

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ - NA62 First Result

Bob Velghe^{*}, on behalf of the NA62 collaboration

Particle Physics Seminar
BNL, NY, May 24, 2018

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Outline of the Talk

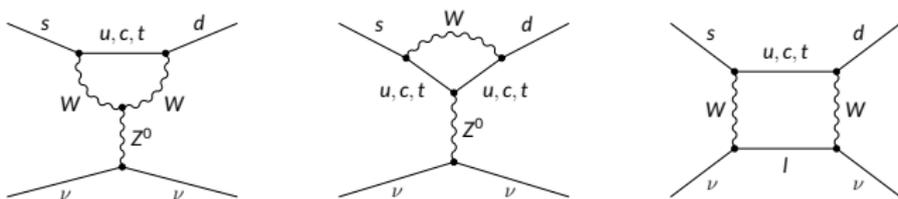
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Decay

BNL E787 / E949 Experiment

NA62 Experiment



$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ - In the Standard Model



Flavour Changing Neutral Current:

GIM suppression, involved CKM matrix elements are small

$$(|V_{ts}| \approx 0.039, |V_{td}| \approx 0.008)$$

Hadronic matrix element related to $K^+ \rightarrow \pi^0 e^+ \nu_e$ decay F. Mescia and C. Smith

[arXiv:0705.2025]

In terms of the CKM parameters:

$$\begin{aligned} \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) &= (8.39 \pm 0.30) \times 10^{-11} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}} \right]^{2.8} \left[\frac{\gamma}{73.2^\circ} \right]^{0.74} \\ &= (8.4 \pm 1.0) \times 10^{-11} \end{aligned}$$

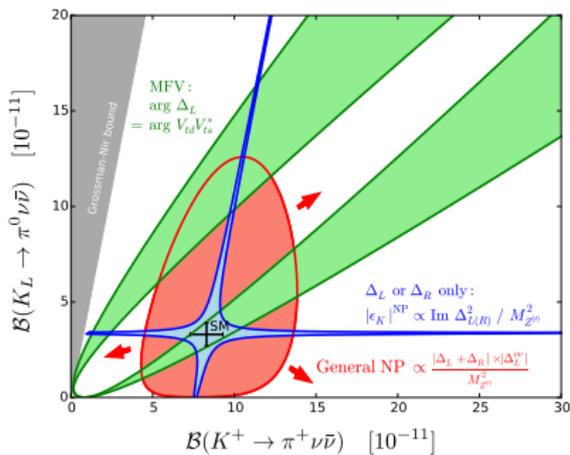
A. J. Buras et al [arXiv:1503.02693]

Note: $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8}$ J.K. Ahn et al [arXiv:0911.4789]

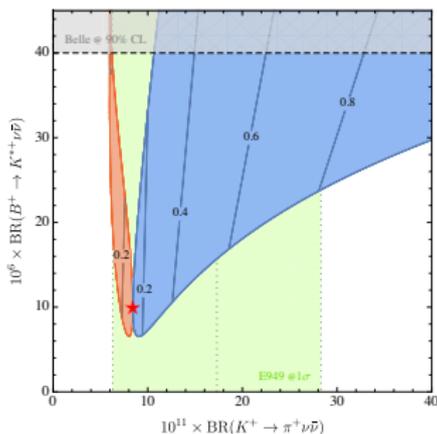
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ – Beyond the Standard Model

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ has been studied in many BSM scenarios. To name a few:

- ▶ *Z' models*, A. Buras et al [arXiv:1211.1896],[arXiv:1507.08672]
- ▶ *Randall and Sandrum models*, M. Blanke et al [arXiv:0812.3803]
- ▶ *Littlest Higgs models*, M. Blanke et al [arXiv:1507.06316]
- ▶ *Supersymmetry*, M. Tanimoto, K. Yamamoto [arXiv:1603.07960], T. Blažek, P. Maták [arXiv:1410.0055]
- ▶ *Lepton Flavour Violation models*. M. Bordone et al [arXiv:1705.10729]



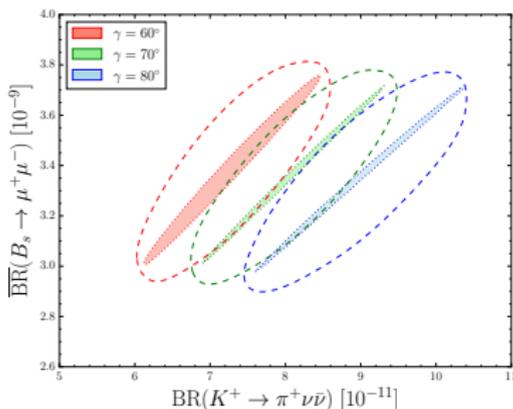
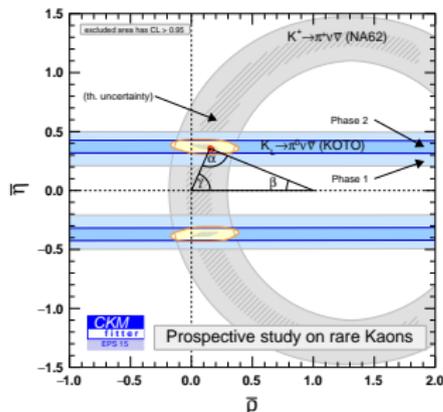
A. J. Buras et al [arXiv:1507.08672]



M. Bordone et al [arXiv:1705.10729]

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ - Flavour Physics

Kaons provide an independent set of constraints on the unitary triangle (Assumes $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ and $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ uncertainty $< 10\%$).



Also, among others, correlations between $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$, $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ and γ .

A. Buras et al [arXiv:1503.02693]

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

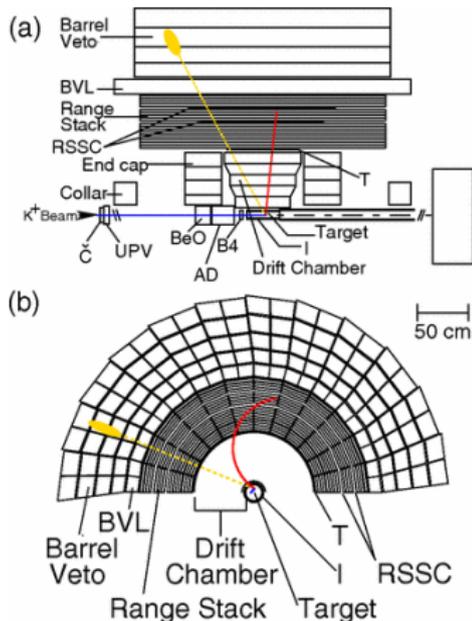
BNL E787 / E949 Experiment

NA62 Experiment

Brought down $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ from $< 1.4 \times 10^{-7}$ to 1.73×10^{-10}

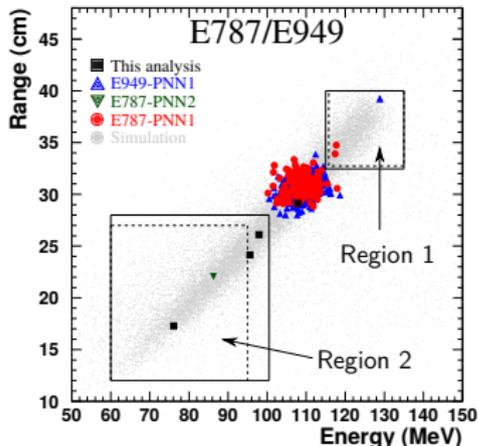
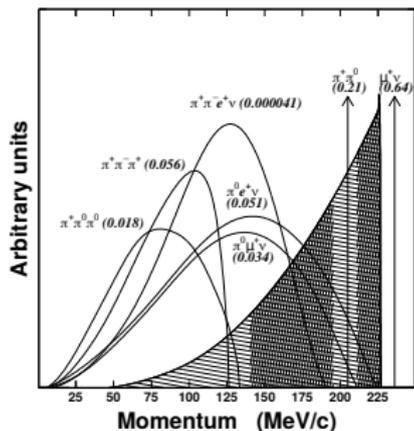
Stopped kaon experiment:

- ▶ 710 MeV/c K^+ beam,
- ▶ 1 T magnetic field,
- ▶ Scintillating fibers target,
- ▶ Low mass central drift chamber,
- ▶ Range / energy measurements and $\pi \rightarrow \mu \rightarrow e$ decays observation,
- ▶ 4π sr photon vetos,
- ▶ Blinded analysis, bifurcation method.



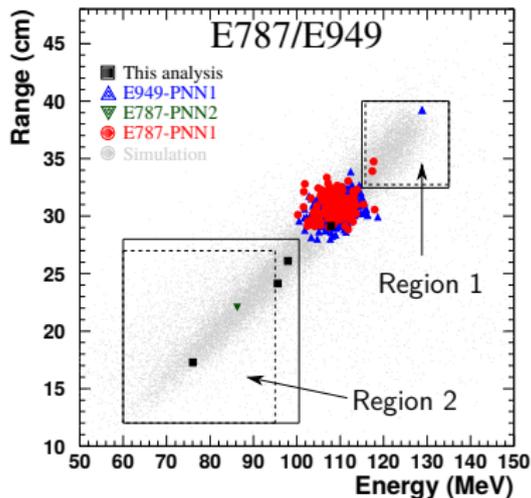
E949 $K^+ \rightarrow \pi^+ \pi^0$ event

Observed seven candidates.

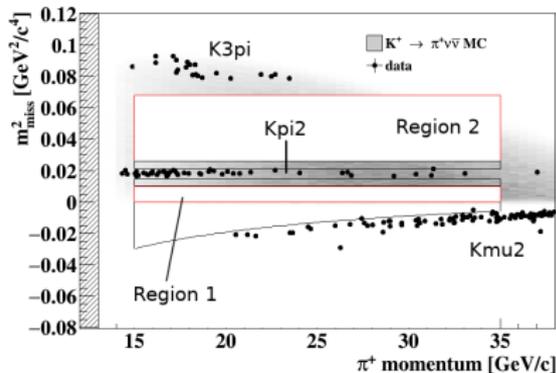


	R1 ($211 < P < 229$ MeV/c)		R2 ($140 < P < 195$ MeV/c)			
	E787	E949	E787	E949		
N_k	5.9×10^{12}	1.8×10^{12}	1.7×10^{12}	1.7×10^{12}		
$N_{bkg.}$	0.14	0.30	1.22	0.927		
S/B	50	7	0.20	0.20	0.42	0.47

Decay at rest



Decay in flight



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

Today's topic

Compatible with SM prediction.

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

BNL E787 / E949 Experiment

NA62 Experiment

- Setup & Measurement Principle

- Signal Selection

- Single Event Sensitivity

- Backgrounds Evaluation

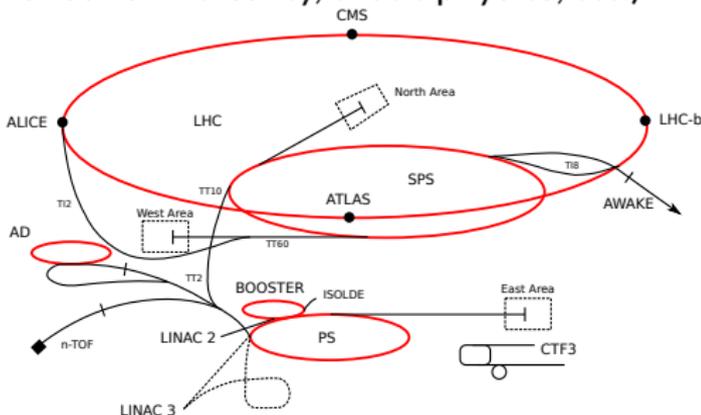
- Preliminary Results and Future Prospects

Setup & Measurement Principle

NA62 is a kaon decay in flight experiment. The main objective is to measure $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ with a relative uncertainty around 10%.

(Also, heavy neutrinos, lepton flavour universality, exotic physics, etc.)

- ▶ 2005 Proposal,
- ▶ 2009 Approved,
- ▶ 2010 Technical design,
- ▶ 2012 Technical run,
- ▶ 2014–15 Pilot runs,
- ▶ 2016–18 Physics runs.

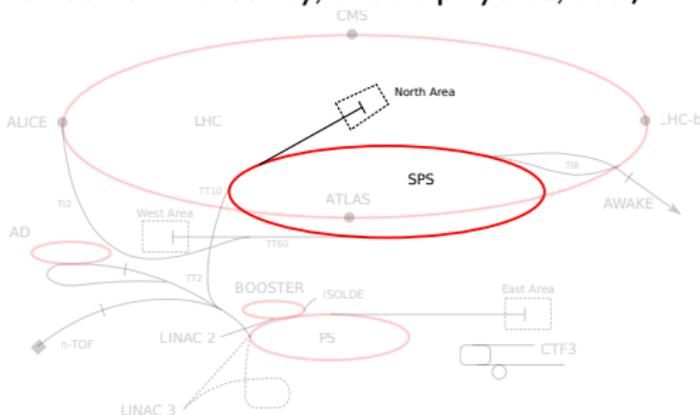


14 countries, 31 institutes, 214 authors.

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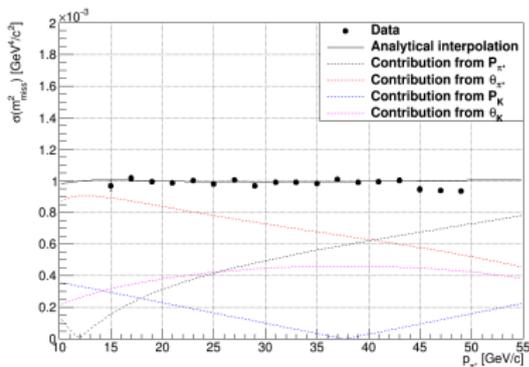
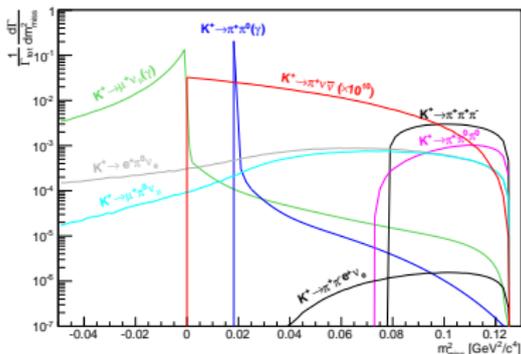
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$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ - Measurement Principle

Main kaon backgrounds: $K^+ \rightarrow \mu^+ \nu_\mu (\gamma)$ [$K\mu 2 (\gamma)$], $K^+ \rightarrow \pi^+ \pi^0 (\gamma)$ [$K\pi 2 (\gamma)$], $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ [$K3\pi$], $K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$ [$Ke4$].

The missing mass squared, $m_{\text{miss}}^2 = (p_k - p_\pi)^2$, gives an handle on 92 % of the background channels \rightarrow Core aspect of the experiment.

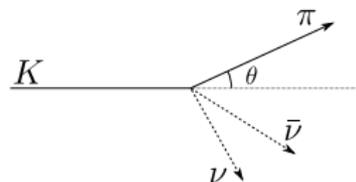


$$\sigma_{m_{\text{miss}}^2} \approx 1 \times 10^{-3} \text{ GeV}^2/c^4.$$

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ - Measurement Principle

The signal is one kaon upstream, one pion downstream and nothing else.

- ▶ Identification of K and π ,
- ▶ Measurements of K and π momentum,
- ▶ Vetoes for γ and μ ,
- ▶ $\mathcal{O}(100 \text{ ps})$ timing capabilities for $K - \pi$ matching.



Signal selection sketch:

- ▶ $K - \pi$ association,
- ▶ $15 < P_\pi < 35 \text{ GeV}/c$,
- ▶ Decay vertex in fiducial volume,
- ▶ No photon / muon / upstream activity.

Nominal Beam Parameters

5×10^{12} kaon decays in fiducial volume / year, 5 seconds *spills*.

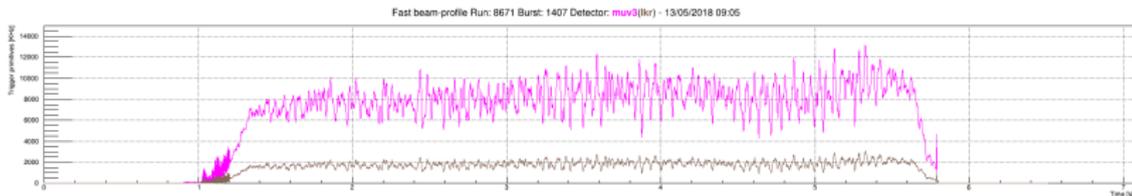
Primary beam:
400 GeV/c protons, 10^{12} p/s on target.

Secondary beam:
75 GeV/c $\pm 1\%$,
K, π and p (6:70:23), 750 MHz.

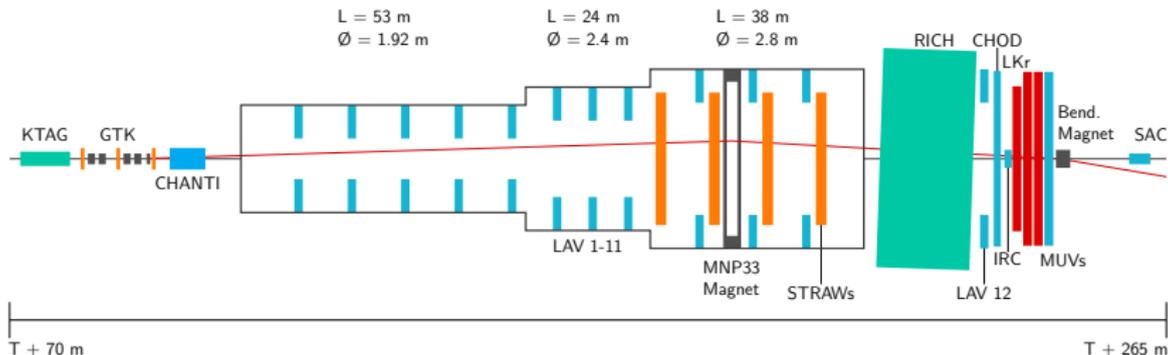
Beam size (at GTK): 6×2.7 cm²,
divergence ≈ 100 μ rad.

Kaon decay rate in fiducial region: ≈ 4.5 MHz.

Actual average intensity: 2016 \rightarrow 35 – 40%, 2017–2018 \rightarrow 60 – 65%.



Layout Overview



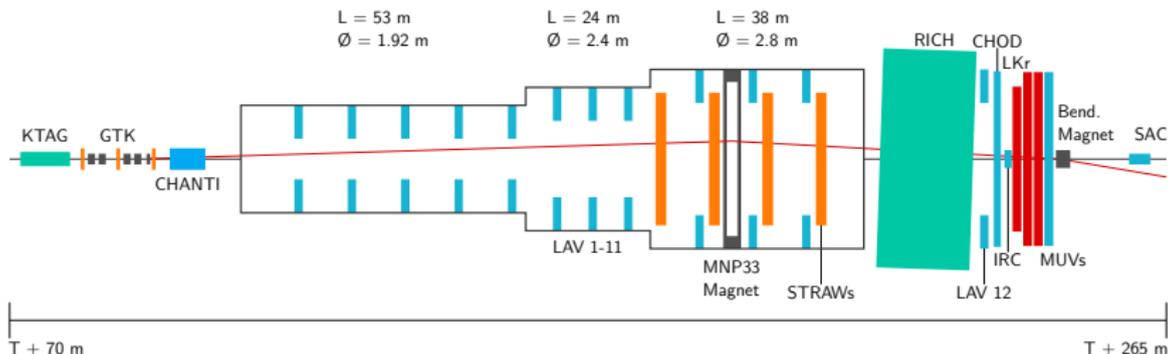
NA62 Collaboration [arXiv:1703.08501]

Kaon & pion tracking, PID, calorimeters, hermetic photon vetos, muon veto, hodoscope and inelastic interactions veto → **Redundancy.**

Minimize inelastic interactions:

- ▶ Beam - Gas → Vacuum 10^{-6} mbar,
- ▶ GigaTracker & STRAW → $X/X_0 < 0.5/1.8\%$.

KTAG and GigaTracker see the whole beam, “undecayed” beam particles travel undisturbed across the downstream detectors.



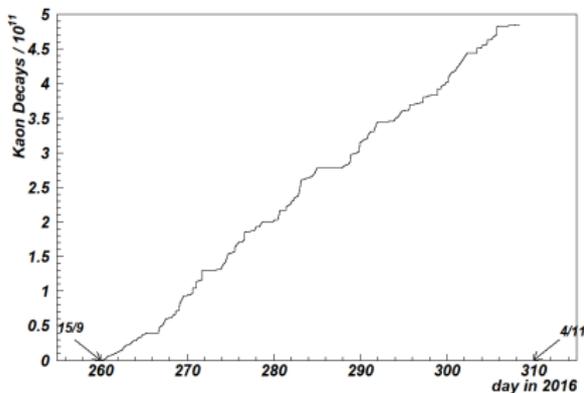
- ▶ “PNN” trigger, RICH hits, track in hodoscope, no muons, $< 20 \text{ GeV}$ in LKr, TKag in time, no signals in LAV, $P_{\text{track}} < 50 \text{ GeV}/c$.
- ▶ Control trigger (minimum bias), at least one charged particle in the downstream acceptance. Downscaled by 400.

Main data samples used for the 2016 analysis: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ “PNN” / $K^+ \rightarrow \pi^+ \pi^0$, $K^+ \rightarrow \pi^+ \pi^+ \pi^-$, $K^+ \rightarrow \mu^+ \nu_\mu$ “Control”.

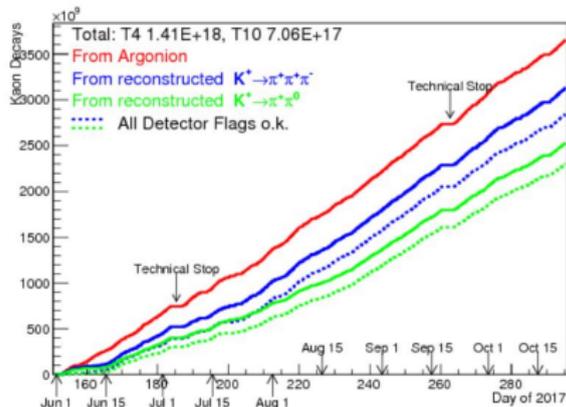
Signal and control regions blinded, selection developed on about 10% of the data set.

This talk: **2016 data**, 4 weeks of data taking, 35 – 40% of the nominal intensity.

2017 data, about 23 weeks of data taking, 60 – 65% of the nominal intensity, higher data quality → about $10\times$ more data.



$\approx 1 \times 10^{11}$ good K^+ decays.



$> 3 \times 10^{12}$ good K^+ decays.

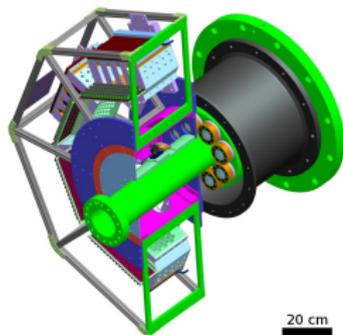
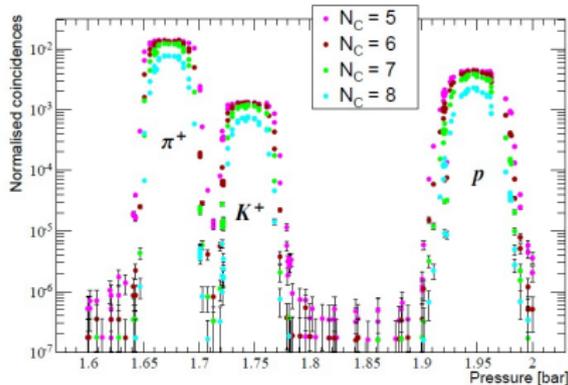
Signal Selection

Kaon identification – KTAG

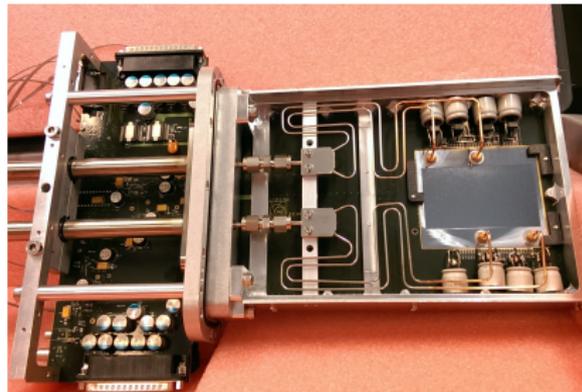
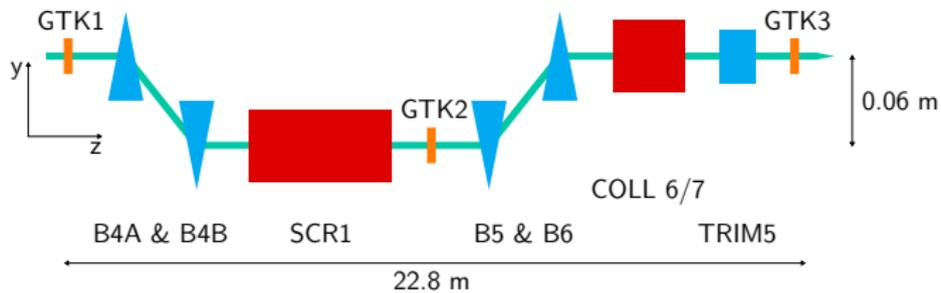
Differential Cherenkov counter

- ▶ N₂ (H₂) gas radiator,
- ▶ Kaon time resolution ≈ 70 ps,
- ▶ > 98% K ID efficiency (99.9% purity).

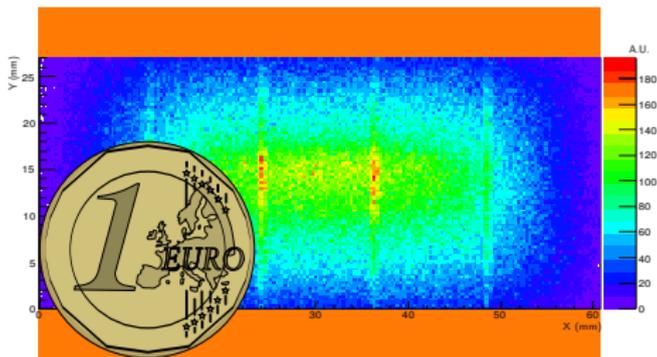
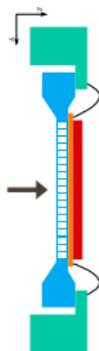
Gas pressure / diaphragm adjusted to see only the kaon light. Require coincidences in 5/8 sectors.



Kaon Tracking



Physical dimension driven by the physics program requirements.



- ▶ Sensor surface is 60 by 27 mm – Match beam size,
- ▶ Pixels are 300 by 300 μm – Meet momentum resolution requirement,
- ▶ Thickness $\leq 0.5\%$ X/X_0 – Minimize beam induced background,
- ▶ Temporal resolution < 150 ps – K^+ – π^+ matching.

KTag and GTK : 75% K^+ reconstruction and identification efficiency.

Pion spectrometer – STRAW

Four STRAW chambers,

- ▶ 4 views / chamber, 448 straws / view,
- ▶ 1.3 m long dipole (0.9 Tm),
- ▶ straws are 2.1 m long, 9.8 mm in diam., $36 \mu\text{m}$ walls,
- ▶ $X/X_0 < 1.8\%$,
- ▶ 70% Ar, 30% CO_2 .

> 95% reconstruction efficiency.

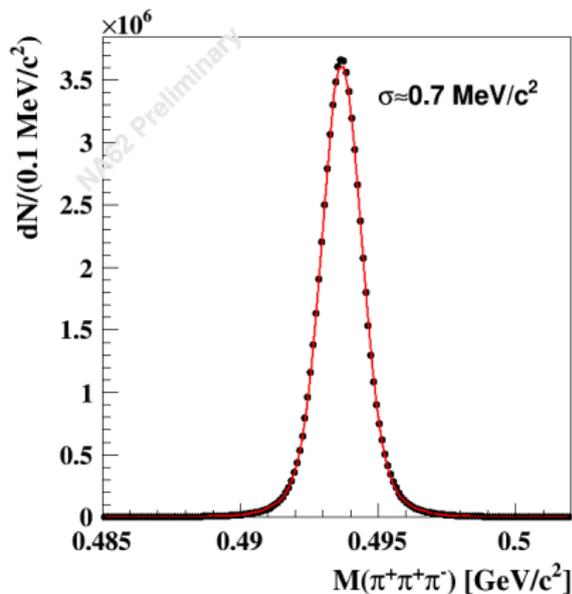


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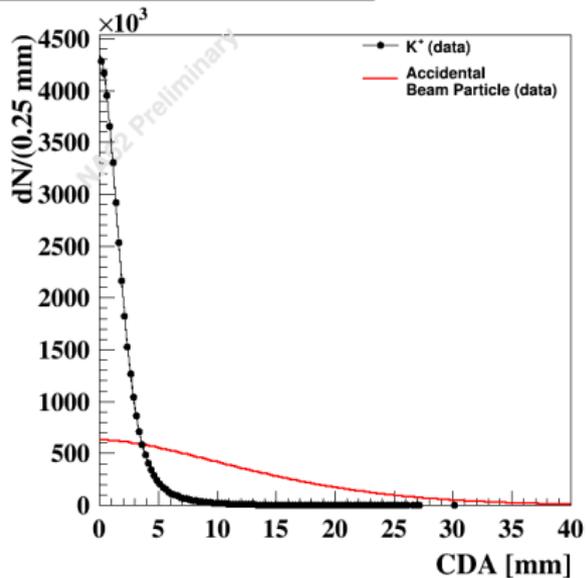
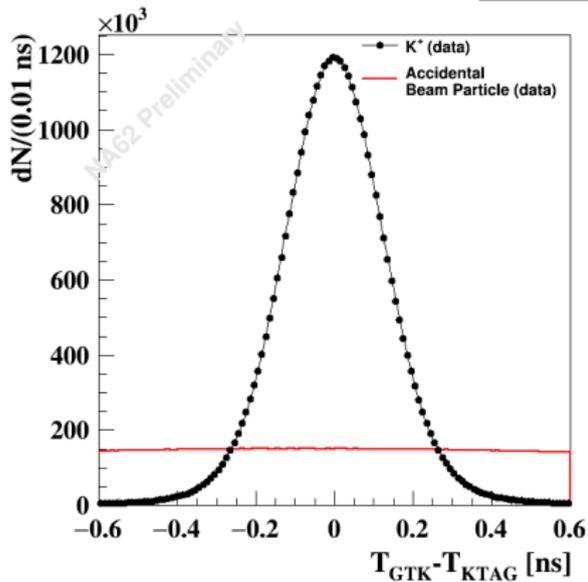
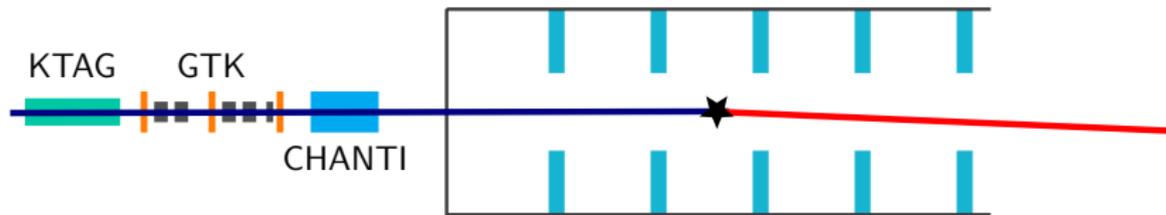
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Kaon - Pion Matching

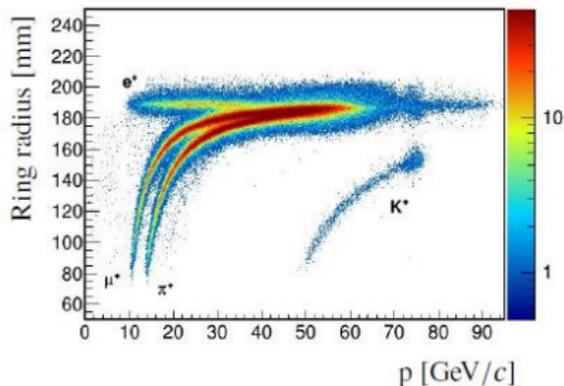


3.5% K^+ mis-tagging if K^+ present.

Pion / muon separation – RICH

Ring-imaging Cherenkov detector,

- ▶ Ne gas radiator,
- ▶ Ring time resolution ≈ 80 ps,
- ▶ μ/π separation $> 10^2$
($15 < P < 35$ GeV/c).

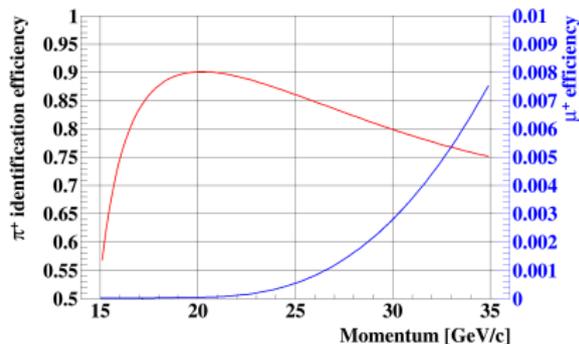


Likelihood PID discriminant. Efficiency $2.5 \times 10^{-3}/0.75$ for μ^+/π^+ .

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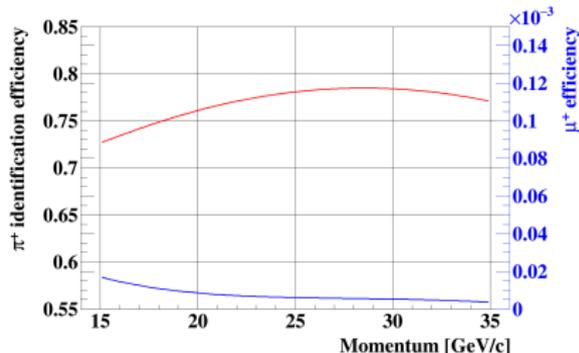


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Particle Identification – Calorimeters

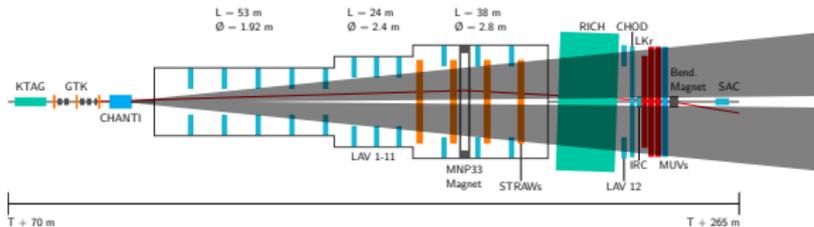
Pion / muon separation – Calorimeters

- ▶ Electromagnetic calo. (LKr),
- ▶ Hadronic calo. (MUV1,2),
- ▶ Scintillator pads behind 80 cm Fe wall (MUV3).



MUV3 and BDT classifier. Efficiency $0.6 \times 10^{-5}/0.77$ for μ^+/π^+ .

Photon VETOs – LKr, LAV, SAV



Liquid Krypton calorimeter,

- ▶ 1 – 8.5 mrad,
- ▶ High time, energy and position resolution.

IRC & SAC: “Shashlik” calo.,

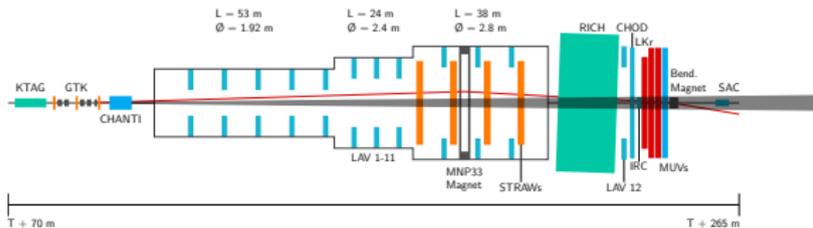
- ▶ < 1 mrad,
- ▶ < 3 ns time resolution.

LAV: Lead glass calorimeters,

- ▶ 8.5 – 50 mrad,
- ▶ 1 ns time resolution.



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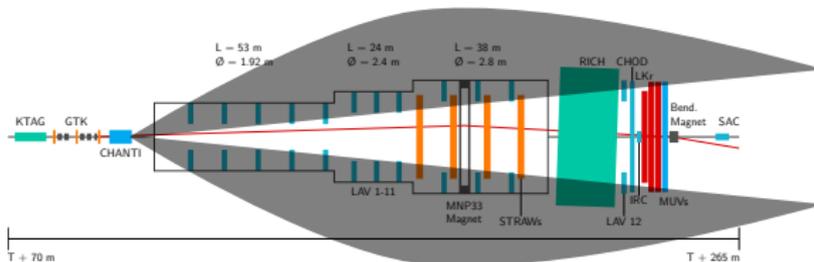
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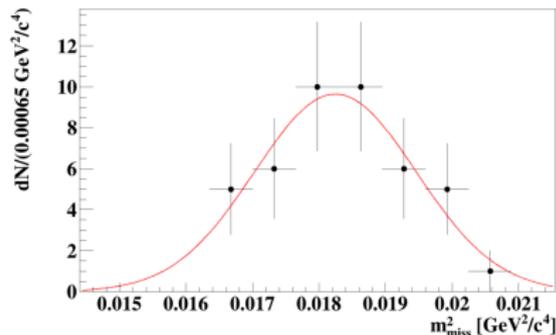
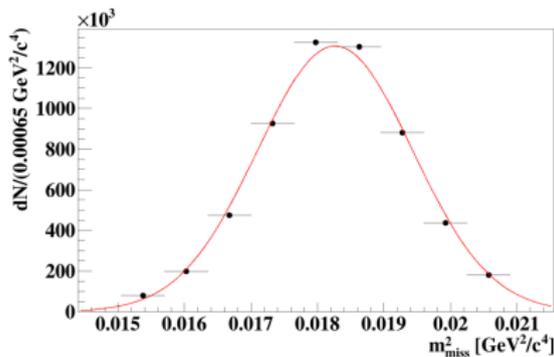
- ▶ 8.5 – 50 mrad,
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Main cuts:

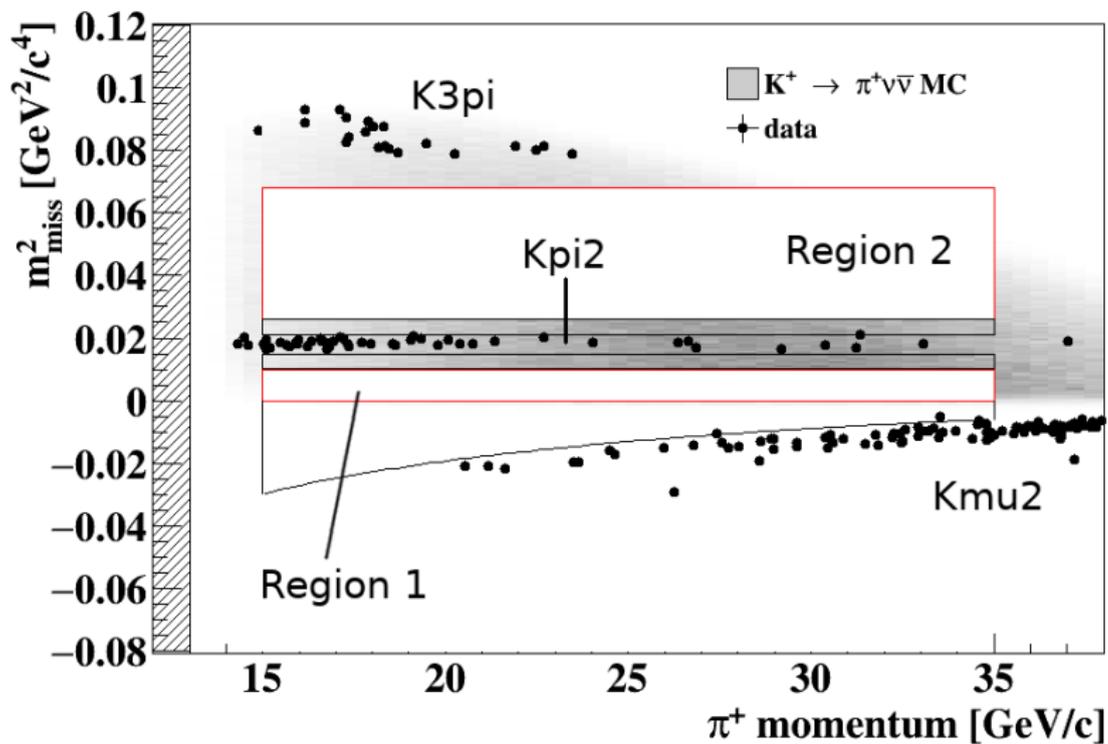
- ▶ No in-time signals in LAVs and SAV,
- ▶ No in-time signals in hodoscope and LKr (if not associated with π^+),
- ▶ Segment rejection in Straw.

Typical timing coincidence: $\pm 3/ \pm 5$ ns, energy dependent for LKr.



Fraction of $K^+ \rightarrow \pi^+ \pi^0$ passing the cuts: 2.5×10^{-8} .

Signal Selection – Result



Single Event Sensitivity

SES - Definition

$K^+ \rightarrow \pi^+ \pi^0$ (from control data) used as normalization channel: $\pi^+ \nu \bar{\nu}$ selection without photon and multiplicity cuts, m_{miss}^2 cuts modified.

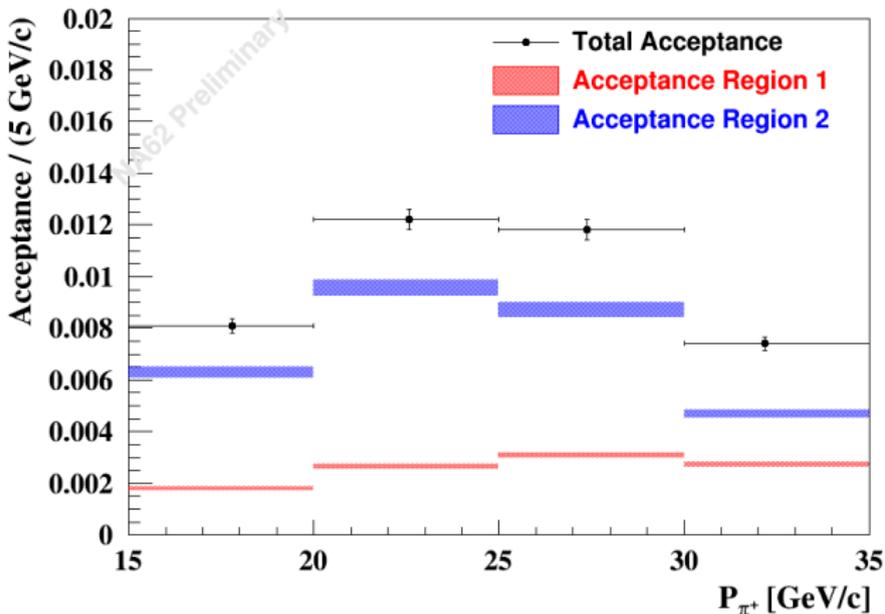
$$N_K = \frac{N_{\pi\pi} \cdot D}{A_{\pi\pi} \cdot \mathcal{B}_{\pi\pi}}$$

$$\text{SES} = \frac{1}{N_K \sum_i \left(A_{\pi\nu\nu}^i \cdot \epsilon_{\text{RV}}^i \cdot \epsilon_{\text{Trig.}}^i \right)}$$

$N_{\pi\pi}$	Number of $K^+ \rightarrow \pi^+ \pi^0$ decays	$(6.145 \pm 0.002) \times 10^6$
$A_{\pi\pi}$	$K^+ \rightarrow \pi^+ \pi^0$ acceptance (MC)	$(9.883 \pm 0.004) \times 10^{-2}$
D	Control trigger downscaling	400

i	Momentum bin	Four 5 GeV/c bins
N_K	Number of K^+ decays	$(1.21 \pm 0.02) \times 10^{11}$
$A_{\pi\nu\nu}$	$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ acceptance (MC)	$(4.0 \pm 0.1) \times 10^{-2}$
ϵ_{RV}	Random veto efficiency	0.76 ± 0.04
$\epsilon_{\text{Trig.}}$	Trigger efficiency	0.87 ± 0.2

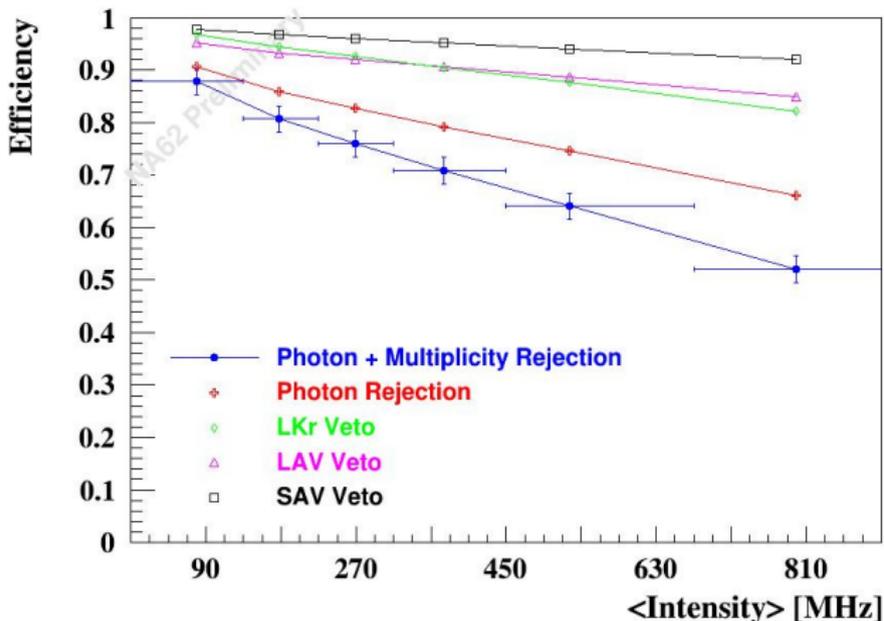
Acceptance extracted from MC.



$$R1: (1.03 \pm 0.04) \times 10^{-2} \quad R2: (2.93 \pm 0.07) \times 10^{-2}$$

Random Veto Efficiency

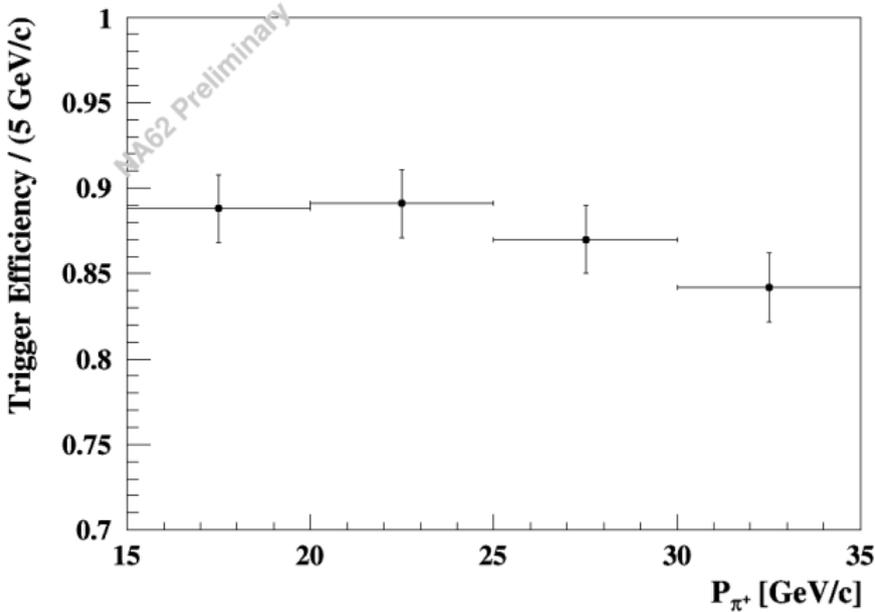
Accidental losses due to photon vetos and multiplicity rejection, extracted from $K^+ \rightarrow \mu^+ \nu_\mu$.



$$\epsilon_{RV} = 0.76 \pm 0.04$$

Trigger Efficiency

Trigger efficiency extracted from $K^+ \rightarrow \pi^+ \pi^0$ (control trigger), mainly due to L0, (L1 efficiency ≈ 0.97).

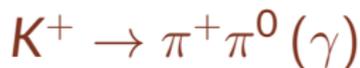


$$\epsilon_{\text{Trig.}} = 0.87 \pm 0.2$$

$$\text{SES} = (3.15 \pm 0.01_{\text{stat.}} \pm 0.24_{\text{syst.}}) \times 10^{-10}$$

Source	$\delta \text{SES} (10^{-10})$
Random veto	± 0.17
Definition of $\pi^+ \pi^0$ region	± 0.10
Simulation of π^+ interactions	± 0.09
N_K	± 0.05
Trigger efficiency	± 0.04
Extra activity	± 0.02
GTK pileup simulation	± 0.02
Momentum spectrum	± 0.01
Total	± 0.24

Backgrounds Evaluation

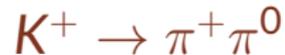


Assume that π^0 rejection cuts and kinematic cuts are independent.

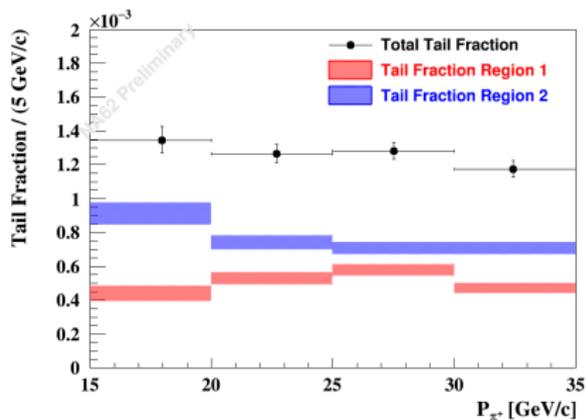
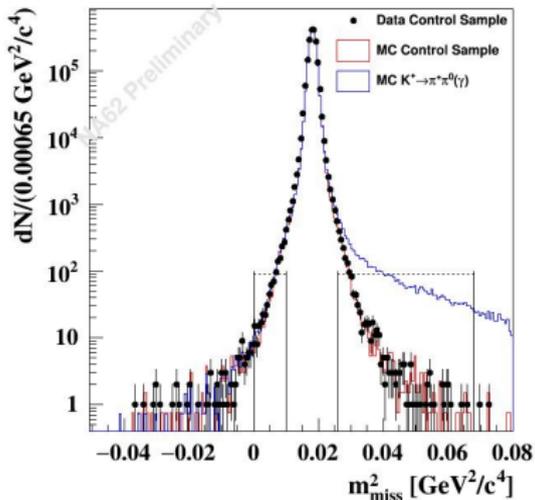
$$N_{\pi\pi}^{\text{exp.}}(\text{region}) = \sum_i \left[N_{\pi\pi}(\pi^+\pi^0)_i \cdot f_i^{\text{kin.}}(\text{region}) \right]$$

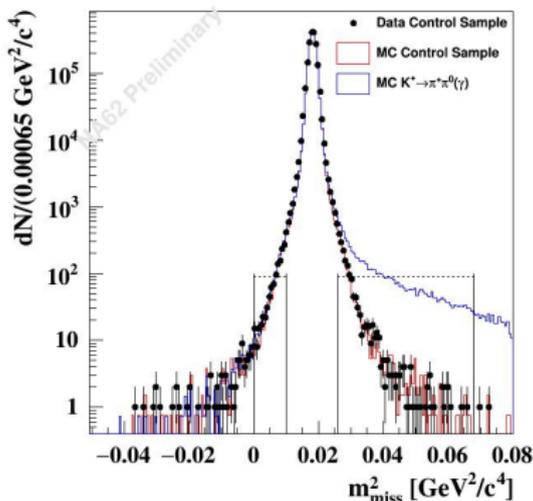
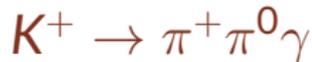
- $N_{\pi\pi}^{\text{exp.}}$ Expected background events
- $N_{\pi\pi}$ Event in the $\pi^+\pi^0$ after $\pi^+\nu\bar{\nu}$ selection
- $f_i^{\text{kin.}}$ Fraction of events left over after the kinematic rejection

$f_i^{\text{kin.}}$ measured on $\pi^+\pi^0$ with *tagged* π^0 ($\gamma\gamma$ in LKr).



π^0 forced in $LKr \rightarrow K^+ \rightarrow \pi^+ \pi^0$ fully constrained, radiative part is suppressed.

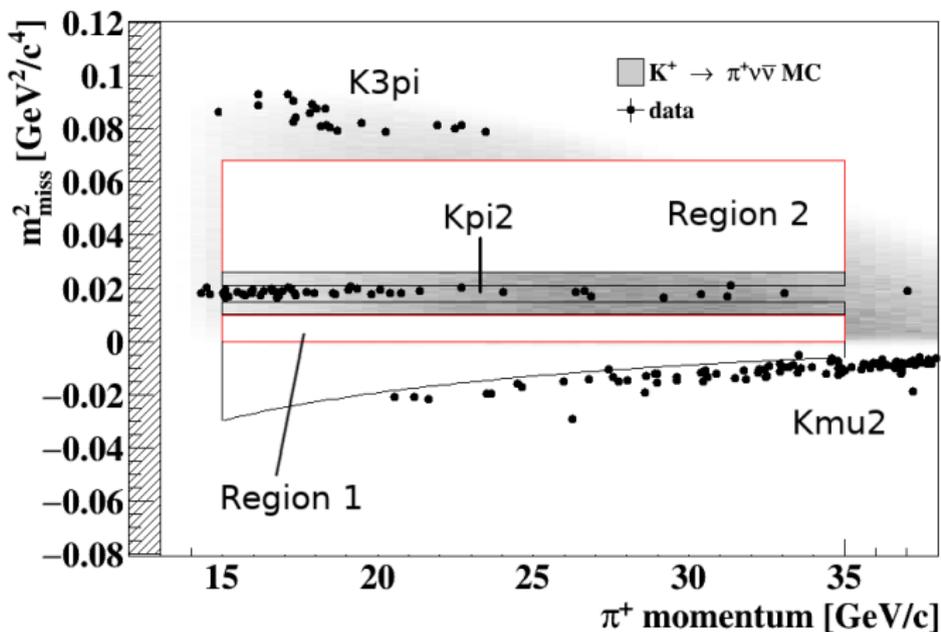




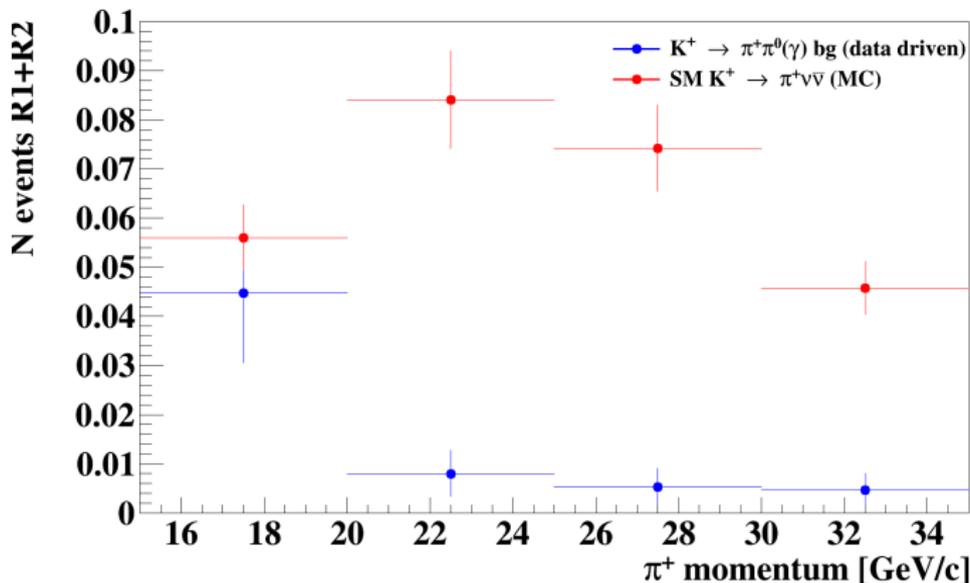
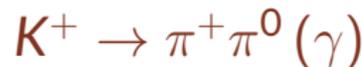
- ▶ Radiative tail in R2 estimated from MC,
- ▶ Single- γ veto efficiency measured on data,
- ▶ $\pi^0 \gamma$ rejection on the radiative tail estimated from data.

Compared to $K^+ \rightarrow \pi^+ \pi^0$, tail $\times 6$ bigger and $\pi^0 \gamma$ rejection $\times 30$.

$K^+ \rightarrow \pi^+ \pi^0 \gamma$ - Control Regions



Region	$N_{\pi\pi\gamma}^{\text{exp.}}$	$N_{\pi\pi\gamma}^{\text{obs.}}$
CR1	$0.52 \pm 0.08 \pm 0.03$	0
CR2	$0.94 \pm 0.14 \pm 0.05$	1

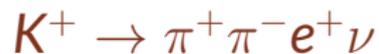


Non-radiative

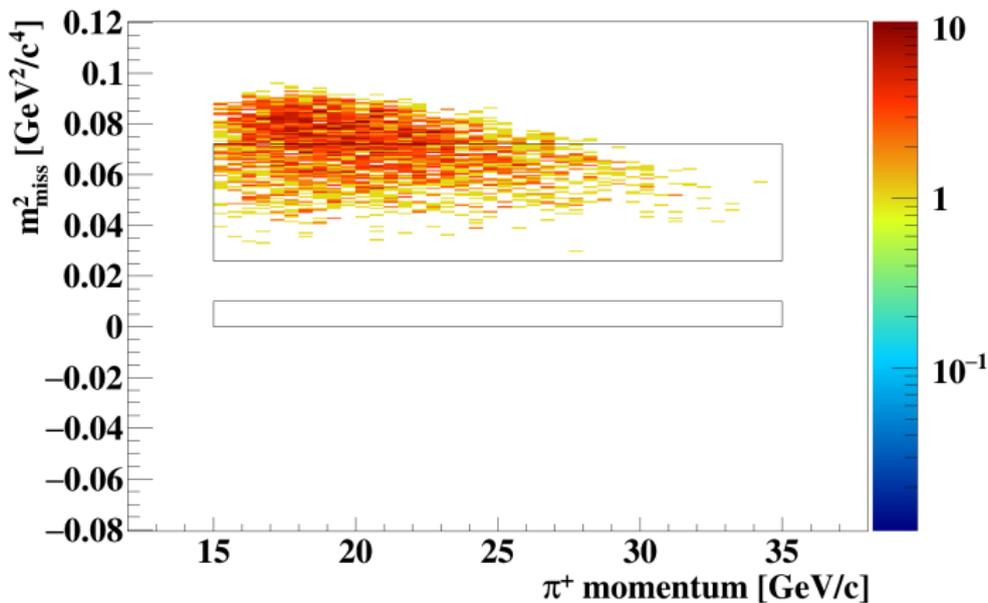
Region	$N_{\pi\pi}^{\text{exp.}}$
R1	$0.022 \pm 0.004 \pm 0.002$
R2	$0.037 \pm 0.006 \pm 0.003$

Radiative

Region	$N_{\pi\pi\gamma}^{\text{exp.}}$
R1	0
R2	$0.005 \pm 0.005_{\text{sys.}}$

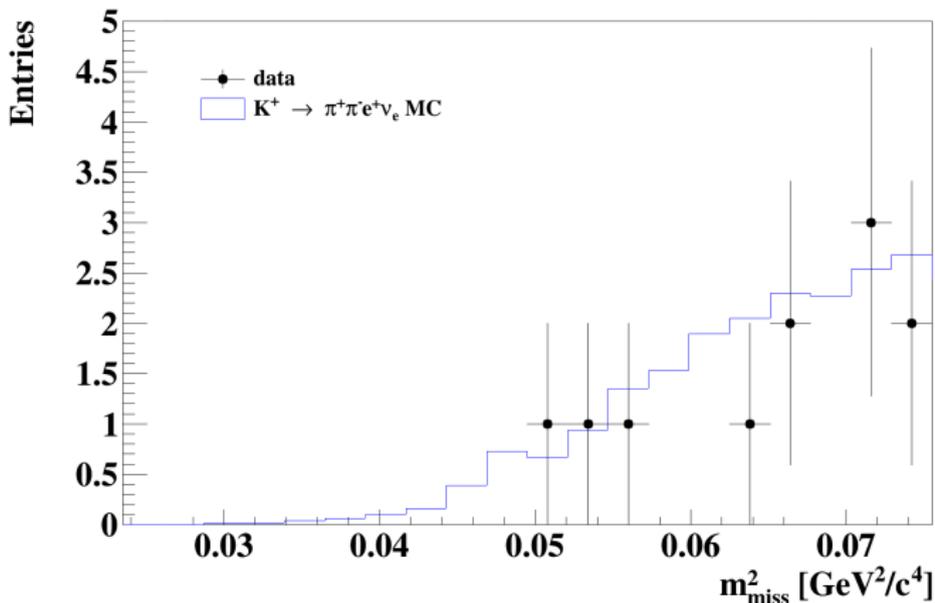


Estimated using MC, $\approx 4 \times 10^8$ events generated.



$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ - Validation

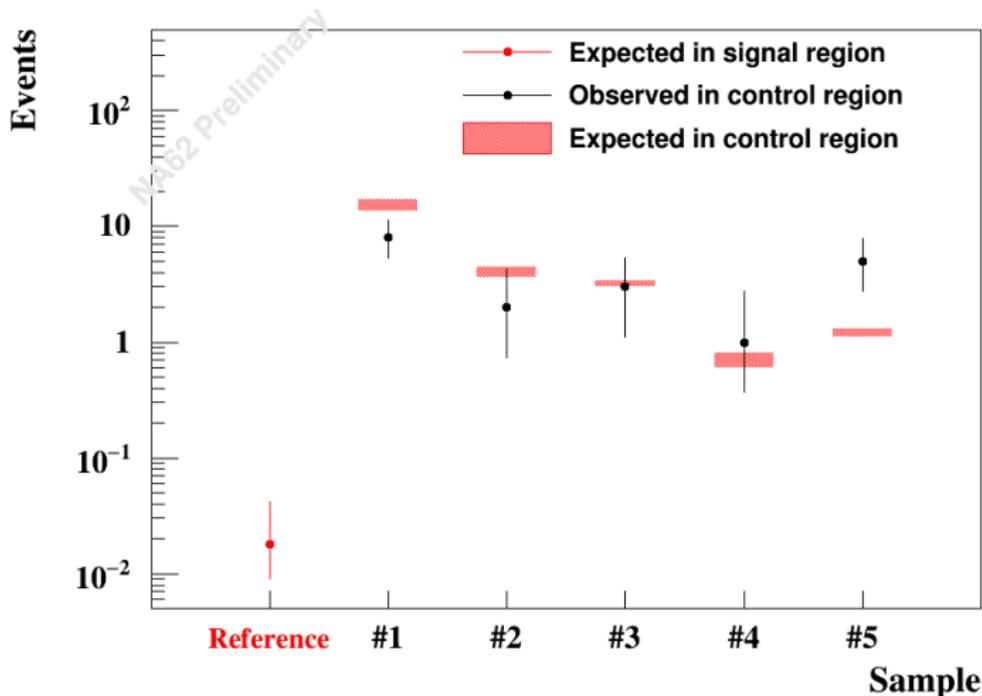
Single π^- events, full $\pi\nu\bar{\nu}$ selection, STRAW multiplicity cuts inverted.



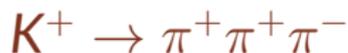
$0.026 < m_{\text{miss}}^2 < 0.072 \text{ GeV}^2/c^4$ region used for validation, free from other background processes.

$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ - Result

Five selections used for Data/MC comparison.



$$N_{\pi\pi e\nu}^{\text{exp.}} = 0.018_{-0.017}^{+0.024} \pm 0.009$$

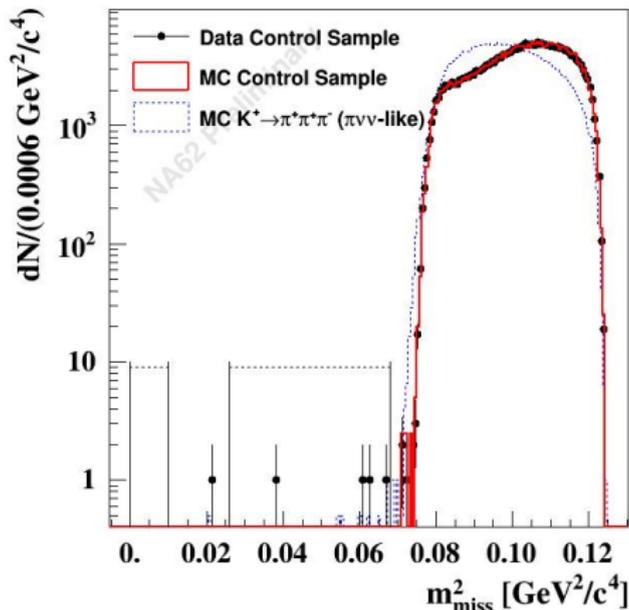


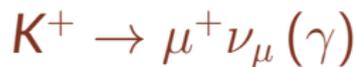
$$N_{\pi\pi\pi}^{\text{exp.}} = N_{\pi\pi\pi} (\pi^+ \pi^+ \pi^-) \cdot f^{\text{kin.}} \quad (\text{R2})$$

$N_{\pi\pi\pi}$ Events in $\pi^+ \pi^+ \pi^-$ region after $\pi^+ \nu \bar{\nu}$ selection

$f^{\text{kin.}}$ Measured on $\pi^+ \pi^+ \pi^-$ control sample selected tagging the $\pi^+ \pi^-$ pair

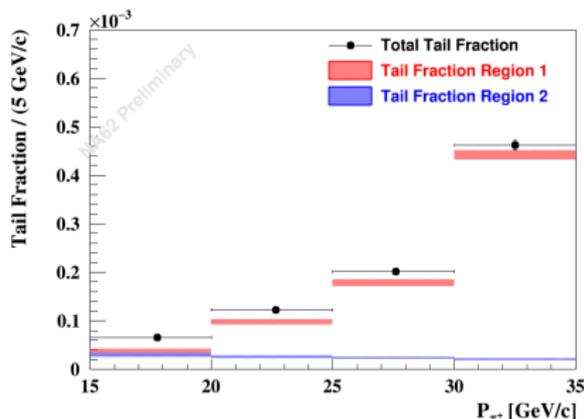
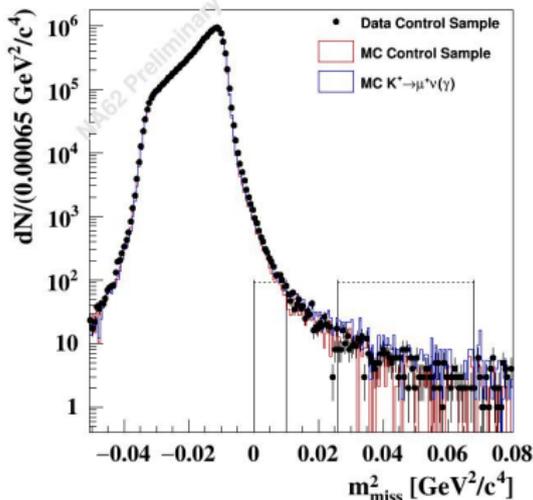
$f^{\text{kin.}} (\text{R2}) \leq 10^{-4}$, corrected for selection bias using the MC.





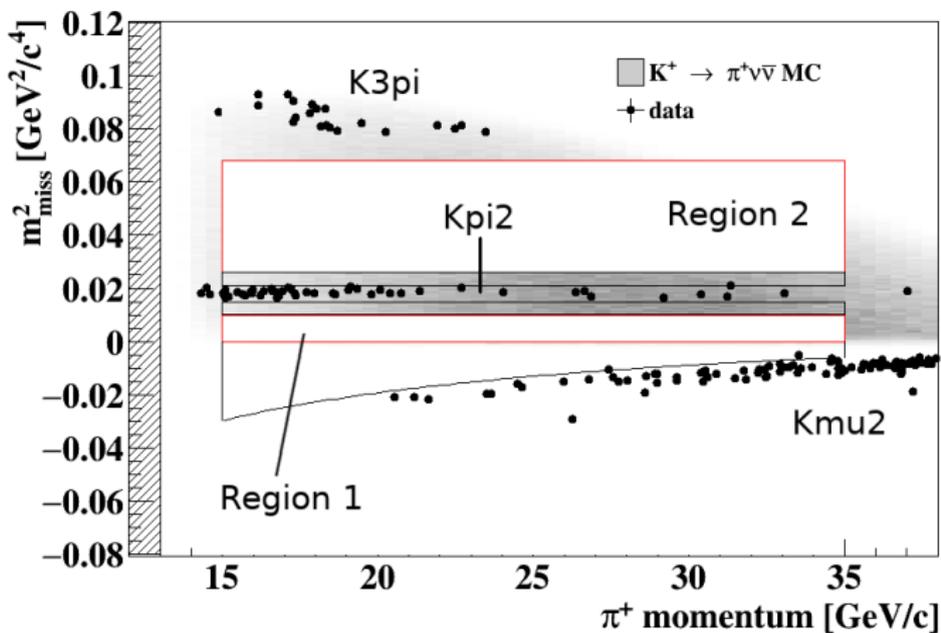
Same approach as $K^+ \rightarrow \pi^+ \pi^0 (\gamma)$, assume that PID rejection cuts and kinematic cuts are independent.

$$N_{\mu\mu}^{\text{exp.}}(\text{region}) = \sum_i \left[N_{\pi\pi}(\mu^+ \nu)_i \cdot f_i^{\text{kin.}}(\text{region}) \right]$$



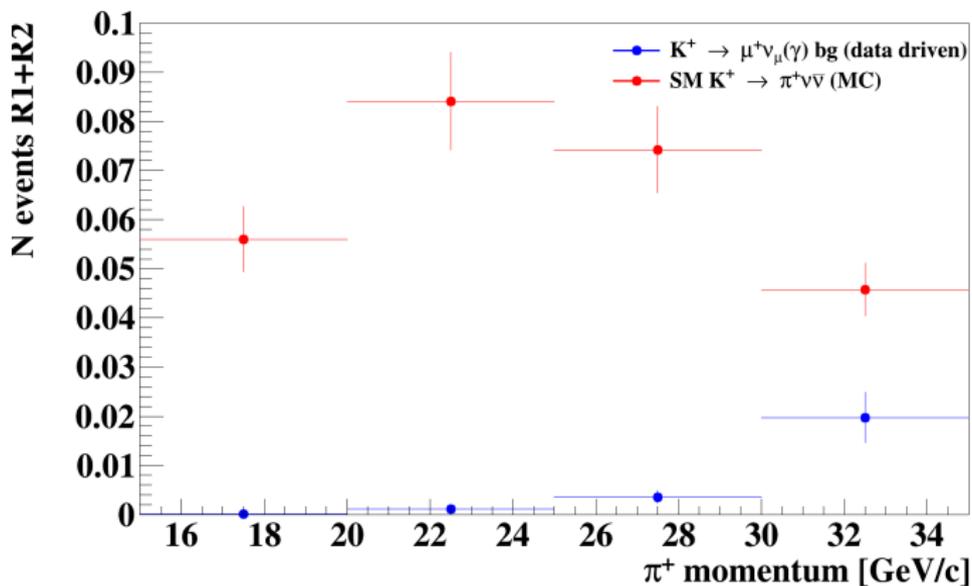
$f_i^{\text{kin.}}$ measured on $\mu^+ \nu_\mu$ sample, applying the γ rejection.

$K^+ \rightarrow \mu^+ \nu_\mu (\gamma)$ - Control Region



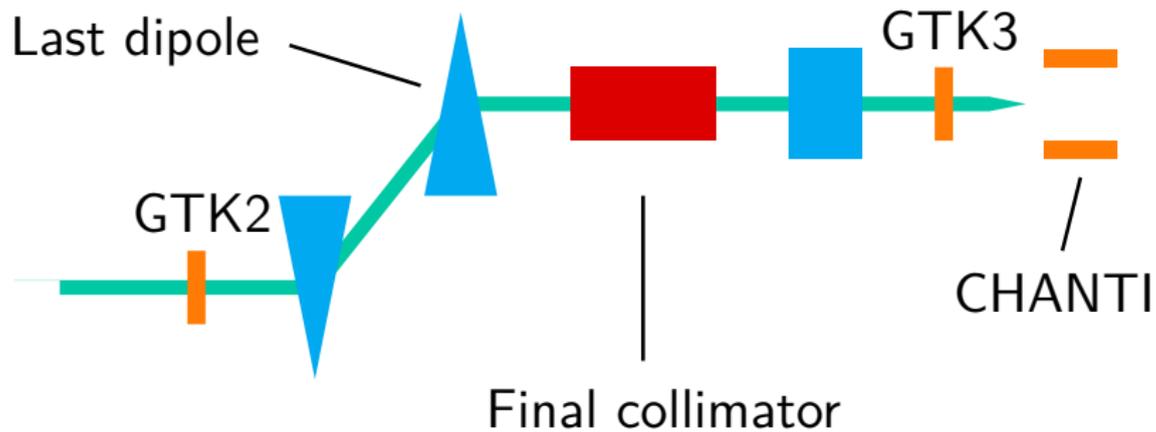
Region	$N_{\mu\nu(\gamma)}^{\text{exp.}}$	$N_{\mu\nu(\gamma)}^{\text{obs.}}$
CR	1.02 ± 0.16	2

$$K^+ \rightarrow \mu^+ \nu_\mu (\gamma)$$

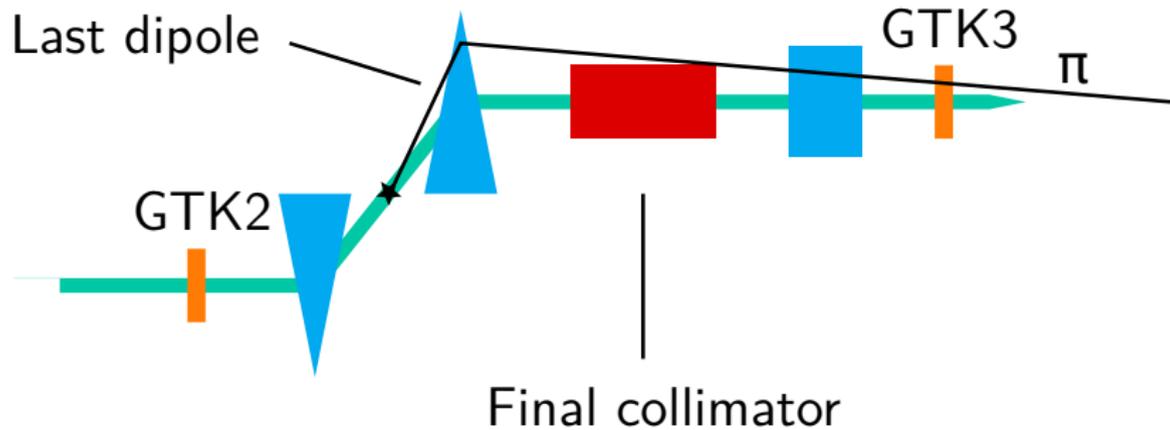


Region	$N_{\mu\nu(\gamma)}^{\text{exp.}}$
R1	$0.019 \pm 0.003 \pm 0.003$
R2	$0.0012 \pm 0.0002 \pm 0.0006$

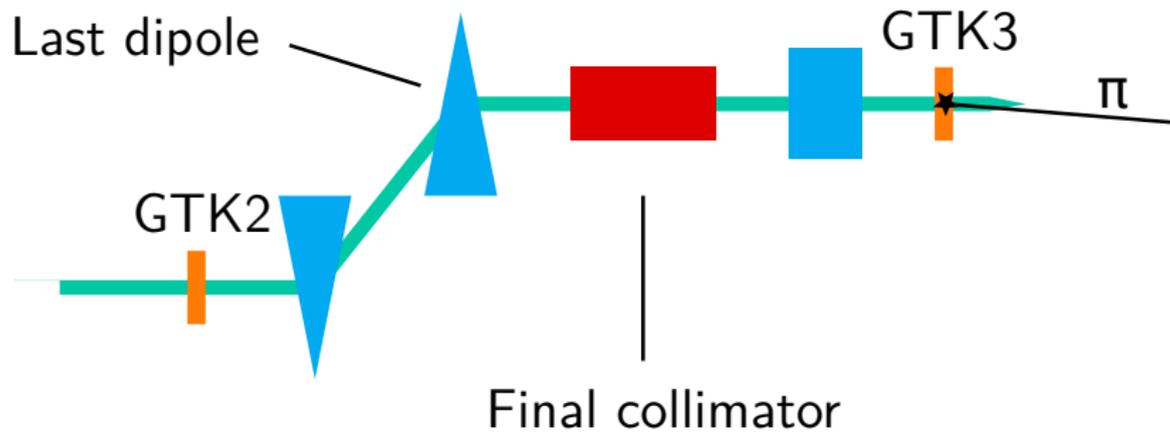
Upstream Backgrounds



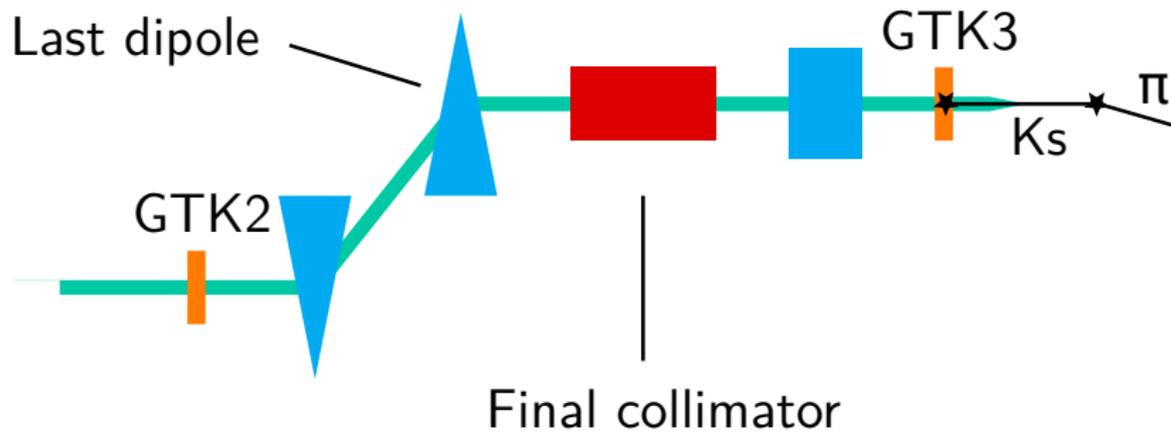
Upstream Backgrounds



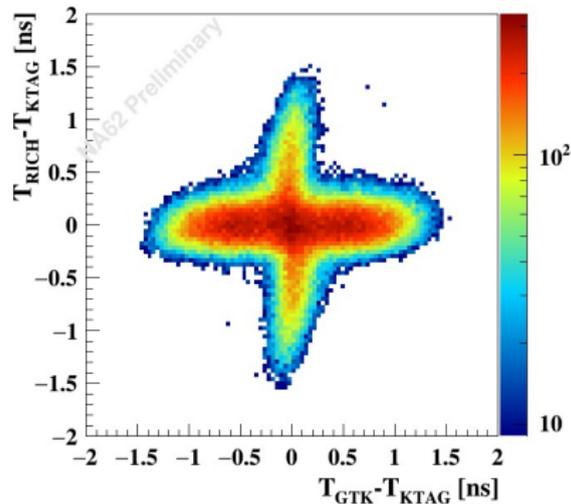
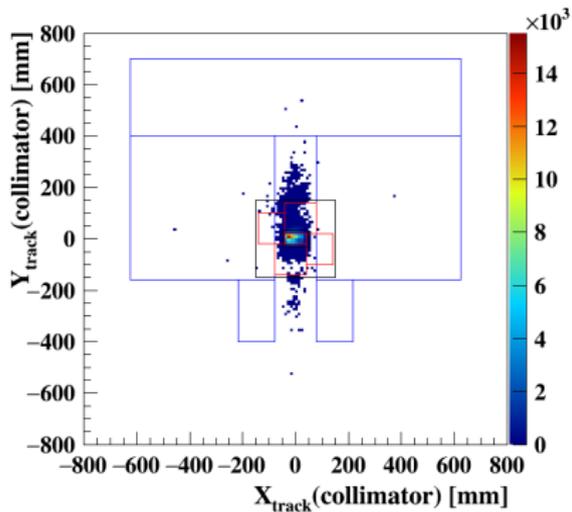
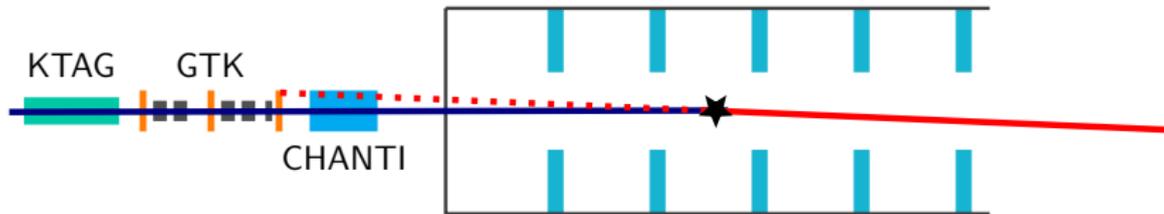
Upstream Backgrounds



Upstream Backgrounds

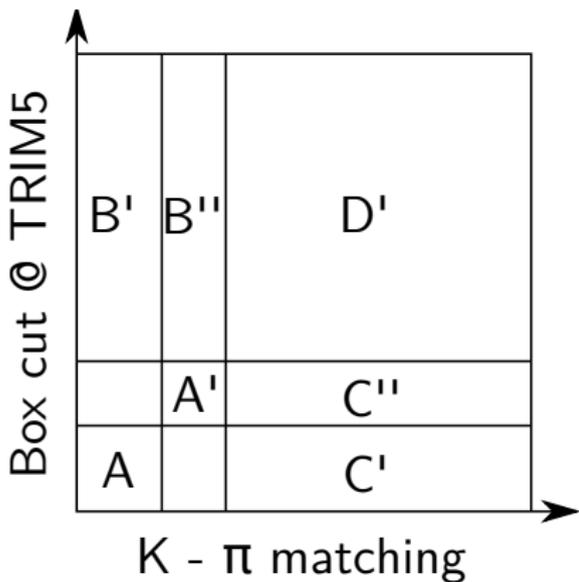


Upstream Backgrounds



Bifurcation Analysis

Estimate the number of background event in the signal region (A) using control regions B' , C' and D' :



A: signal region

A' : control region, B' , B'' , C' , C'' and D' : control samples.

If the two cuts are independent:

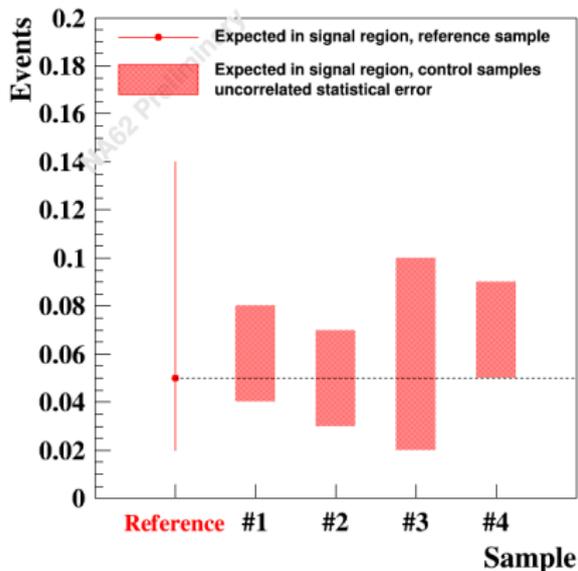
$$\rightarrow A = \frac{B'C'}{D'}$$

$$\rightarrow A' = \frac{B''C''}{D'}$$

Upstream Backgrounds – Result

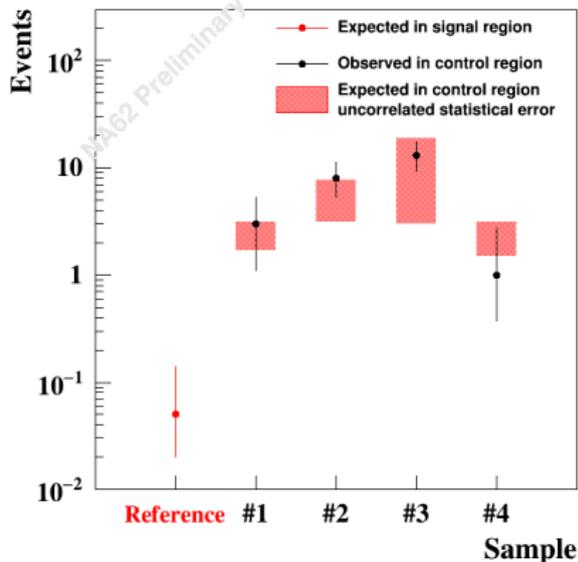
Method validated using four samples (different cut values).

Result



$$N_{\text{upstream}}^{\text{exp.}} = 0.050^{+0.090}_{-0.030}$$

Validation

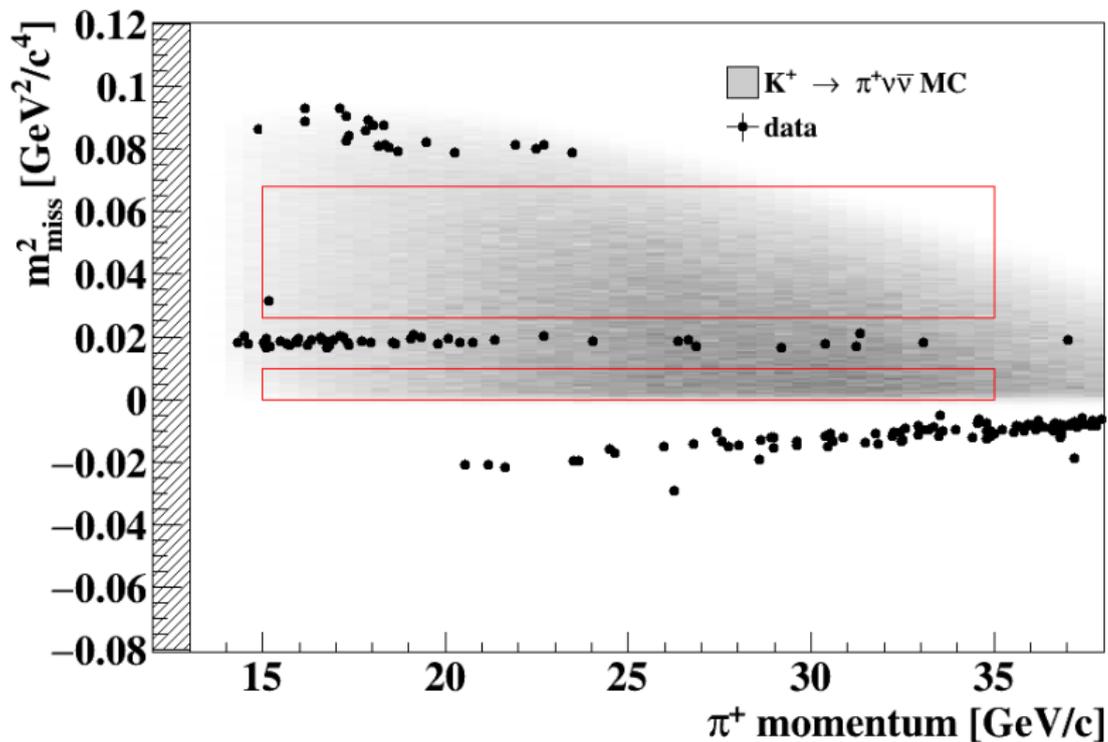


Backgrounds Summary

Process	Expected events		
	R1	R2	R1+R2
$K^+ \rightarrow \pi^+ \pi^0 (\gamma)$	0.022	0.037	$0.064 \pm 0.007 \pm 0.006$
Upstream backgrounds	-	-	$0.050^{+0.090}_{-0.030}$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	0	0.018	$0.018^{+0.024}_{-0.017} \pm 0.009$
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	0	0.0020	$0.002 \pm 0.001 \pm 0.002$
$K^+ \rightarrow \mu^+ \nu (\gamma)$	0.019	0.0012	$0.020 \pm 0.003 \pm 0.003$
Total backgrounds	-	-	$0.15 \pm 0.09 \pm 0.01$
$K^+ \rightarrow \pi^+ \nu \bar{\nu} (\text{SM})$	0.069	0.198	$0.267 \pm 0.001 \pm 0.020 \pm 0.032$

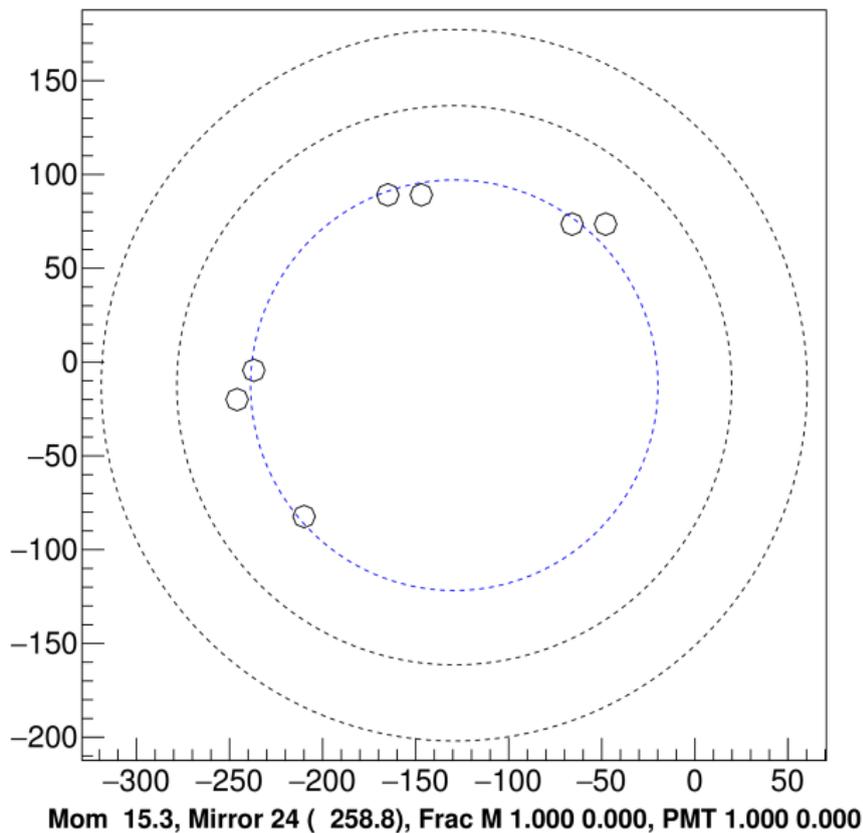
Preliminary Results

Preliminary Results



The Candidate in the RICH

Run 6646, burst 953, event 543854.



Cut based analysis of about 4 weeks worth of data.

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 14 \times 10^{-10} \text{ 95\% C.L.}$$

Candidate	1
N_K	$(1.21 \pm 0.02) \times 10^{11}$
SES	$(3.15 \pm 0.01 \pm 0.24) \times 10^{-10}$
Expected SM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$	$0.267 \pm 0.001 \pm 0.020 \pm 0.032_{\text{ext.}}$
Expected background	$0.15 \pm 0.09 \pm 0.01$

Decay-in-flight technique works!

More decays collected in 2017/2018:

- ▶ Data quality greatly improved in 2017/2018,
- ▶ Higher beam intensity (40–45% → 60–65% of nominal),
- ▶ 161 days in 2018, 217 days scheduled for 2018.

Already $> 10 \times$ more data on tape.

Other improvements:

- ▶ Copper plug added in 2017 to help mitigate upstream backgrounds,
- ▶ Adjustable final collimator to be replaced by fixed one,
- ▶ More sophisticated data analysis (cut base → multi-variate).

About 20 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ SM events expected before LS2 (end of 2018).

$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ - Theoretical Error Budget

The branching ratio, summing over the three neutrino flavours reads

[arXiv:hep-ph/0405132]:

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \kappa_+ (1 + \Delta_{\text{EM}}) \left[\left(\frac{\text{Im } \lambda_t}{\lambda^5} \chi_t(x_t) \right)^2 + \left(\frac{\text{Re } \lambda_c}{\lambda} [P_c + \delta P_{c,u}] + \frac{\text{Re } \lambda_t}{\lambda^5} \chi_t(x_t) \right)^2 \right], \quad (1)$$

where $\lambda_i = V_{is}^* V_{id}$, $x_t = m_t^2/M_W^2$. The parameter $\Delta_{\text{EM}} \approx -0.3\%$ encodes the QED long distance radiative corrections [arXiv:0705.2025v2].

$$\kappa_+ = (0.5173 \pm 0.0025) \times 10^{-10} \left(\frac{|V_{us}|}{0.225} \right)^8, \quad (2)$$

summarises the long-distance contributions extracted from the $K^+ \rightarrow \pi^0 e^+ \nu_e$ decay [arXiv:0705.2025v2].

$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ - Theoretical Error Budget

Table: Error budget of the parameters entering in the $K \rightarrow \pi \nu \bar{\nu}$ branching ratio computation [arXiv:1503.02693].

Quantity	Error budget (%)	Comment
$ V_{cb} $	9.9	-
γ	6.7	-
P_c	1.8	Charm quark contribution
$\delta P_{c,u}$	2.9	Long distance charm-quark contribution
X_t	0.9	Top-quark contribution
Other	0.5	-

KLEVER - $K_L \rightarrow \pi^0 \nu \bar{\nu}$

widthwidth