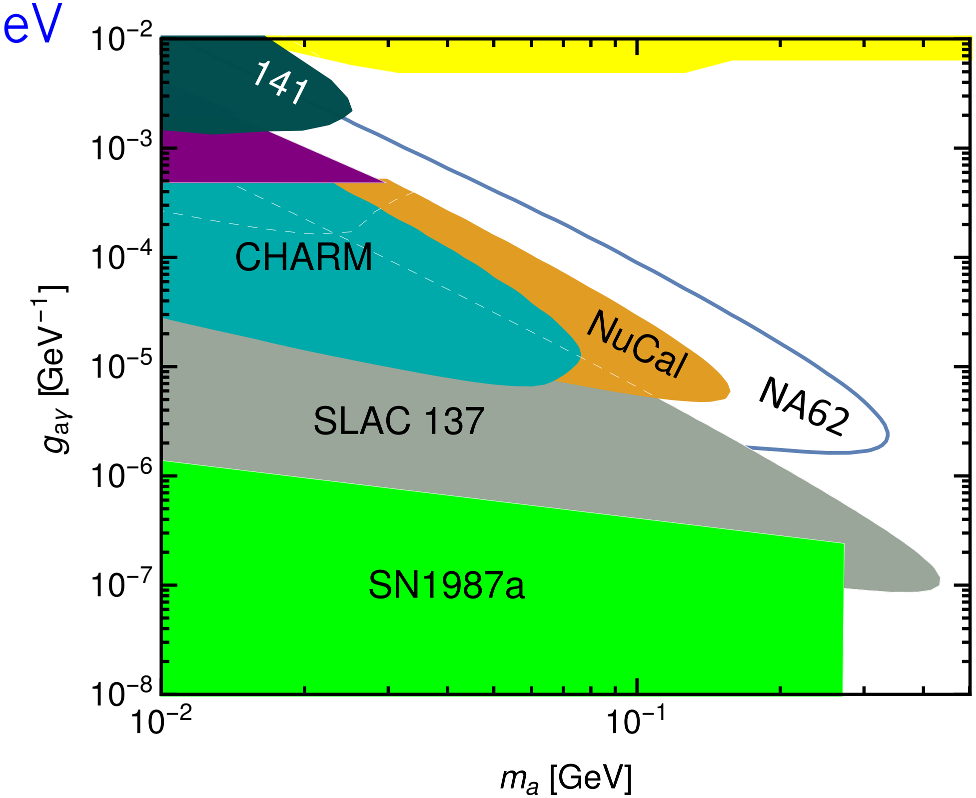
- After particle ID and photon veto cuts
  - 2.3×10 K⁺ decays (5% of 2016 data) used



- Expected signal: 0.064, expected background: 0.057, observed: 0 events
  - (The event in the box fails m^2_{miss}(w/o GTK) cut)
  - Signal acceptance: 3.3%
    - Will be improved
- The SM sensitivity, BR<10^{-9}, expected to be reached using the ~full 2016 data
- Expected **~15** signal events in 2017 data

NP Searches in Dump Mode: ALP

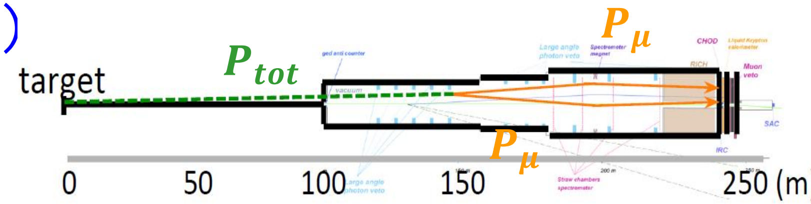
- ~1 day NA62 data from running in dump mode already sensitive to ALPs (created in photon fussion) at 90% CL
  - Large proton energy, 400 GeV
  - Long decay volume, 65 m
  - Assume 0 background
    - Rather realistic

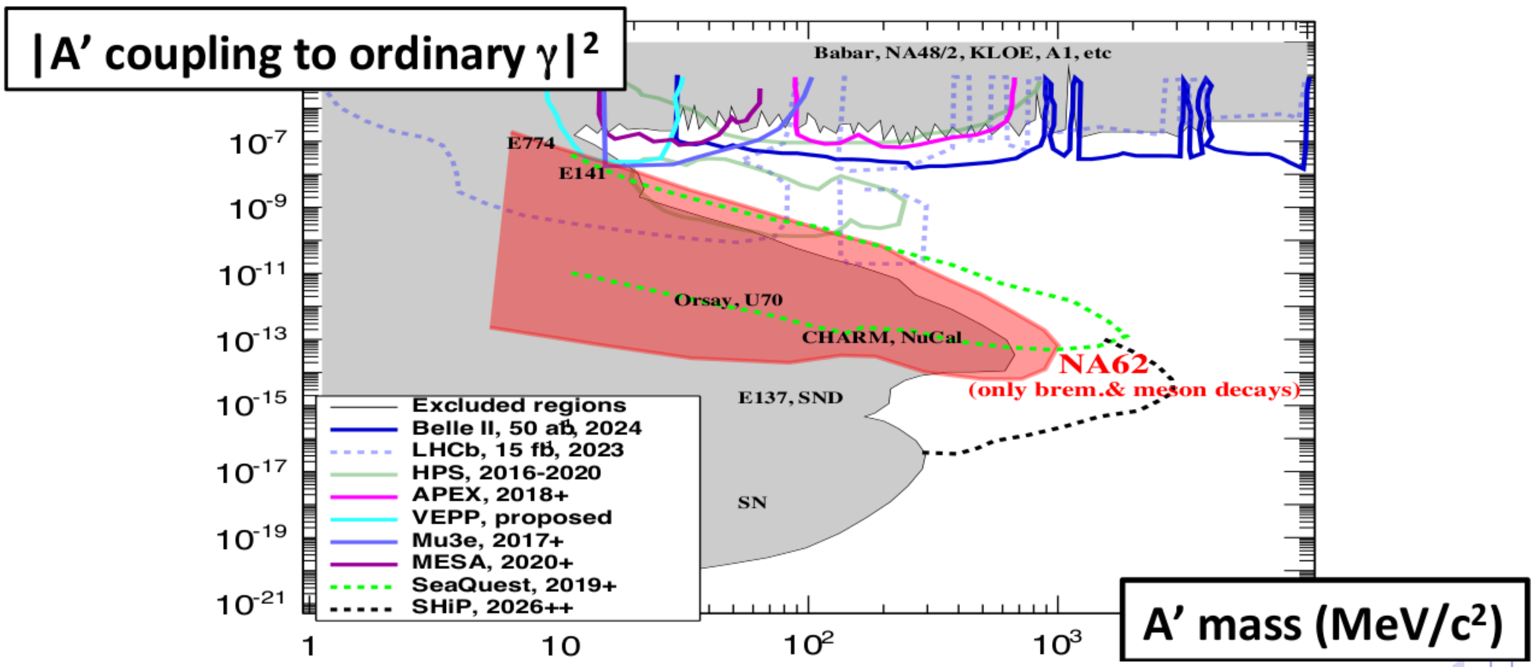


- Dependence of the projected limits on
  - Production differential cross section of ALPs and lifetime
  - Acceptance photons in the LKr electromagnetic calorimeter

NP Searches in Dump Mode: A'

- Search for displaced di-lepton decays: $A' \rightarrow e^+e^-$, $A' \rightarrow \mu^+\mu^-$
  - 2×10^{18} protons on target (~2 years)
  - Limits at 90% CL, 0 background
    - Production only in target, no TAXes





- Higher sensitivity is expected considering direct QCD production of A' and dump on TAXes

NP Searches in Dump Mode: HNL

- Search for visible decays of long-lived HNL → πe, πμ
  - Limits depend on the relation of HNL couplings with the SM leptons, $U_e:U_\mu:U_\tau$
  - 2×10^{18} protons on target (~2 years)
  - Limits at 90% CL, 0 background