$K^+ \rightarrow \pi^+ \nu \overline{\nu}$ – NA62 First Result

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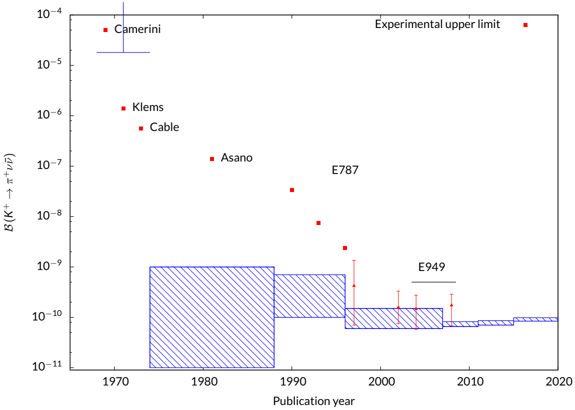
Palm Springs, CA, May 29, 2018

*TRIUMF, Vancouver, BC

Outline of the Talk

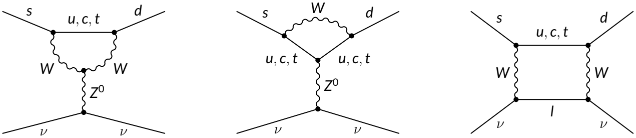
$K^+ \to \pi^+ \nu\overline{\nu}$ Decay

NA62 Experiment



In blue: Dahl 1969, Gaillard 1974, Ellis 1988, Buchalla 1996, Mescia 2007, Brod 2011 and Buras 2015

$K^+ \to \pi^+ \nu \bar{\nu}$ – 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 $K^+ \to \pi^0 e^+ \nu_e$ decay F. Mescia and C. Smith [arXiv:0705.2025]

In terms of the CKM parameters:

$$\mathcal{B}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = (8.39 \pm 0.30) \times 10^{-11} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2°}\right]^{0.74}$$

$$= (8.4 \pm 1.0) \times 10^{-11}$$

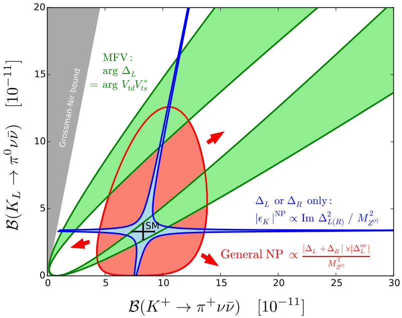
A. J. Buras et al [arXiv:1503.02693]

$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ E787/949 Collaboration [arXiv:0808.2459]

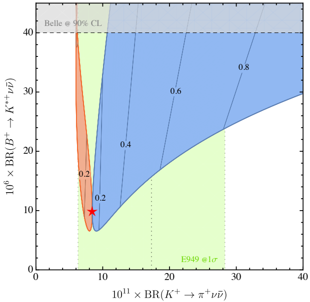
$K^+ \to \pi^+ \nu\bar{\nu}$ – Beyond the Standard Model

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

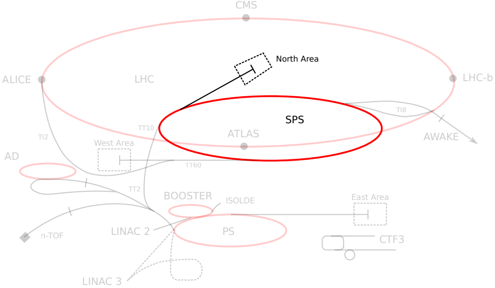
Setup & Measurement Principle

NA62 / CERN SPS

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

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

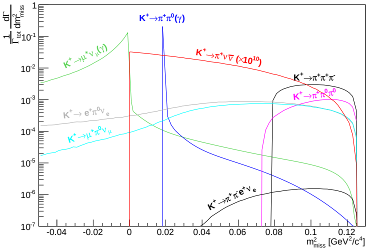
- 2005 Proposal,
- 2009 Approved,
- 2010 Technical design,
- 2012 Technical run,
- 2014–15 Pilot runs,
- 2016–18 Physics runs.

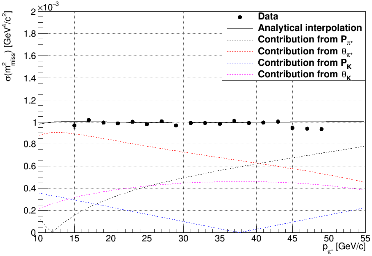


14 countries, 31 institutes, 214 authors.

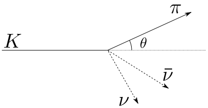
$K^+ \to \pi^+ \nu \bar{\nu}$ – Measurement Principle

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





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

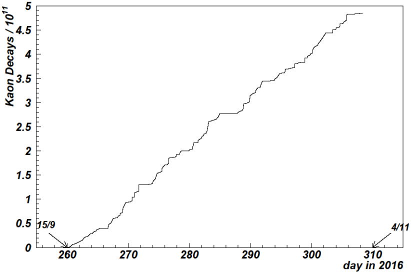


Main kaon backgrounds: $K^+ \to \mu^+ \nu_\mu\,(\gamma)$, $K^+ \to \pi^+ \pi^0\,(\gamma)$, $K^+ \to \pi^+ \pi^+ \pi^-$, $K^+ \to \pi^+ \pi^- e^+ \nu_e$.

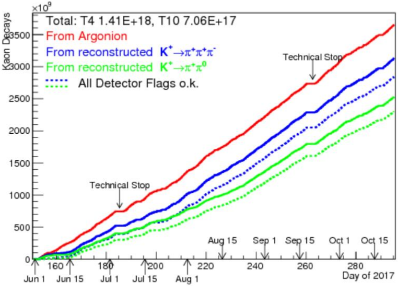
Kaon Collected

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 $\rightarrow$ about $10\times$ more data.

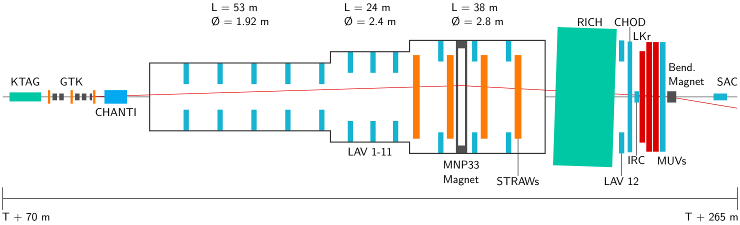


$\approx 1\times 10^{11}$ good K^+ decays.



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

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



NA62 Collaboration [arXiv:1703.08501]

Kaon & pion tracking, PID, calorimeters, hermetic photon vetos, muon veto, hodoscope and inelastic interactions veto $\rightarrow$ **redundancy.**

Minimize beam – gas interactions: vacuum 10^{-6} mbar.

Signal selection sketch: *K* - π association, $15 < P_\pi < 35$ GeV/*c*, decay vertex in fiducial volume, no photon / muon / upstream activity.

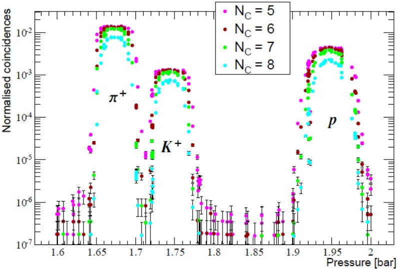
Signal Selection

Kaon Identification & Tracking

Average beam intensity: 2016 $\rightarrow$ 35 $-$ 40%, 2017–2018 $\rightarrow$ 60 $-$ 65%.

KTag – Diff. Cherenkov counter,

- N_2 (H_2) gas radiator,
- Kaon time resolution $\approx$ 70 ps,
- $>$ 98% K ID efficiency.



GigaTracker – Silicon pixel tracker,

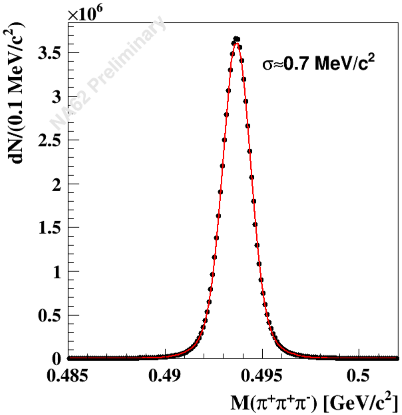
- Sensor surface is 60 by 27 mm – Match beam size,
- Thickness $\leq$ 0.5 % X/X_0 – Minimize beam induced background,
- Temporal resolution $<$ 150 ps – K^+ – π^+ matching.

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 μm walls,
- $X/X_0 < 1.8\%$,
- 70% Ar, 30% CO_2.

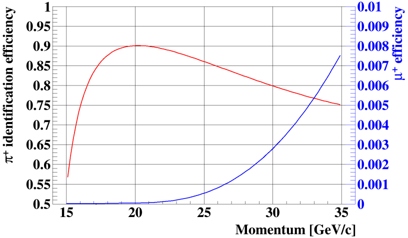


$>$ 95% reconstruction efficiency.

Pion / muon separation – RICH & Calorimeters

Ring-imaging Cherenkov detector,

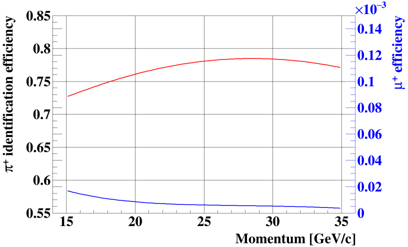
- Ne gas radiator,
- Ring time resolution $\approx$ 80 ps,
- μ/π separation $> 10^2$ ($15 < P < 35$ GeV/c).



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

Calorimeters,

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



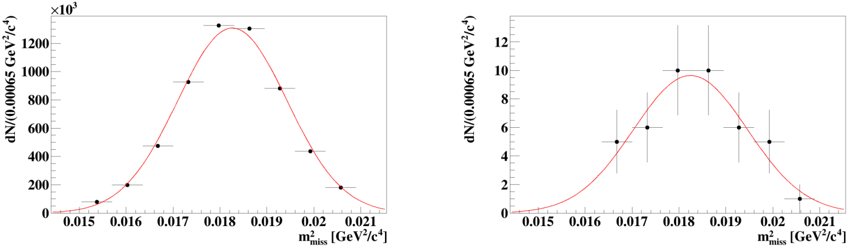
MUV3 and BDT classifier. Efficiency 0.6×10^{-5} / 0.77 for μ^+/π^+.

Photon VETOs

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.

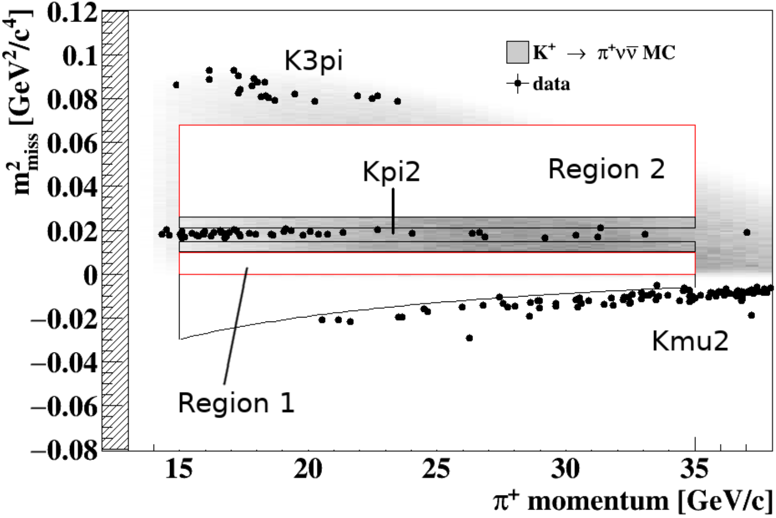
Typical timing coincidence: $\pm 3 / \pm 5$ ns, energy dependent for LKr.



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

Signal Selection – Result

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



Single Event Sensitivity

Single Event Sensitivity (SES)

$K^+ \to \pi^+\pi^0$ (from control data) used as normalization channel.

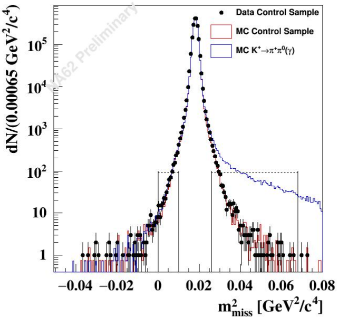
$K^+ \to \pi^+\nu\overline{\nu}$ acceptance (MC)	$(4.0 \pm 0.1) \times 10^{-2}$
Random veto efficiency	0.76 ± 0.04
Trigger efficiency	0.87 ± 0.2

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

Source	δ 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, kinematic rejection measured on $\pi^+\pi^0$ with *tagged* π^0 ($\gamma\gamma$ in LKr).



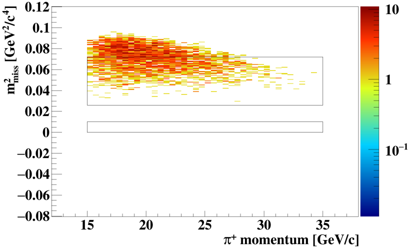
- Radiative tail in R2 estimated from MC,
- Single-γ veto efficiency measured on data,
- $\pi^0\gamma$ rejection on the radiative tail estimated from data.

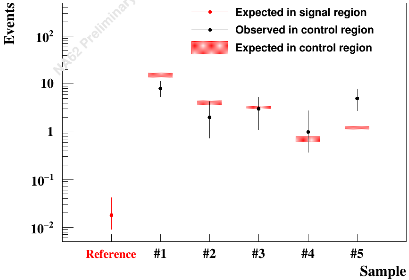
Radiative tail $\times 6$ bigger but $\pi^0\gamma$ rejection $\times 30$.

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

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

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



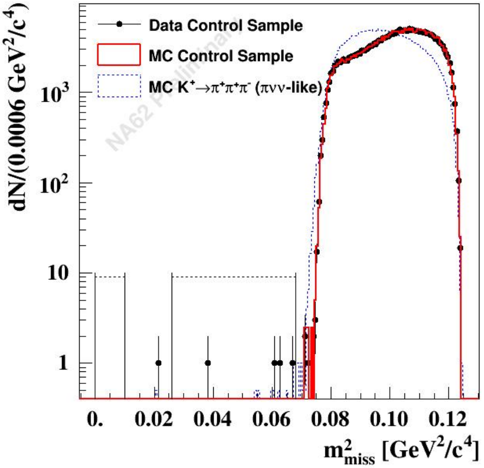


$0.026 < m^2_{\rm miss} < 0.072\,\mathrm{GeV}^2/c^4$ region used for validation, free from other background processes.

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

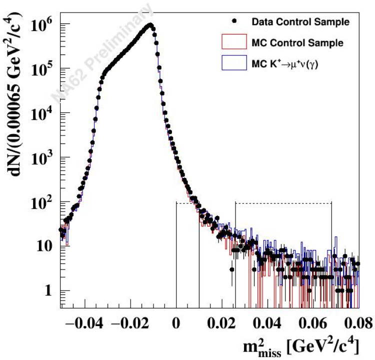
$N^{\rm exp.}_{\pi\pi e\nu} = 0.018^{+0.024}_{-0.017} \pm 0.009$

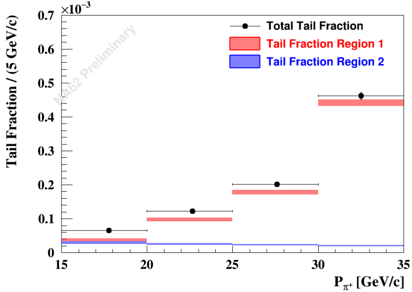
Kinematic rejection in R2 $\leq 10^{-4}$, corrected for selection bias using the MC.



$N^{\text{exp.}}_{\pi\pi\pi} = 0.002 \pm 0.001 \pm 0.002$

Same approach as $K^+ \to \pi^+\pi^0(\gamma)$, assume that PID rejection cuts and kinematic cuts are independent. Kinematic rejection measured on $\mu^+\nu_\mu$ sample, applying the γ rejection.

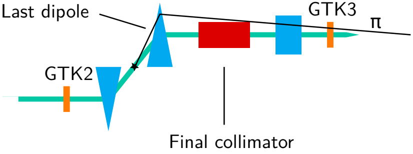


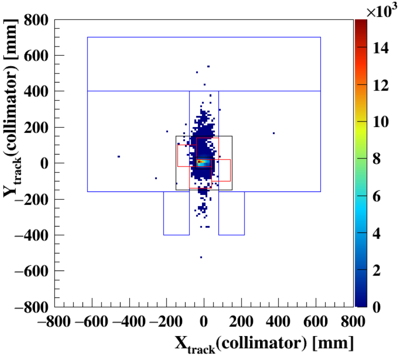


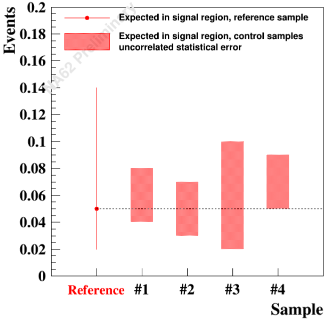
Region	$N^{\text{exp.}}_{\mu\nu(\gamma)}$
R1	$0.019 \pm 0.003 \pm 0.003$
R2	$0.0012 \pm 0.0002 \pm 0.0006$

Upstream Backgrounds

Estimation based on a “bifurcation” analysis.

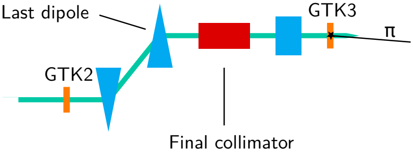


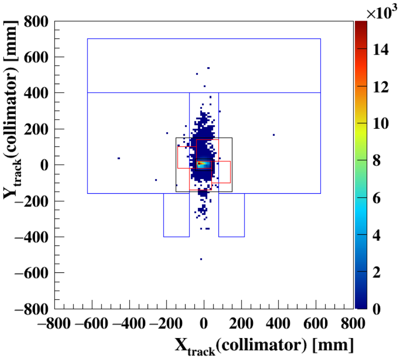


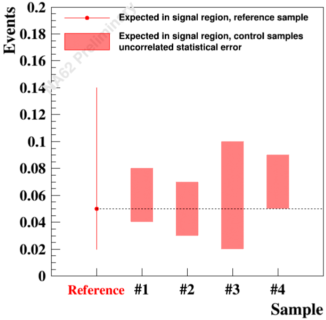


$$N^{exp.}_{\mathrm{upstream}} = 0.050^{+0.090}_{-0.030}$$

Estimation based on a “bifurcation” analysis.







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Upstream Backgrounds

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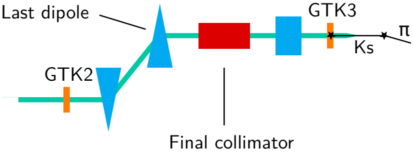
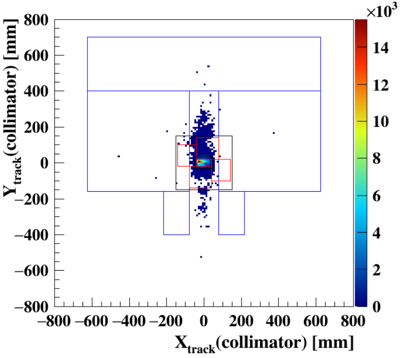
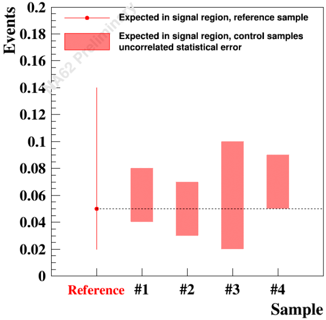






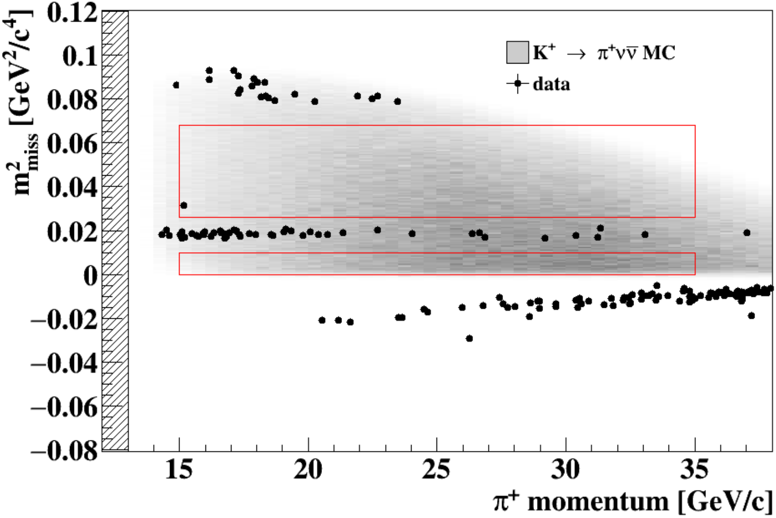
$$N^{exp.}_{\text{upstream}} = 0.050^{+0.090}_{-0.030}$$

Backgrounds Summary

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

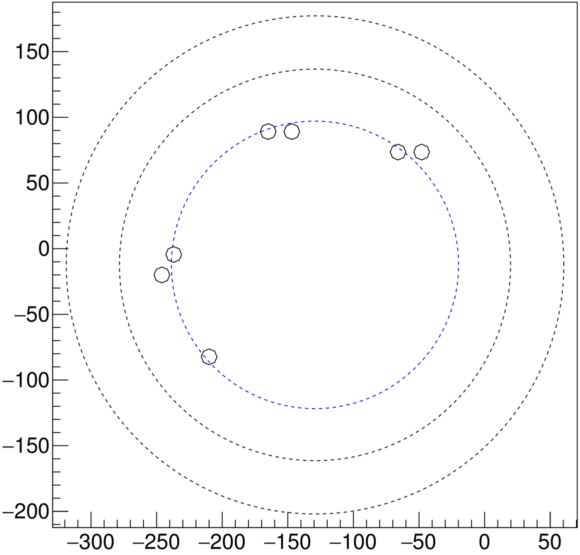
Preliminary Results

Preliminary Results



The Candidate in the RICH

Run 6646, burst 953, event 543854.



Mom 15.3, Mirror 24 (258.8), Frac M 1.000 0.000, PMT 1.000 0.000

2016 Data Set – Summary

Cut based analysis of about 4 weeks worth of data.

$$\mathcal{B}\left(K^+ \to \pi^+ \nu\overline{\nu}\right) < 14 \times 10^{-10}\ 95\%\ \mathrm{C.L.}$$

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 $K^+ \to \pi^+ \nu\overline{\nu}$	$0.267 \pm 0.001 \pm 0.020 \pm 0.032_{\mathrm{ext.}}$
Expected background	$0.15 \pm 0.09 \pm 0.01$

Decay-in-flight technique works!

Prospects

More decays collected in 2017/2018:

- Data quality greatly improved in 2017/2018,
- Higher beam intensity (40–45% $\rightarrow$ 60–65% of nominal),
- 161 days in 2018, 217 days scheduled for 2018,
- More sophisticated data analysis (cut base $\rightarrow$ multi-variate).

Already $> 20 \times$ more data on tape.

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

$\mathcal{B}\left(K^+ \to \pi^+\nu\overline{\nu}\right)$ – Theoretical Error Budget

The branching ratio, summing over the three neutrino flavours reads [arXiv:hep-ph/0405132]:

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

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

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

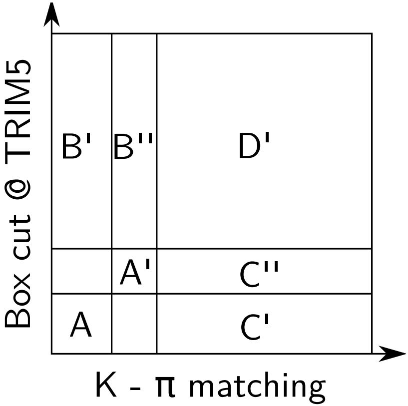
summarises the long-distance contributions extracted from the $K^+ \to \pi^0 e^+ \nu_e$ decay [arXiv:0705.2025v2].

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

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

Quantity	Error budget (%)	Comment
$\lvert V_{cb} \rvert$	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	–

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:

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

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