Testing CKM Unitarity with the NA62 Experiment

Victor Shang (TRIUMF)

Testing the Standard Model in Charged-Weak Decays (INT-26-95W)

Seattle, WA, January 15, 2026

1^{st}-row CKM Unitarity

Unitarity condition for 1^{st}-row of CKM Matrix:

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1$$

~ 0.949 ~ 0.05 $\sim 2 \times 10^{-5}$

$$\Delta_{\mathrm{CKM}} \cong |V_{ud}|^2 + |V_{us}|^2 - 1$$

- V_{ub} : measured from B meson decays ($B \to X_u \ell \bar{v}$, $B \to \pi \ell \bar{v}$), can ignore
- V_{ud} : most precise determination from super-allowed nuclear β decays

$$|V_{ud}| = 0.97367(11)_{\mathrm{exp}}(13)_{\mathrm{Rad.Cor.}}(27)_{\mathrm{Nucl.}}$$

- **Focus on determination of V_{us} and V_{us} / V_{ud} from kaon decays**

V_{us} from $K_{\ell 3}$ decays

$$\Gamma(K_{\ell 3}) = |V_{us}|^2 \frac{C_K^2 G_f^2 m_K^5}{192\pi^3} S_{\text{EW}} |f_+^{K^0\pi^-}|^2 I_{K\ell}(\lambda_{K\ell}) \left(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{\text{EM}}\right)$$

where $K \in [K^+, K^0]$, $\ell \in [e, \mu]$, $C_K^2 = \begin{cases} \frac{1}{2} \text{ for } K^+ \\ 1 \text{ for } K^0 \end{cases}$

$S_{\text{EW}} = 1.0232$: universal Short-Distance EW Correction

Experiment:

- **$\Gamma(K_{\ell 3})$:** branching ratios for K_S, K_L, $K^{\pm}$, and kaon lifetimes
- **$I_{K\ell}(\lambda_{K\ell})$:** integral of form factor over phase space
  - K_{e3} : Only λ_+ (or λ_+', λ_+'')
  - $K_{\mu 3}$: need λ_+ and λ_0

Theory:

- **$f_+^{K^0\pi^-}$:** hadronic matrix element (form factor) at zero momentum transfer (t=0)
- **$\Delta_K^{SU(2)}$:** Form factor correction for SU(2) breaking
- **$\Delta_{K\ell}^{EM}$:** Form factor correction for Long-Distance EM effects

V_{us} / V_{ud} from $K_{\mu 2}$ and $K_{\pi 2}$ decays

$$\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi} = \left(\frac{\Gamma_{K_{\mu 2(\gamma)}} m_{\pi^\pm}}{\Gamma_{\pi 2(\gamma)} m_{K^\pm}}\right)^{1/2} \frac{1 - m_\mu^2/m_{\pi^\pm}^2}{1 - m_\mu^2/m_{K^\pm}^2}\left(1 - \frac{1}{2}\delta_{\mathrm{EM}} - \frac{1}{2}\delta_{SU(2)}\right)$$

Experiment:

- $\Gamma_{K_{\mu 2(\gamma)}}$: branching ratio Br($K_{\mu 2}$) and lifetime $\tau_{K^\pm}$ from fit to $K^\pm$ decays
- $\Gamma_{\pi 2(\gamma)}$: : branching ratio Br($\pi_{\mu 2}$) and lifetime $\tau_{\pi^\pm}$ from PDG

Theory:

- f_K/f_π: ratio of decay constants
- δ_{EM}: long-distance EM corrections
- $\delta_{SU(2)}$: strong isospin breaking $f_K/f_\pi \to f_{K^\pm}/f_{\pi^\pm}$

$$\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi} = 0.27679(28)_{\mathrm{Br}}(20)_{\mathrm{corr}}$$

See: Boyle et al. (JHEP 2023)

Status of 1st-row CKM Unitarity

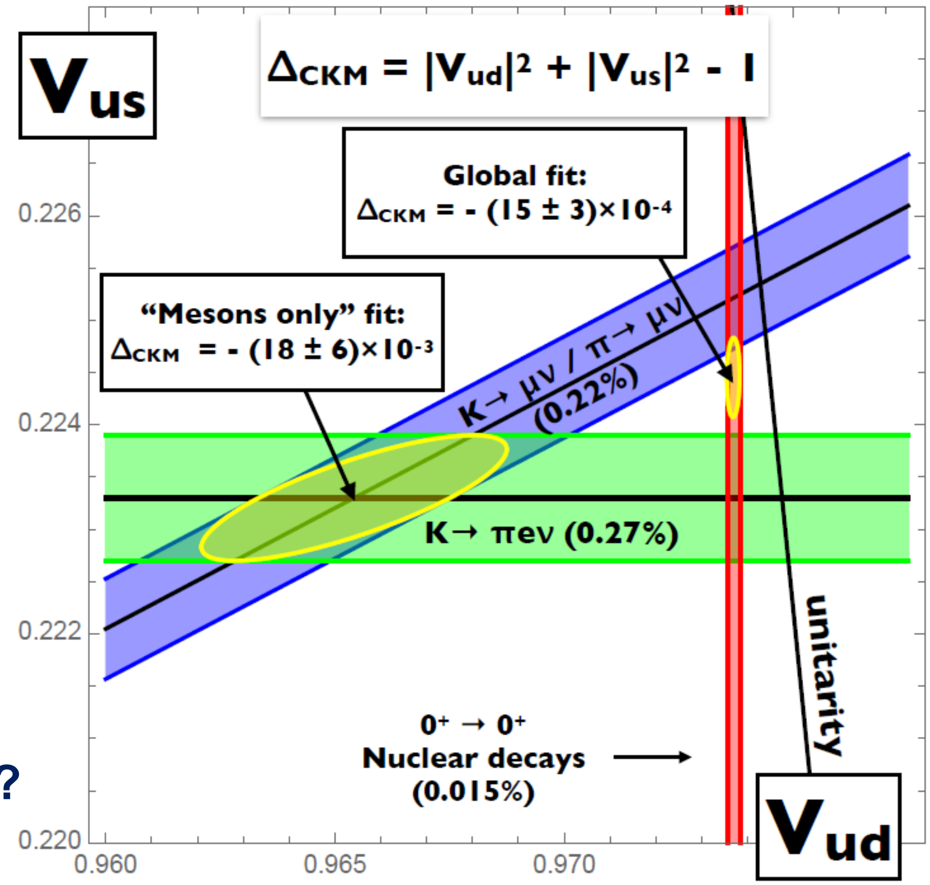
$$\Delta_{\text{CKM}} \cong |V_{ud}|^2 + |V_{us}|^2 - 1$$

	Value	% Error
V_{ud}	0.97373 ± 0.00031	0.032
$V_{us}(K_{\ell 3})$	0.2231 ± 0.0007	0.31
$V_{us}(K_{\mu 2})$	0.2252 ± 0.0005	0.22

Existing tensions:

- 3σ deficit in global fit for 1st row CKM unitary: **Cabibbo angle anomaly**
- 2.6σ discrepancy in $|V_{us}|$ from average of $K_{\ell 3}$ (ℓ = e, μ) modes vs $K_{\mu 2}$ mode

Need for additional experimental data?



Impact of New Measurements

Cirigliano, Crivellin, Hoferichter, Moulson (Phys.Lett.B 2023)

	current fit	$K_{\mu 3}/K_{\mu 2}$ BR at 0.5%		
		central	$+2\sigma$	-2σ
$\Delta^{(1)}_{\text{CKM}}$	$-0.00176(56)$	$-0.00173(55)$	$-0.00162(56)$	$-0.00185(56)$
	-3.1σ	-3.1σ	-2.9σ	-3.3σ
$\Delta^{(2)}_{\text{CKM}}$	$-0.00098(58)$	$-0.00098(58)$	$-0.00108(58)$	$-0.00087(58)$
	-1.7σ	-1.7σ	-1.9σ	-1.5σ
$\Delta^{(3)}_{\text{CKM}}$	$-0.0164(63)$	$-0.0157(60)$	$-0.0118(62)$	$-0.0202(63)$
	-2.6σ	-2.6σ	-1.9σ	-3.2σ

- Measurement of Br($K_{\mu 3}$) / Br($K_{\mu 2}$) could help resolve or confirm discrepancy in $K_{\ell 3}$ vs $K_{\mu 2}$ modes
- Additional measurement of V_{us} / V_{ud} and V_{us} by NA62 could impact 1st-row CKM unitarity test

$$\Delta^{(1)}_{\text{CKM}} = \left|V^{\beta}_{ud}\right|^2 + \left|V^{K_{\ell 3}}_{us}\right|^2 - 1,$$

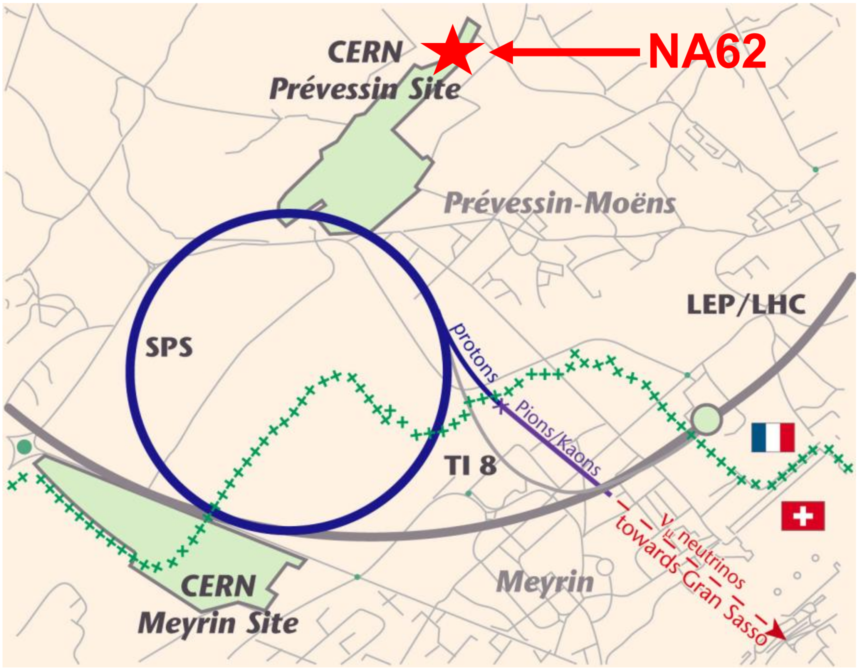
$$\Delta^{(2)}_{\text{CKM}} = \left|V^{\beta}_{ud}\right|^2 + \left|V^{K_{\ell 2}/\pi_{\ell 2},\beta}_{us}\right|^2 - 1,$$

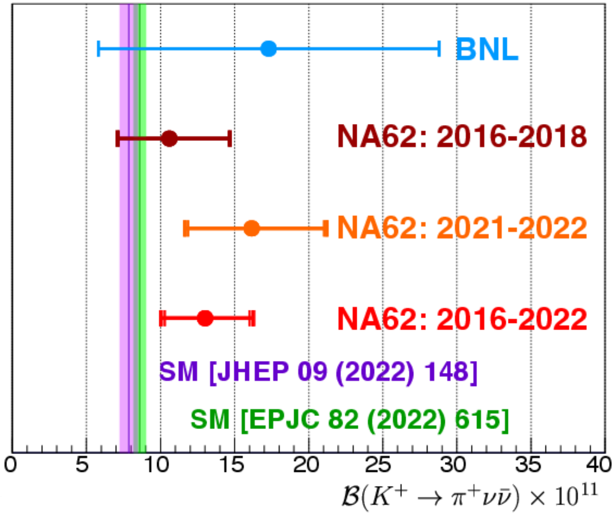
$$\Delta^{(3)}_{\text{CKM}} = \left|V^{K_{\ell 2}/\pi_{\ell 2},\,K_{\ell 3}}_{ud}\right|^2 + \left|V^{K_{\ell 3}}_{us}\right|^2 - 1,$$

The NA62 Experiment

Fixed target kaon decay experiment located at the CERN Prévessin site

- 400 GeV/c proton beam from Super Proton Synchotron (SPS) directed at beryllium target
- Produces secondary 75 GeV/c kaon beam (70% π^+, 23% p, **6% K⁺**)
- Primary goal: to measure rare decay **$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$**
  *JHEP 02 (2025) 191

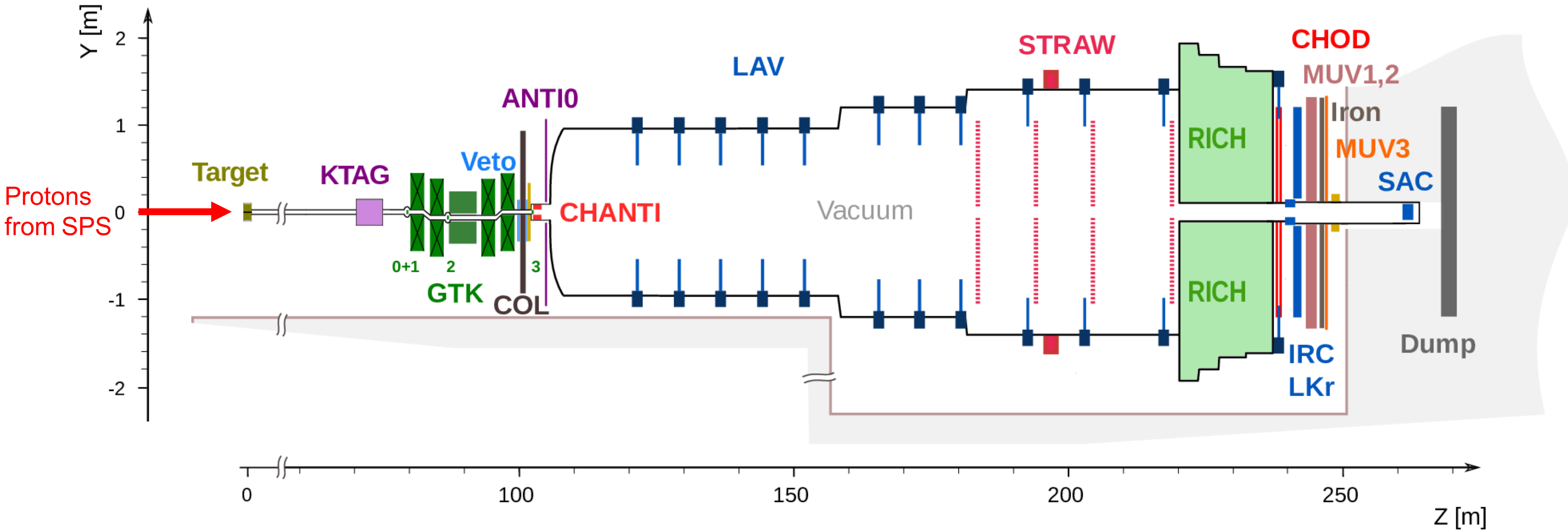




Broader physics program:

- Rare and forbidden K⁺ decays, hidden sectors, exotics
- **Precision Measurements** $(K^+ \to \mu^+ \nu,\ K^+ \to \pi^0 \mu^+ \nu,\ K^+ \to \pi^+ \pi^0)$

The NA62 Detector



Comprehensive system for measuring kaon decays:

- Particle tracking: GTK, STRAW
- Calorimeters: LKr, MUV1, MUV2
- Particle identification: KTAG, MUV3, RICH
- Trigger and Veto systems: CHOD, CHANTI, ANTI-0, SAC, IRC, LAV

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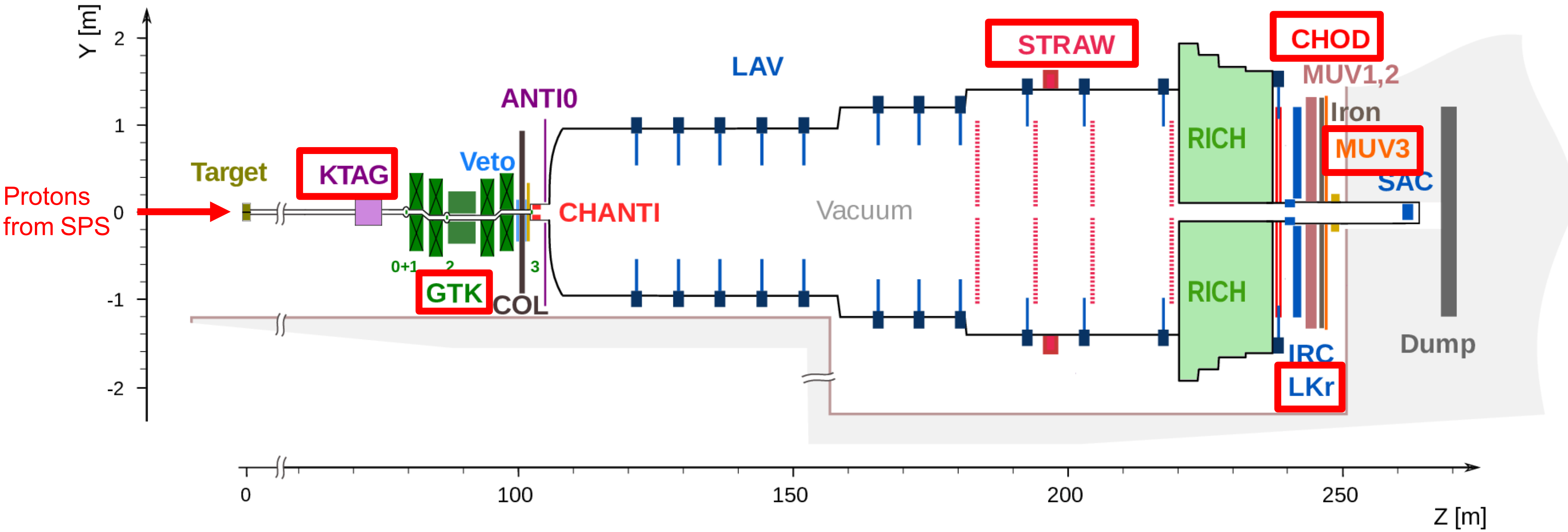

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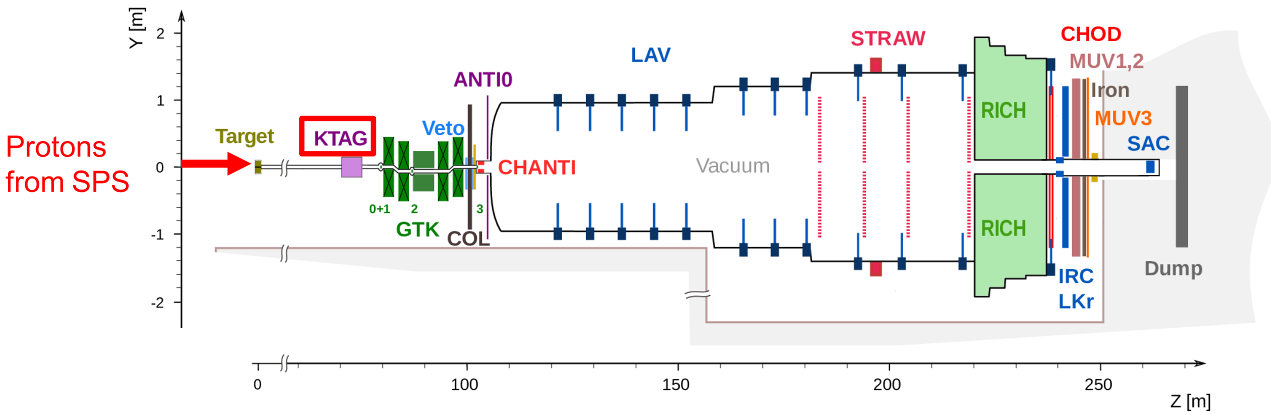
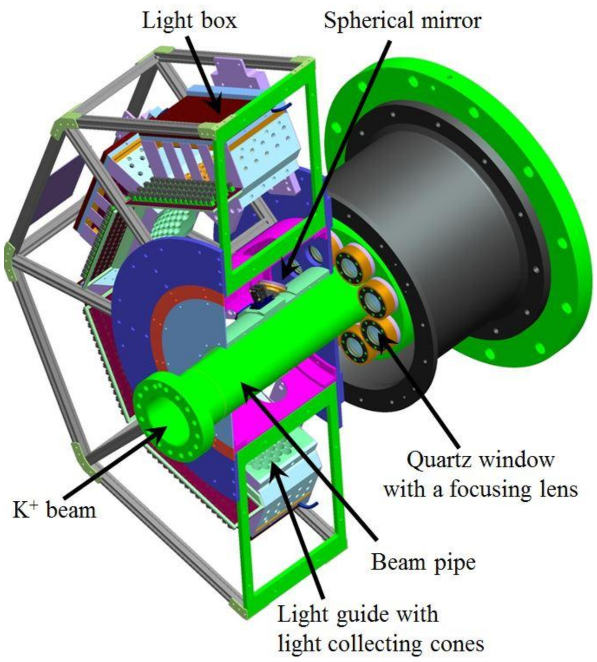


Kaon tagger (KTAG):

- Differential Cherenkov counter for tagging beam kaons
- 70 ps timing resolution
- >95% kaon tagging efficiency, pion misidentification rate $O(10^{-4})$



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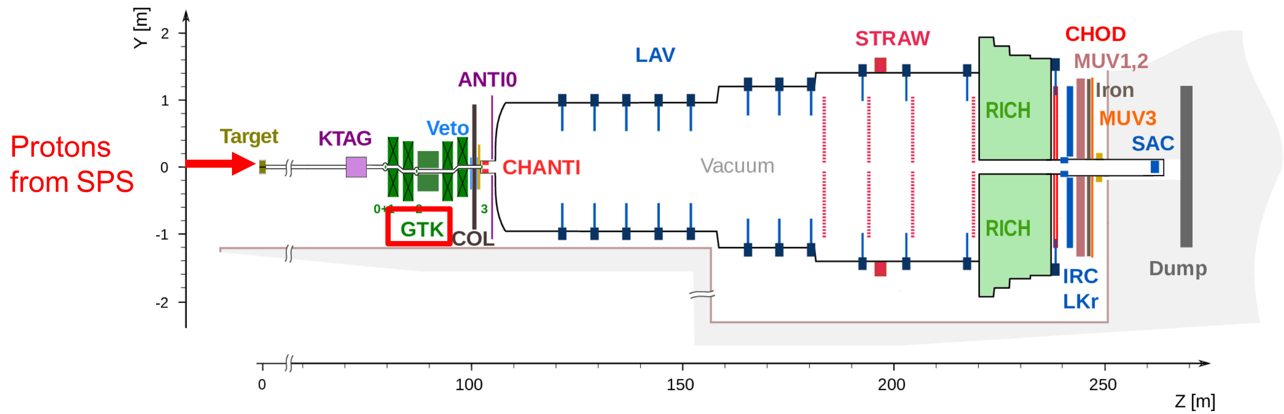
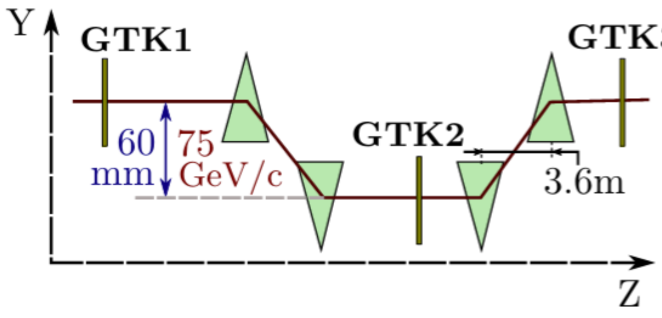
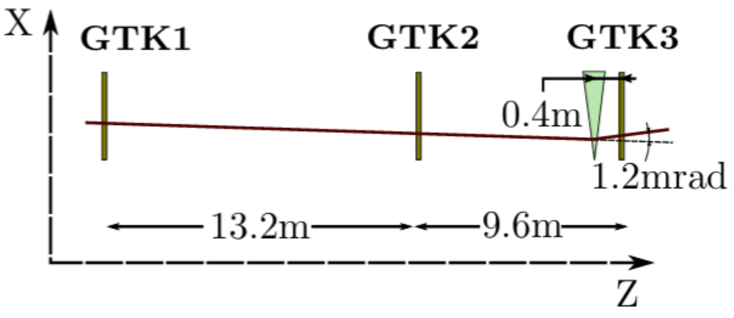


Gigatracker (GTK):

- Silicon hybrid pixel beam spectrometer for measuring beam momentum
- Needed for computing missing mass squared $m_{\mathrm{miss}}^2 = (p_{K^+} - p_{\mathrm{track}})^2$
- 100 ps time resolution, 0.15 GeV/c momentum resolution





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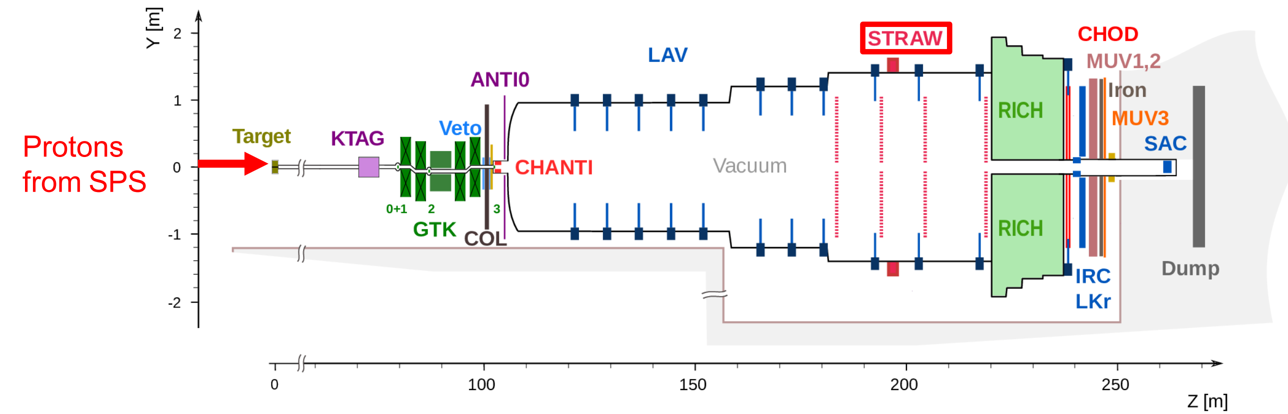
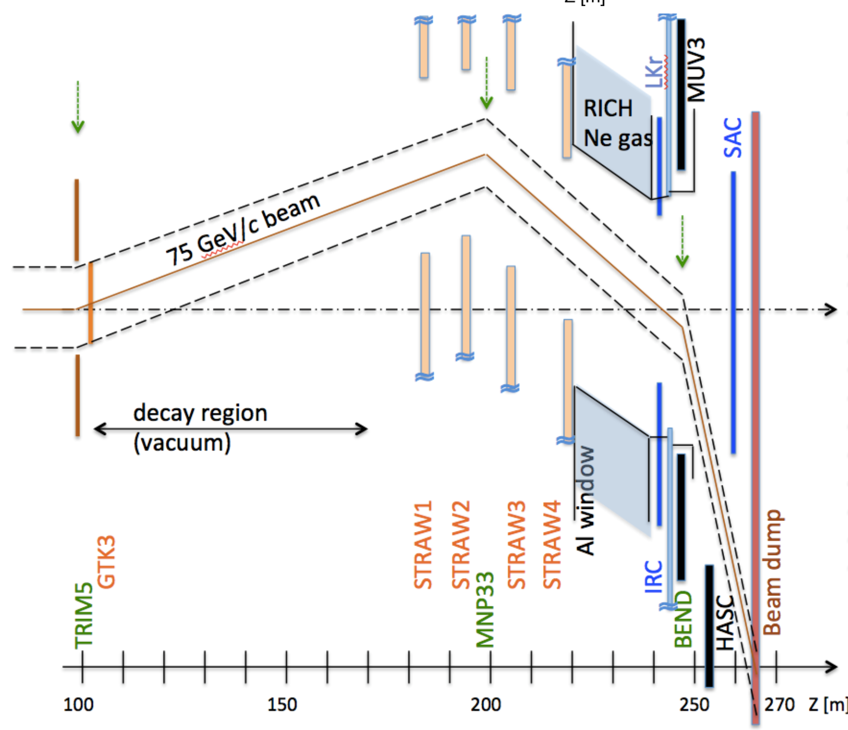
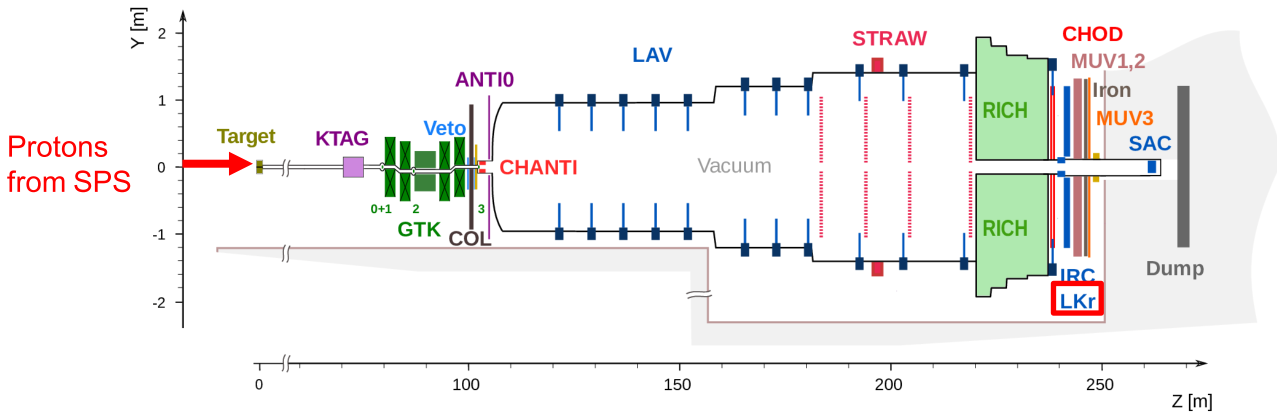


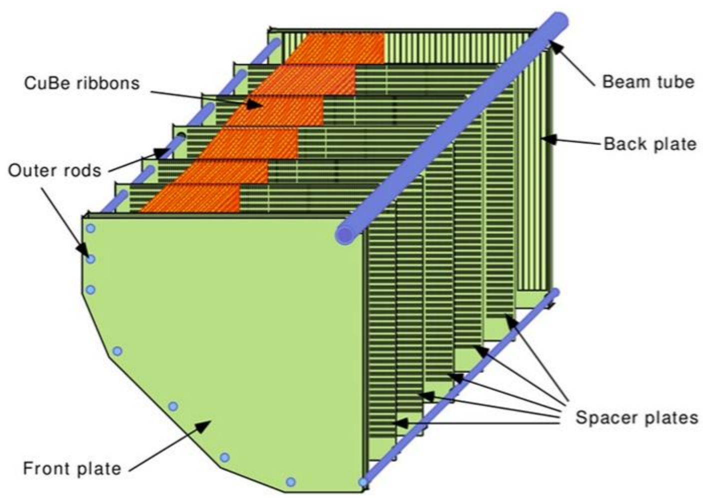
Straw Tracker:

- Four chambers in {x, y, u, v} planes, two both upstream and downstream of dipole magnet (MNP33)
- Measures momentum of charged particles (K^+, π^+, μ^+)
- 130 μm spatial resolution
- $\sigma_p/p = (0.30 \oplus 0.005 \cdot p)\%$



The NA62 Detector

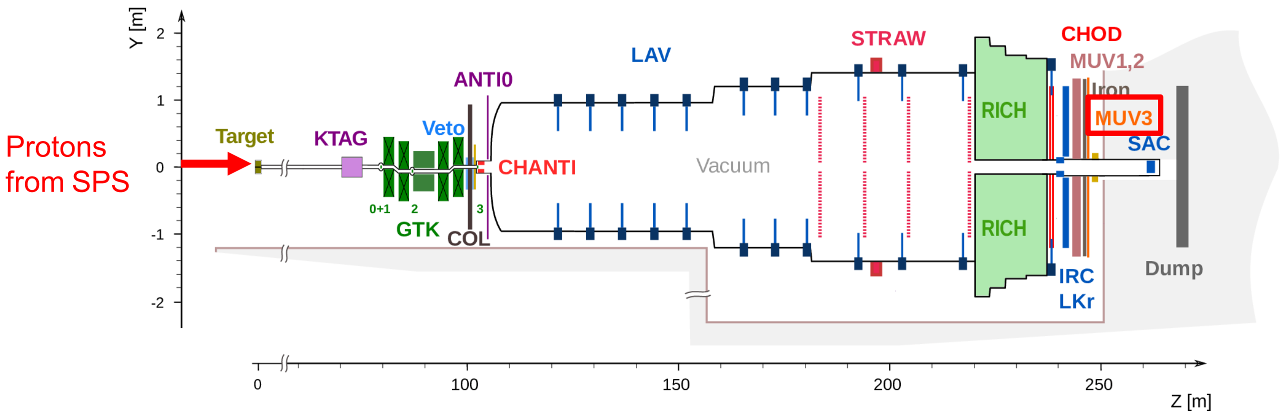




Liquid Krypton Calorimeter (LKr):

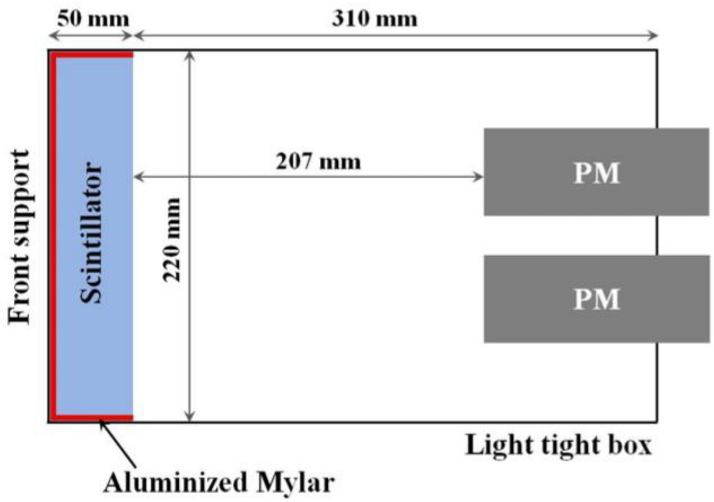
- Measures energy, position and timing of photons → infer presence of π^0
- 1 mm spatial resolution, 0.5 – 1 ns time resolution
- $\sigma_E/\mathrm{E} = (4.8/\sqrt{E} \oplus 11/\mathrm{E} \oplus 0.9)\%$

The NA62 Detector



Muon Veto Station (MUV3):

- muon tagger (hit in-time with STRAW track)
- >99% muon detection efficiency
- Misidentification rate O(<10^{-5})
- ~500 ps time resolution



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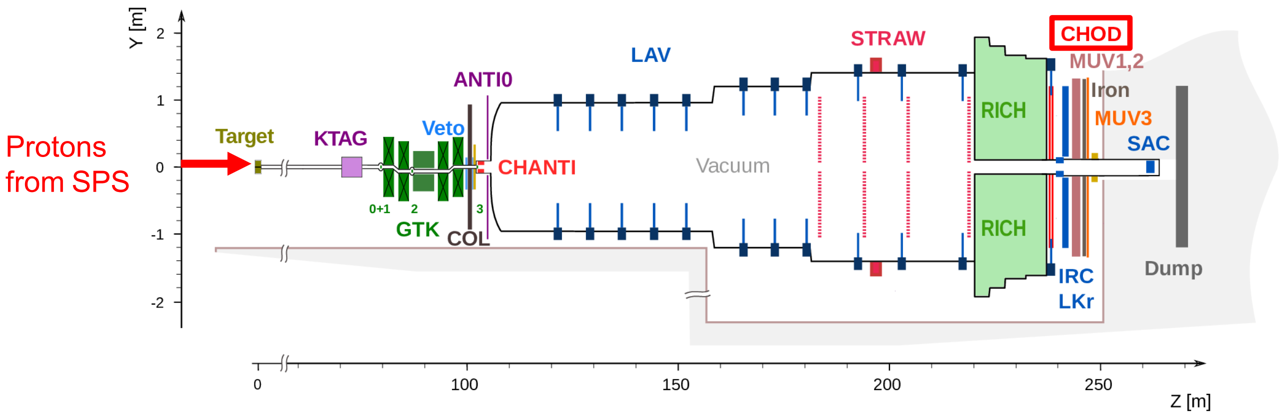
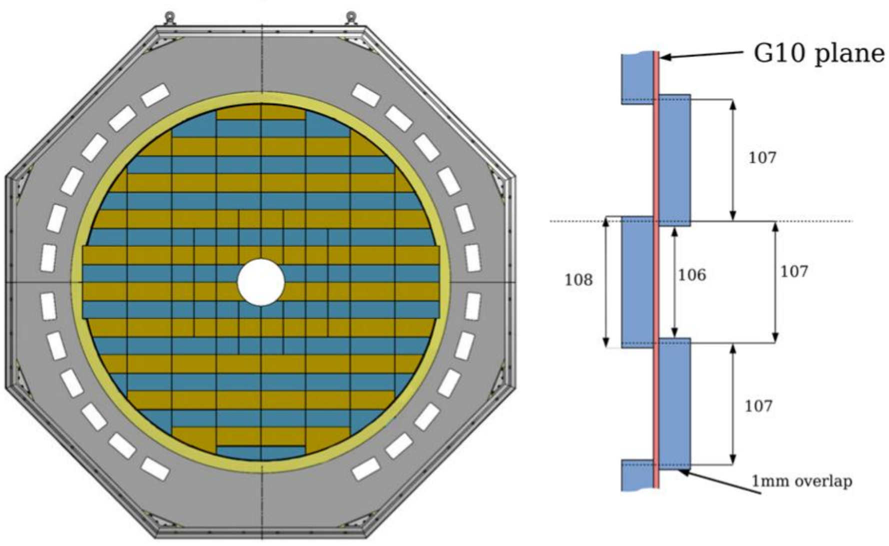




Charged hodoscopes (CHOD):

- Two scintillator hodoscopes: matrix of tiles (CHOD) and two planes of slabs (NA48-CHOD)
- 1 ns (CHOD) and 200 ps (NA48-CHOD) time resolution
- Acts as L0 trigger

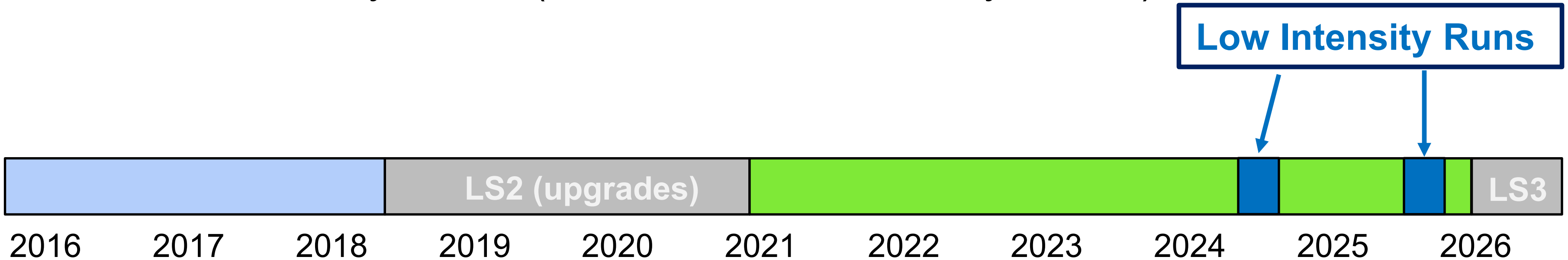
Data Set

Normal data taking conditions at ~750 MHz hadron beam, ~4.5 MHz of kaon decays in fiducial region

- Required for reaching O(10^{13}) total kaon decays for Br($K^+ \to \pi^+ \nu\bar{\nu}$)
- Large amount of overlapping events (pileup) → more difficult to properly simulate detector effects (i.e. worse Data/MC agreement)

Take dedicated low intensity runs at ~1% nominal intensity instead:

- Use **minimum bias trigger** (CHOD + STRAW) for measurement, **control trigger** (NA48-CHOD + STRAW) for systematic + efficiency studies
- Stable conditions, low overlap → better handle on systematic uncertainties (i.e. better Data/MC agreement)
- One week of data taking in 2024 and 2025 sufficient to ensure uncertainties are not statistically limited (<0.1% for main K^+ decay modes)



Measuring V_{us} / V_{ud}

Use NA62 to measure ratio of $\Gamma(K^+ \rightarrow \mu^+ \nu)$ to $\Gamma(\pi^+ \rightarrow \mu^+ \nu)$:

- $\Gamma(\pi^+ \rightarrow \mu^+ \nu)$ determined from $K^+ \rightarrow \pi^+ \pi^0$ muon DIF decays
- Determine relative yields from maximum likelihood fit of shape templates from Monte Carlo (MC) simulation to **missing mass squared distributions** $(m^2_{K^+ - \mu^+})$
- Multi−bin shape template fit for $K^+ \rightarrow \pi^+ \pi^0$ to separate from $K^+ \rightarrow \pi^0 \mu^+ \nu$ background, single bin fit (i.e. counting experiment) for $K^+ \rightarrow \mu^+ \nu$
- Use this ratio to extract **$|V_{us}|$ / $|V_{ud}|$:**

$$\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi} = \left(\frac{\Gamma_{K_{\mu 2(\gamma)}} m_{\pi^\pm}}{\Gamma_{\pi 2(\gamma)} m_{K^\pm}}\right)^{1/2} \frac{1 - m_\mu^2/m_{\pi^\pm}^2}{1 - m_\mu^2/m_{K^\pm}^2}\left(1 - \frac{1}{2}\delta_{\mathrm{EM}} - \frac{1}{2}\delta_{SU(2)}\right)$$

- Big advantage: first-order cancellation of shared systematic effects
- Aim is ≤0.5% precision (limited by ~0.4% uncertainty on Br($K_{\pi 2}$))

Measuring V_{us} / V_{ud}

1) $\Gamma(K^+ \to \mu^+ v) = \frac{Br(K^+ \to \mu^+ v)}{\tau_{K^+}} = \frac{1}{\tau_{K^+}} \frac{N_\mu^{K\mu 2}}{N_K a_\mu^{K\mu 2}}$

2) $\Gamma(\pi^+ \to \mu^+ v) = \frac{Br(\pi^+ \to \mu^+ v)}{\tau_{\pi^+}} = \frac{1}{\tau_{\pi^+}} \frac{N_{\mu-\pi^0}^{\pi\mu 2}}{N_K Br(K^+ \to \pi^+ \pi^0) a_{\pi^+ \to X}^{K\pi 2} a_{\mu-\pi^0}^{\pi\mu 2}}$

$$R_A^{K\mu 2} = \frac{\Gamma(K^+ \to \mu^+ v)}{\Gamma(\pi^+ \to \mu^+ v)} = \frac{Br(\pi^+ \to \mu^+ v)\tau_{\pi^+}}{\tau_{K^+}} \frac{N_\mu^{K\mu 2}}{N_{\mu-\pi^0}^{\pi\mu 2}} \frac{a_{\pi^+ \to X}^{K\pi 2} a_{\mu-\pi^0}^{\pi\mu 2}}{a_\mu^{K\mu 2}}$$

$N_\mu^{K\mu 2}$ = number of tagged muons from $K^+ \to \mu^+ v$

$N_{\mu-\pi^0}^{\pi\mu 2}$ = number of tagged muon-pi0 from $K^+ \to \pi^+ \pi^0 \to \pi^+ \to \mu^+ v$

$a_\mu^{K\mu 2}$ = acceptance for $K_{\mu 2}$ muons

$a_{\mu-\pi^0}^{\pi\mu 2}$ = combined acceptance for muon-pi0 from $K_{\pi 2}$ pi0 and $\pi_{\mu 2}$ DIF muon

$a_{\pi^+ \to X}^{K\pi 2}$ = acceptance for π^+ decay from $K_{\pi 2}$ decays

Obtain from Data

Obtain from MC

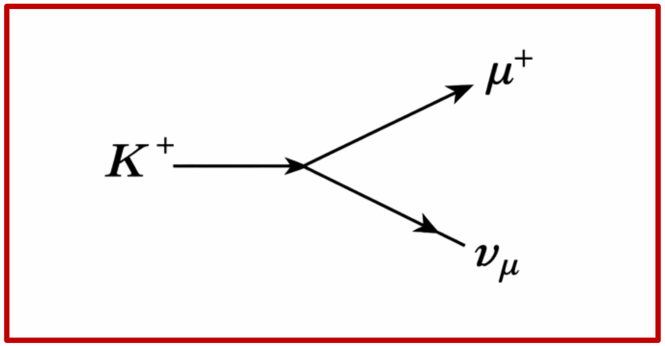
Signal Selections

Two signal regions (SRs) separately defined for both based on $\boldsymbol{n_{\pi^0}}$ and missing mass squared (MMS) selections **($m^2_{K^+-\mu^+}$, $m^2_{K^+-\pi^0}$)**:

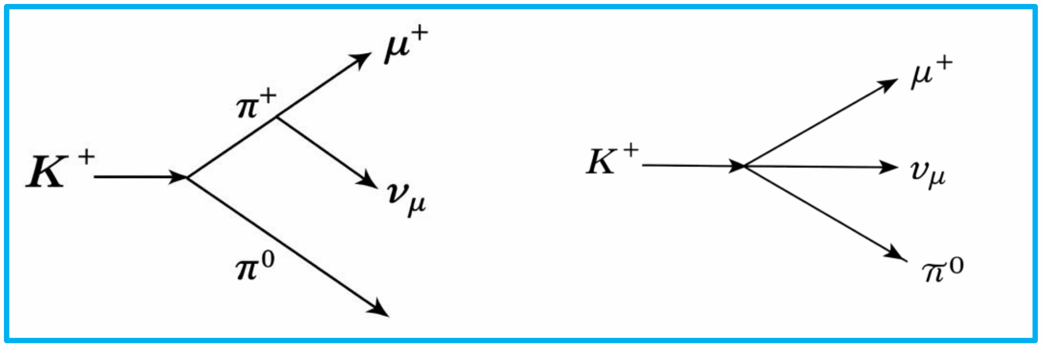
- Presence of π^0 determined from photon candidates in **LKr**
- Muon candidate determined from **STRAW track** matched to hit in **MUV3**
- Kaon decay determined from presence of **KTAG candidate** and kaon candidate in **GTK** matched to **STRAW track**
- Additional selections to reduce remaining background (track momentum, ratio of LKr energy to track momentum)

Goal is to keep selections simple, **minimize systematic effects** from selections

$\boldsymbol{n_{\pi^0} = 0}$

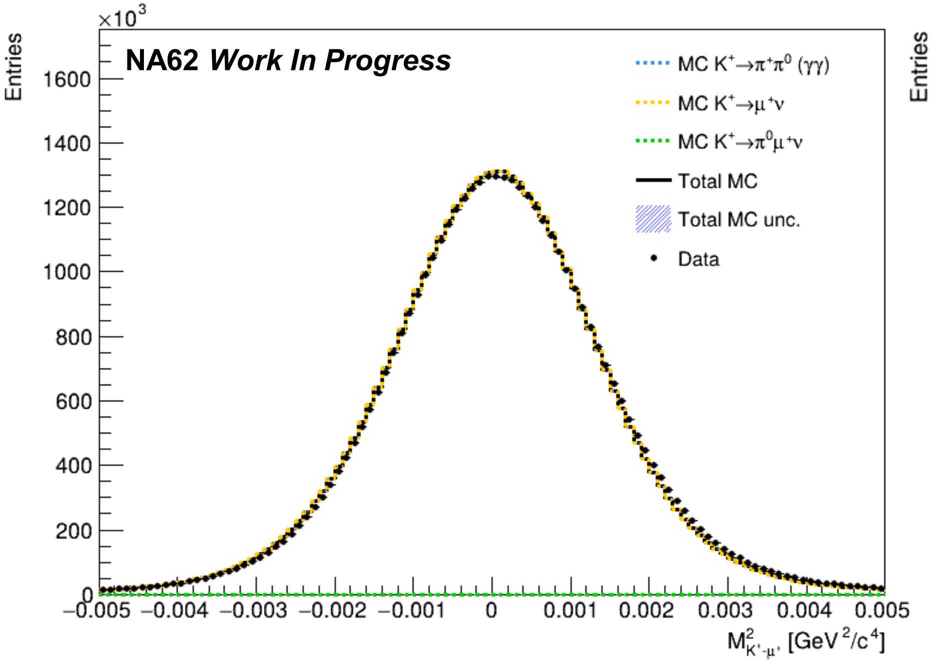


$\boldsymbol{n_{\pi^0} = 1}$

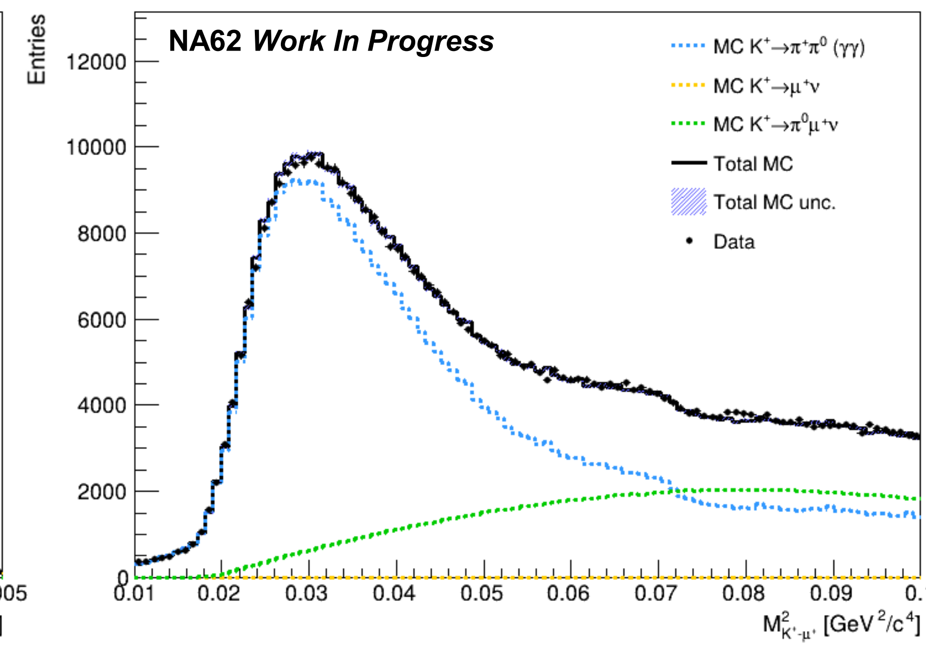


Signal Regions

Km2 SR ($K^+ \rightarrow \mu^+ \nu$)



K2pi SR ($K^+ \rightarrow \pi^+ \pi^0$)



Process	MC Acceptance ($n_{\pi^0} = 0$)	MC Acceptance ($n_{\pi^0} = 1$)
Km2	$0.42 \pm 7.6\times10^{-4}$	0.0 ± 0.0
K2pi	$5.7\times10^{-5} \pm 1.0\times10^{-6}$	$1.1\times10^{-2} \pm 1.0\times10^{-5}$
Km3	$6.0\times10^{-6} \pm 1.0\times10^{-7}$	$2.6\times10^{-2} \pm 1.7\times10^{-5}$

Data shown for **single run** in 2024 (out of 25 total), rest of data set blinded

Systematic Uncertainties

Implement systematic effects on yield through nuisance parameters in fit:

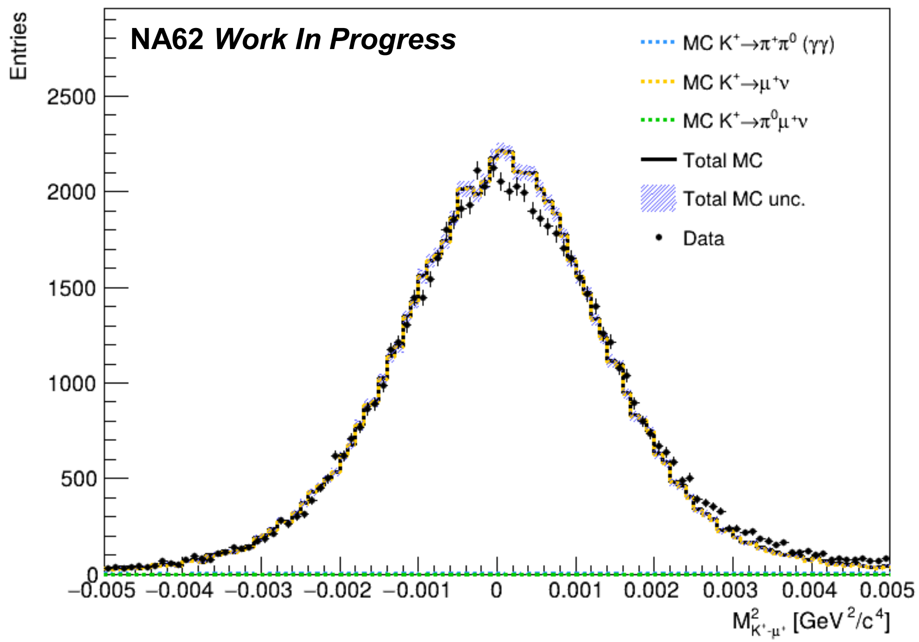
Systematic	Type	Relevant processes	Size
PDG Br	logN	Background	~0.4-2%
Pi0 selection efficiency in Data vs MC	logN	Signal + background (only in K2pi SR)	0.5%
MC Acceptance	Shape	K2pi, Km3 (K2pi SR) Km2 (Km2 SR)	2% (K2pi), 1% (Km3) 5% (Km2)

To determine effect of MC acceptance systematics on extracted yield, define separate control regions (CRs) orthogonal to signal regions to evaluate Data/MC agreement:

- $K^+ \rightarrow \mu^+ \nu$ ($n_{\pi^0} = 0$): SR selection with MUV3 selection inverted (veto)
- $K^+ \rightarrow \pi^+ \pi^0$ ($n_{\pi^0} = 1$): SR selection with MUV3 selection inverted (veto)
- $K^+ \rightarrow \pi^0 \mu^+ \nu$ ($n_{\pi^0} = 1$): SR selection with $m^2_{K^+ - \pi^0}$ > 0.035 GeV^2/c^4
- For remaining backgrounds (≪1%), rely on MC

Control Regions ($n_{\pi^0} = 0$)

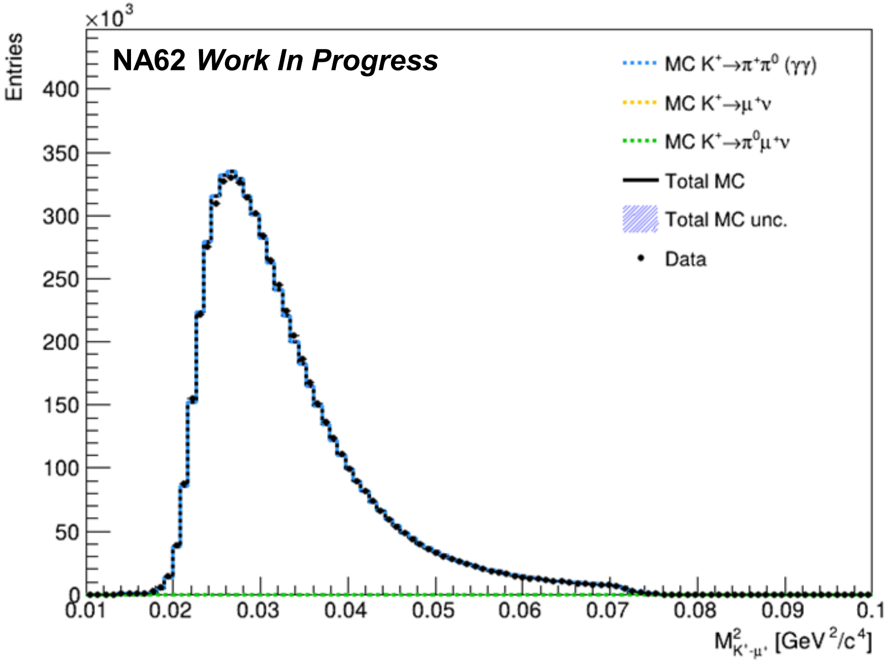
Km2 CR ($K^+ \to \mu^+ \nu$)



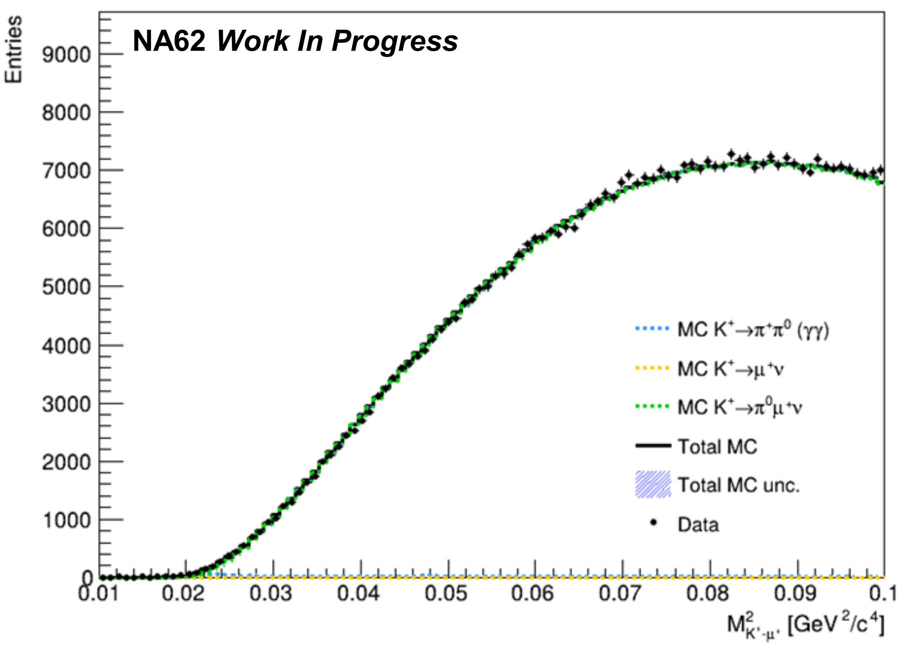
Data shown for **single run** in 2024 (out of 25 total), rest of data set blinded

Control Regions ($n_{\pi^0} = 1$)

K2pi CR ($K^+ \to \pi^+\pi^0$)



Km3 SR ($K^+ \to \pi^0\mu^+\nu$)



Data shown for **single run** in 2024 (out of 25 total), rest of data set blinded

Estimated Total Uncertainty on V_{us} / V_{ud}

Rough estimate using statistical uncertainties for MC acceptances and external uncertainty on $Br(K_{\pi 2})$):

	Relative Uncertainty
N_{Km2}	2.9×10^{-3}
N_{K2pi}	2.2×10^{-3}
a_{Km2}	9.3×10^{-4}
a_{K2pi}	1.8×10^{-4}
$Br(K_{\pi 2})$	3.9×10^{-3}
Vus/Vud	5.4×10^{-3}

Caveats:

- Systematic studies incomplete (MUV3 efficiency, L0/L1 trigger efficiency, etc.)
- Limited statistics from looking at single run

However, demonstrates that precision of O(0.5%) can be achieved!

Measuring $Br(K_{\mu3}) / Br(K_{\mu2})$ and V_{us}

Can also use NA62 to measure ratio $\mathbf{R_{32} = Br(K_{\mu3}) / Br(K_{\mu2})}$:

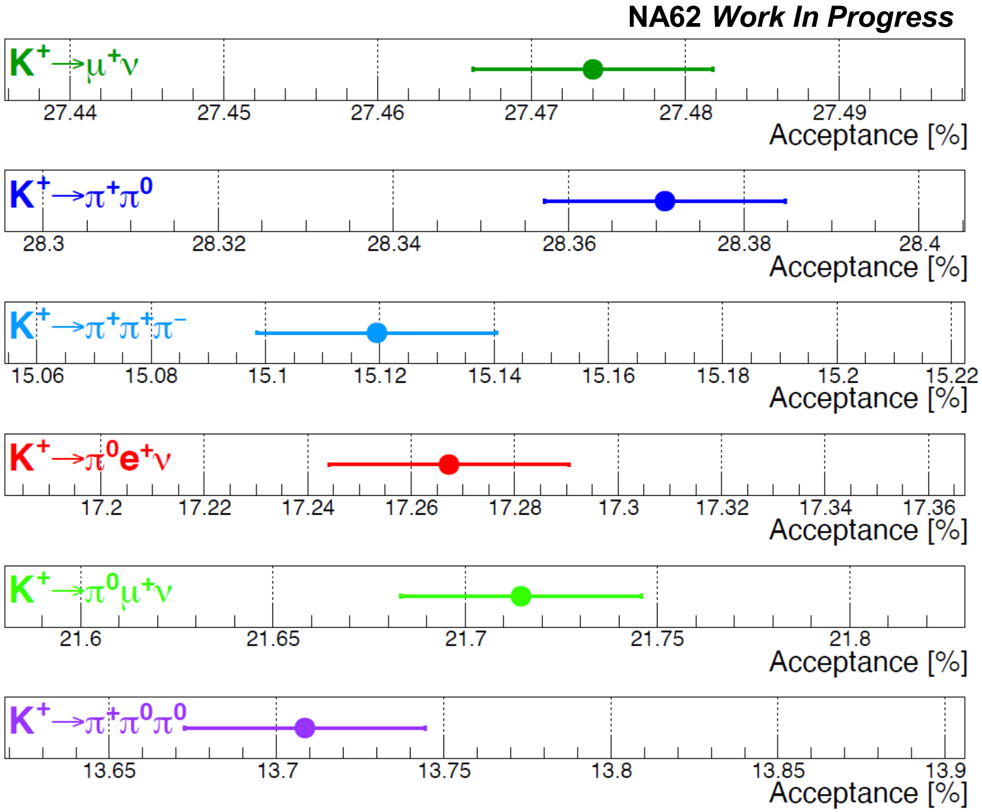
- Use distributions of MC simulated kinematic variables to perform template fit of six main K^+ decay modes
- Determine branching ratios of main decay modes from fraction of the data for each component

Compute expected fraction:

$$f_i = \frac{\mathscr{B}_i A_i}{\sum_{i=1}^{i=6} \mathscr{B}_i A_i}$$

$$f_i' = \frac{N'_{\mathrm{MC},i}}{N_{\mathrm{data}}} = \frac{N'_{\mathrm{MC},i}}{\sum_i N'_{\mathrm{MC,i}}}$$

$$\mathscr{B}_i' = \frac{f_i'}{A_i} \cdot \sum_{i=1}^{i=6} \mathscr{B}_i A_i$$



Measuring Br($K_{\mu 3}$) / Br($K_{\mu 2}$) and V_{us}

Advantage: can extract branching ratios without absolute normalization

- Use PDG value for K^+ lifetime
- Use branching ratios to determine both **Br($K_{\mu 3}$) / Br($K_{\mu 2}$)** and **V_{us} :**

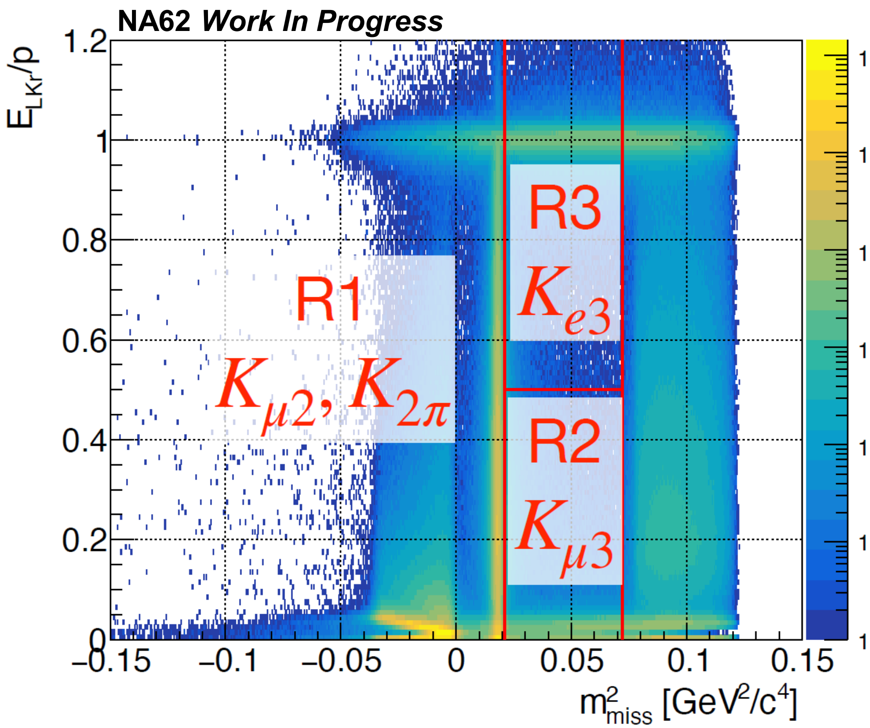
$$\Gamma(K_{\ell 3}) = |V_{us}|^2 \frac{C_K^2 G_f^2 m_K^5}{192\pi^3} S_{\mathrm{EW}} |f_+^{K^0\pi^-}|^2 I_{K\ell}(\lambda_{K\ell}) \left(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{\mathrm{EM}}\right)$$

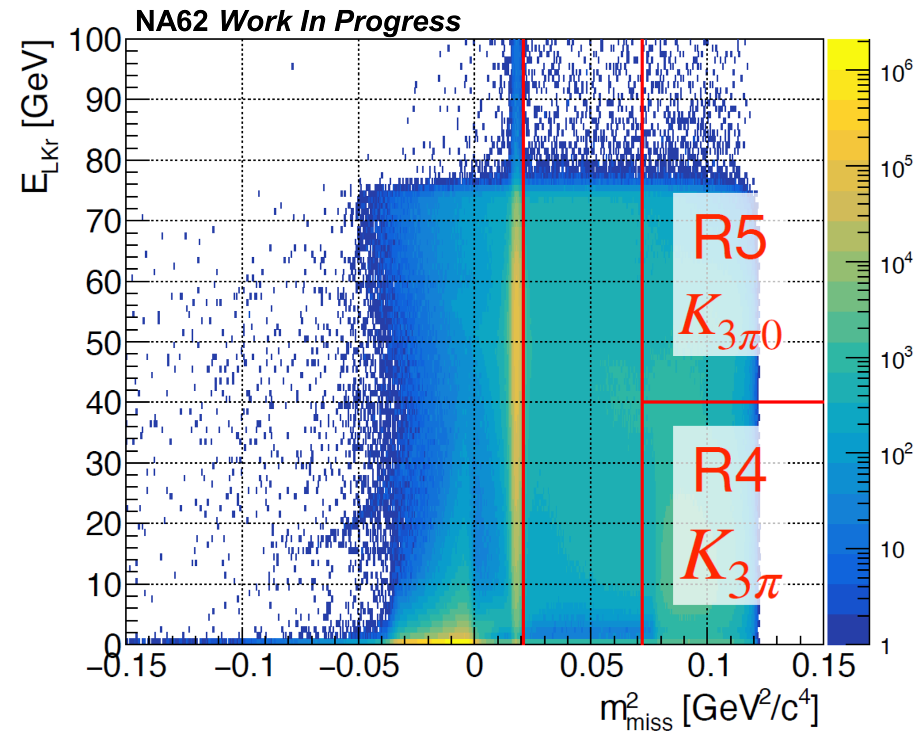
- **Similar target precision of ~0.5%**

Two approaches to template fit:

- Maximum likelihood fit vs minimizing χ^2
- Use one as a cross-check for the other

Selectons and Fit Bin Definitions



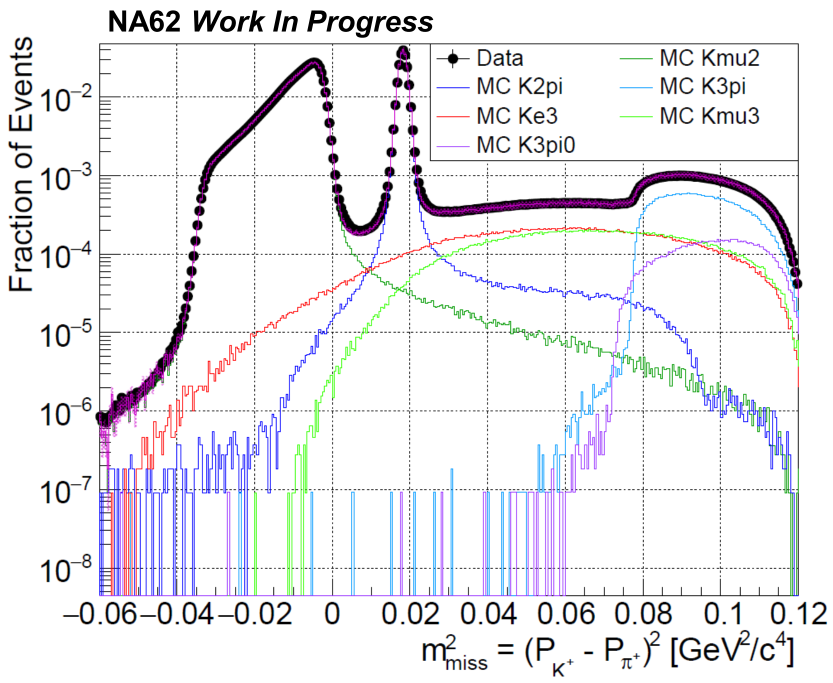


Similar selection criteria to V_{us} / V_{ud} :

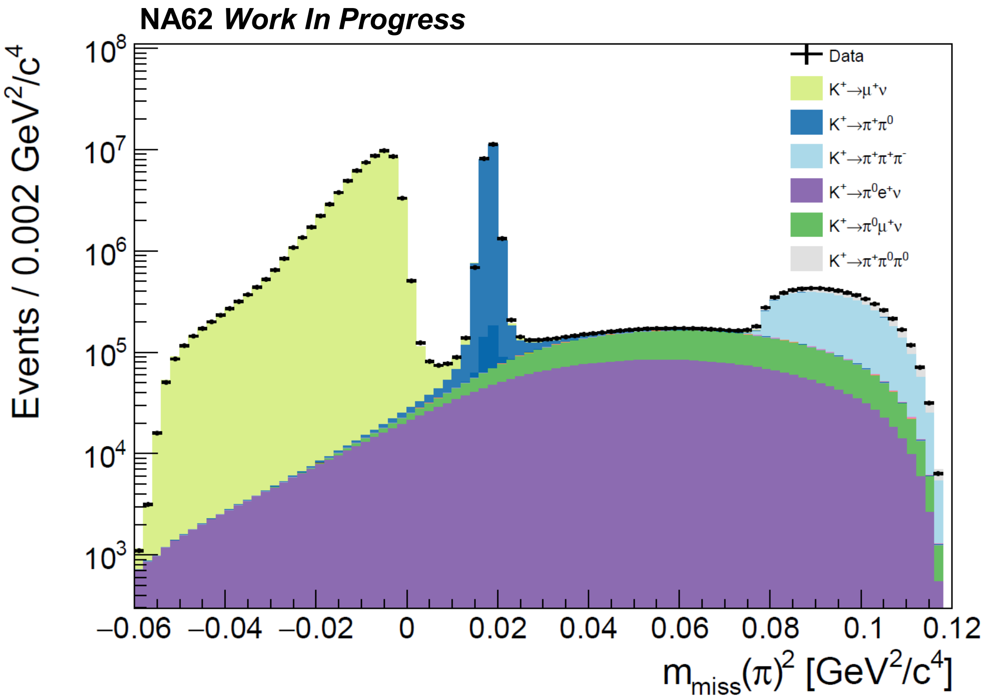
- One positively charged track, KTAG association, STRAW track matched to GTK candidate
- To avoid strong correlations between K_{e3} vs $K_{\mu3}$ and $K_{3\pi}$ and $K_{3\pi0}$, define five separate MMS bins

Template Fits to MMS

Maximum Likelihood Fit



χ^2 Fit



Data shown for **single run** in 2024 (out of 25 total), rest of data set blinded

Current Status and Prospects

- Analysis frameworks developed, systematic studies underway
- Only small portion of 2024 low intensity data set analyzed, 2025 available and planned to be included
- Even with limited data set, statistical uncertainties comparable to systematics → **final measurement not expected to be statistical limited**, current data set is sufficient

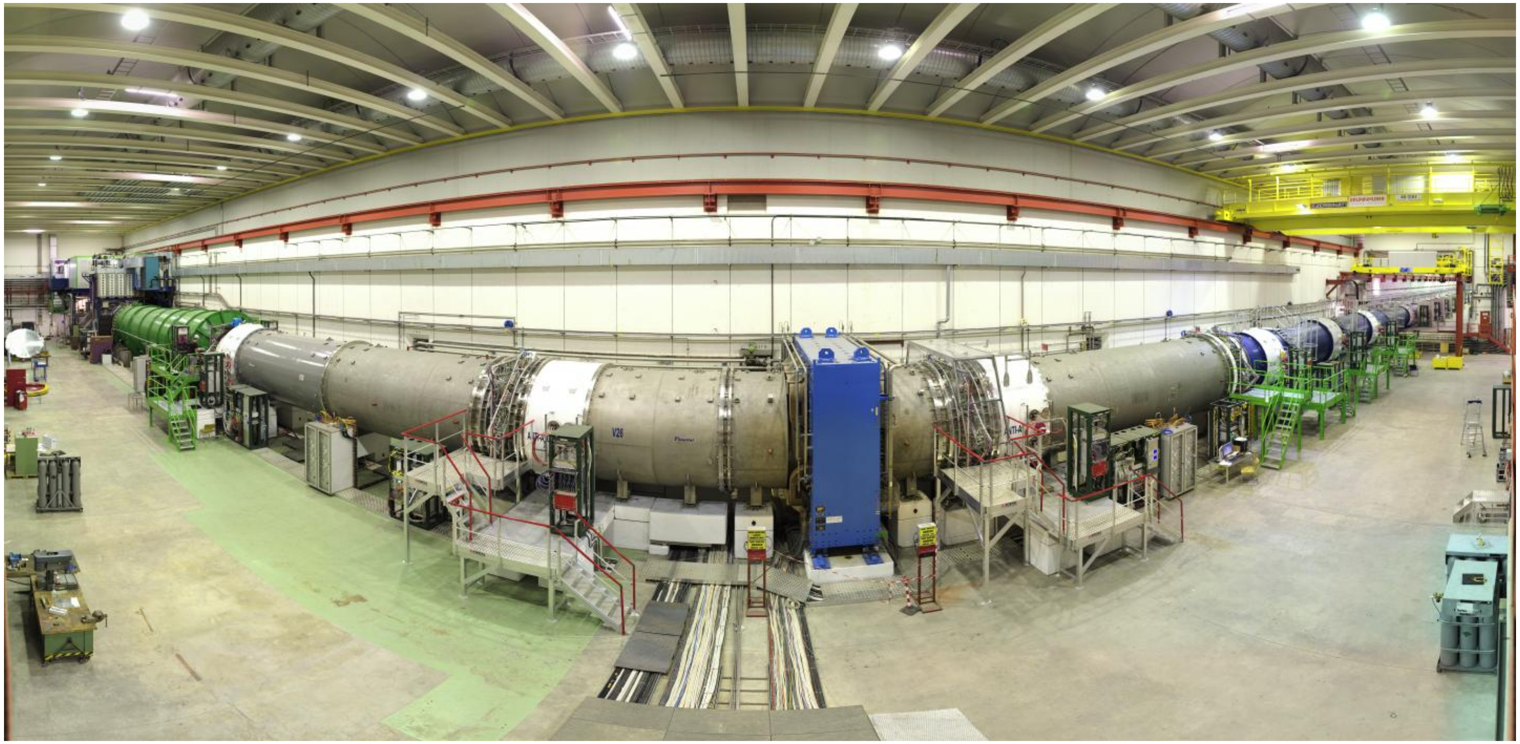
Largest external uncertainties:

- V_{us} / V_{ud} : Br($K_{\pi 2}$) (~0.4%)
- Br($K_{\mu 3}$) / Br($K_{\mu 2}$) and V_{us} : $\tau(K^+)$ (~0.16%)

Theoretical uncertainties not a limiting factor to achieving O(0.5%) precision

Summary

- Efforts at NA62 underway to test 1st-row CKM unitarity through measurement of V_{us} / V_{ud} , $Br(K_{\mu3})$ / $Br(K_{\mu2})$, and V_{us}
- Target precision of 0.5% is realistic and can have significant impact on status of Cabibbo angle anomalies
- Look forward to new results!



Backup

V_{us} / V_{ud} Analysis Selection Details

- **MinBias Trigger (non-overlapping with CTRL trigger events)**
- **At least one "good" downstream track**
- **At least 1 good KTAG candidate**
- **Track-associated and in-time MUV3 hit**
- **Track energy-to-momentum ratio < 0.8**
- **Track momentum between 10 and 60 GeV**
- **GTK matched tracks (SpectrometerGigaTrackerMatching)**

Common preselections (k2pi + km2 SRs)

- **0 good pi0 candidate**
- -0.0025 < $m^2_{K^+-\mu^+}$ < 0.0025 GeV^2/c^4

Only $n_{\pi^0} = 0$ selection (km2 SR)

- **1 good pi0 candidate**
- 0.01 < $m^2_{K^+-\pi^0}$ < 0.03 GeV^2/c^4
- 0.01 < $m^2_{K^+-\mu^+}$ < 0.1 GeV^2/c^4

Only $n_{\pi^0} = 1$ selection (k2pi SR)

V_{us} / V_{ud} Analysis Systematics

- Evaluate systematic uncertainties as either normalization or shape variations on initial estimated MC yield
- Normalization uncertainties:
  - Implemented as flat logN parameters in fit
  - PDG BRs: Assign flat unc to backgrounds based on PDG uncertainty for background branching ratios
  - Pi0 selection: Assign flat unc to account for difference in pi0 efficiency between Data and MC
- Shape uncertainties:
  - Derived from binned template histograms for both up/down variations
  - MC acceptance: Assign conservative flat bin-by-bin variation to signal (k2pi, km2) as well as dominant background in k2pi SR (km3)

Systematic	Type	Relevant processes	Size
PDG Br	logN	Background	~0.4-2%
Pi0 selection efficiency in Data vs MC	logN	Signal + background (only in K2pi SR)	0.5%
MC Acceptance	Shape	K2pi, Km3 (K2pi SR) Km2 (Km2 SR)	2% (K2pi), 1% (Km3) 5% (Km2)

Br($K_{\mu3}$) / Br($K_{\mu2}$) and V_{us} Analysis Selection Details

PRE-SELECTION: match and reconstruction of good-quality one positive tracks

1. Track size: [1,20] after Trigger/L0Emulator Check (Mask2 Events);
2. One positive good downstream track:
   - Track-CHOD association and $|t_{trigger} - t_{track}| \leq 2$ ns;
   - Q==+1;
   - Fake Vertex mask;
   - $|P_{beam} - P_{track}| < 20$ GeV;
   - P_{track} : [5, 70] GeV;
   - Z_{track} : [105,180] m;
   - CDA < 30 mm and $\chi^2 < 20$;
   - Hit at each four straw chambers;
   - Acceptance in STRAW, CHODs, RICH, LKr, MUV1-3, no IRC and LAV;
   - CHANTI non-association and RICH association;
   - If more than one good track exists, the track with highest momentum considered;
3. Kaon TAGging:
   - closest in time with at least a hit in five sectors; $|t_{Cedar} - t_{track}| \leq 5$ ns;
4. Upstream-Downstream matching:
   - Matching quality check
   - $\chi_{GTK}^2 < 40$ and $\chi_{GTK\text{-}event}^2 < 10$
   - $N_{matched\ GTK} == 1$

FINAL-SELECTION: apply kinematic and upstream cuts to evaluate final events for Squared Missing Mass plot

Kinematic cuts

1. CDA ≤ 3.5 mm;
2. Z_{vertex}: [115, 175] m;
3. P_{beam}: [73,77] GeV & P_{track}: [10, 65] GeV;
4. P_t : [25,285];

Upstream bkg cuts

5. Upstream-matter interactions:
   - $X(Y)_{track@GTK3} < 30$ (15) cm;
   - $|XY_{track@GTK3} - XY_{GTK3\ hit}| < 24$ cm;
   - $|t_{Cedar} - t_{GTK3\ hit}| > 1.2$ ns && ToT GTK3 hit >23ns && $N_{GTK3\ hits} > 50$;
   - 100m < Ztrack@GTK3 <105 m;
6. Upstream decay cuts:
   - $m_{\pi\mu2}^2 < -0.02$ GeV^2 and box cut $|X(Y)_{track\ @\ TRIM5}| < 10$cm;

PID

➢ Squared missing mass as PID: $m_{miss}^2 = (\boldsymbol{P}_K^{\mu} - \boldsymbol{P}_{track}^{\mu})^2$

24